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Agreement in anterior segment measurements between swept-source and Scheimpflug-based optical biometries in keratoconic eyes: a pilot study

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Abstract

Background: Cataract surgery in keratoconic patients is challenging because of the corneal distortion, which can lead to inaccurate keratometry readings. This study is a comparison of the accuracy of keratometry readings by two types of devices in a tertiary hospital.

Purpose: To evaluate the comparability of corneal power measurements, anterior chamber depth (ACD), and white-to-white (WTW) distance between Scheimpflug-based tomography (Pentacam AXL; OCULUS GmbH, Wetzlar, Germany) and swept-source optical biometry (IOLMaster 700; Carl Zeiss Meditec AG, Jena, Germany) in patients with keratoconus.

Methods: This pilot, prospective, interinstrument reliability study included 30 keratoconic eyes of 15 individuals who had not undergone any kind of corneal surgery. Standard K and total refractive power (TK®) of the flattest and steepest axes of the IOLMaster 700 were compared with the standard keratometry (SimK), true net power (TNP), equivalent keratometer readings (EKR), and total corneal refractive power (TCRP) of the Pentacam. The Bland–Altman analysis was used to evaluate the agreement between the measurements of both devices. The paired-samples *t*-test and the Wilcoxon signed-rank test were performed to compare the mean values of the variables obtained with the devices.

Results: The K1 value of the IOLMaster 700 was significantly higher from EKR K1 along the 3-mm (mean difference: 0.79 diopters, $p = 0.01$), 4-mm (mean difference: 1.01 D, $p = 0.01$), and 4.5-mm zones (mean difference: 1.20 D, $p = 0.01$) and TNP K1 along the 3-mm (mean difference: 0.88 D, $p < 0.001$) and 4-mm zones (mean difference: 0.97 D, $p < 0.001$). The TK1 value was significantly higher from EKR K1 along the 2-mm (mean difference: 0.42 D, $p = 0.04$), 3-mm (mean difference: 0.83 D, $p = 0.003$), 4-mm (mean difference: 1.05 D, $p = 0.004$), and 4.5-mm zones (mean difference: 1.24 D, $p = 0.005$) and TNP K1 along the 3-mm (mean difference: 0.92 D, $p < 0.001$) and 4-mm zones (mean difference: 1.01 D, $p < 0.001$). The K2 value of the IOLMaster 700 was significantly higher from TK2 (mean difference: 0.11 D, $p = 0.04$) and all the corresponding variables of the Pentacam device. The TK2 value was significantly higher from all the corresponding variables of the Pentacam device. The Pentacam also yielded significantly lower values for the WTW distance (mean difference: 0.31 mm, $p < 0.001$) and no significant difference in terms of ACD values ($p = 0.9$).

Conclusion: The IOLMaster measured significantly greater keratometry readings in the steep axis for all the variables studied. The keratometry and WTW measurements of the investigated devices cannot be used interchangeably in keratoconus.

Keywords: IOLMaster 700, keratoconus, keratometry, Pentacam AXL, total refractive power

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Introduction

Keratoconus is a chronic and degenerative corneal ectatic disease, which is characterized by progressive thinning and steepening of the cornea.[1] As keratoconus patients age, the probability of developing cataract increases, even at a younger age than non-keratoconic eyes.[2,3] Patients with advanced keratoconus may choose to have a keratoplasty combined with cataract extraction and intraocular lens (IOL) implantation. However, patients who have maintained a good corrected vision with glasses or contact lenses prior to the onset of cataract may not want corneal surgery. In such patients, cataract surgery is challenging because of the corneal distortion which may make accurate keratometry impossible and introduce uncertainty when estimating the corneal power for IOL selection.[2–4]

Manual and automated keratometry are very common methods; however, they can be used to only examine the anterior surface of the cornea. Newer technologies including optical coherence tomography (OCT) and rotating Scheimpflug devices were developed to measure additionally the posterior corneal curvature.[5,6] The Pentacam AXL (OCULUS GmbH, Wetzlar, Germany) uses a rotating Scheimpflug camera (180°) and has a special 3-dimensional, high-resolution scanning mode, with which the camera captures 138,000 data points in fewer than 2 s. Therefore, a single scan can produce topographic maps of the anterior and posterior corneal surfaces, biometric measurements of the anterior segment, anterior and posterior corneal power calculations, and complete corneal pachymetry. Consequently, the entire cornea is analyzed in multiple ways. Except for the standard, simulated K (SimK) readings which are derived from the images taken exclusively from the anterior corneal surface over a 3-mm ring,[7] the Pentacam AXL also provides the equivalent keratometer readings (EKR), the total corneal refractive power (TCRP) map, and the true net power (TNP). EKR calculates power according to Snell's law using the refractive indices of the corneal tissue (i.e. 1.376) and aqueous humor (i.e. 1.336) and aggregating the values for anterior and posterior power, whereas TCRP uses ray tracing and takes into account how parallel light beams are refracted according to the relevant refractive indices, the exact location of refraction, and the slope of the surfaces.[7] TNP is the corneal power calculated using a slightly modified Gaussian optics formula for thick lenses,[8,9] which measures both the anterior and posterior surfaces of the cornea. It shows the optical power of the cornea based on the refractive indices of air, corneal tissue, and the aqueous humor. It also combines partial coherence interferometry for measuring the axial length.[7]

The IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) is a newer optical biometer which is based on the principle of swept-source OCT (SS-OCT) and enables the visualization of the complete longitudinal section of the eye.[10] It uses a telecentric technique for keratometric measurements, which is distance-independent,[11] and incorporates the influence of the posterior corneal curvature with the measurement of the total corneal power, total keratometry (TK®).[12] IOLMaster 700 uses a keratometric index of 1.3375 to convert the anterior corneal curvature measurements in millimeters to corneal power in diopters (D). It can even provide information on the central corneal shape by using the central topography software feature, which is based on telecentric 3-zone keratometry and SS-OCT. However, its agreement with other topographies, as well as the clinical significance of this newly introduced topography, remains to be further studied.

The objective of this pilot study was to assess the agreement of K readings, white-to-white (WTW) distance, and anterior chamber depth (ACD) obtained with the Pentacam AXL and IOLMaster 700 in eyes with keratoconus. A detailed analysis of the differences between the keratometry readings of a gold standard corneal topography such as the Pentacam AXL and the most recently introduced optical biometer IOLMaster 700 may provide further insights into the precise IOL power calculation for keratoconic patients with cataract.

Methods

For this prospective, comparative study, we enrolled 15 patients diagnosed with keratoconus based on slit-lamp findings (corneal stromal thinning, corneal protrusion at the apex, apical scar, Fleisher ring, or Vogt striae)[1] and topographic pattern characteristics. Exclusion criteria included corneal scarring or edema visible on slit-lamp examination, history of ocular trauma, contact lens wear, uveitis, glaucoma, optic nerve disease, and retinal disease. Patients with a prior history of surgical intervention such as corneal collagen cross-linking, corneal ring implantation, lamellar surgery, or penetrating keratoplasty were also excluded.

Our examination included general anamnesis to gather data regarding age, gender, and medical history. All participants underwent best corrected visual acuity examination with a Snellen chart, anterior slit-lamp biomicroscopy, intraocular pressure (IOP) measurement using the Goldmann applanation tonometer, and dilated pupil examination of the posterior segment. Prior to any manipulations to the eye, one of two experienced ophthalmologists performed three complete, device-specific automated independent measurements using the IOLMaster 700 (software version 1.88.1.64861) and Pentacam AXL (software version 1.22r05) under standardized conditions, and the averaged values were used for statistical analysis. All the examinations were conducted in the same dimly lit room, with a resting interval of 10 min between the examinations, from 11:00 to 13:00, to avoid the effects of diurnal variations in corneal indices. A standard methodology was used to obtain measurements on each device. All patients were asked to perform a complete blink every time just before the measurement, and they were told to sit back after each measurement to ensure the device was realigned before the next measurement. The measurements were considered acceptable only when they satisfied the quality criteria for each individual device according to the manufacturer's instructions. The order of measurement was chosen in a random way. The flat axis measurements were notated with number 1 and the steep axis measurements with number 2. The eyes were divided according to the Belin ABCD classification/grading system. The ABCD system is incorporated into the OCULUS Pentacam software and it was introduced in response to the shortcomings of the historical Amsler–Krumeich system and, in part, in response to the needs outlined in the Global Consensus on Keratoconus and Ectatic Diseases. The ABCD system utilizes four parameters. Parameter 'A' utilizes the anterior radius of curvature in the 3.0-mm zone centered on the thinnest location of the cornea. Parameter 'B' utilizes the posterior radius of curvature in the 3.0-mm zone centered on the thinnest location of the cornea. Parameter 'C' utilizes the thinnest pachymetry in μm, and parameter 'D' utilizes the distance best corrected visual acuity which was entered into the machine by the same experienced doctor.

Corneal power was measured and shown in the power distribution display of the Pentacam AXL for conventional K of the flattest (SimK1) and the steepest (SimK2) axes, the equivalent K-readings (EKR) of the flattest (EKR K1) and the steepest (EKR K2) axes in the 1-, 2-, 3-, 4-, and 4.5-mm zones centered on the pupil center, the TCRP of the flattest (TCRP K1) and the steepest (TCRP K2) axes in the 4-mm zone, and the TNP of the flattest (TNP K1) and the steepest (TNP K2) axes in the 3- and 4-mm zones centered on the apex. The external ACD values, which is the distance from the corneal epithelium to the anterior lens surface and the WTW distance, were also recorded. Using the IOLMaster 700, the flat K (K1), steep K (K2), and TK of the flat axis (TK1), TK of the steep axis (TK2), ACD, and WTW measurements were taken.

Statistical analysis was performed using SPSS 20.0.0 software (IBM Corporation, Armonk, NY, USA). The inter-eye correlation between the two eyes of each participant for all the keratometry values indicated poor consistency between the two eyes [intraclass correlation coefficient (ICC) range: 0.059–0.396].[13] The Kolmogorov–Smirnov test was used to check the normality of the data. The statistical significance of differences between the readings from the two devices was determined using the paired-samples *t*-test for normally distributed data and the Wilcoxon signed-rank test for data following non-normal distribution. The flat axis measurements K1 and TK1 were compared with each other and each one of them was compared with SimK1, EKR K1-1 mm, EKR K1-2 mm, EKR K1-3 mm, EKR K1-4 mm, EKR K1-4.5 mm, TCRP K1, TNP K1-3 mm, and TNP K1-4 mm. Accordingly, the steep axis measurements K2 and TK2 from the IOLMaster were compared between them and each one of them was compared with SimK2, EKR K2-1 mm, EKR K2-2 mm, EKR K2-3 mm, EKR K2-4 mm, EKR K2-4.5 mm, TCRP K2, TNP K2-3 mm, and TNP K2-4 mm. The external ACD and WTW distance of the Pentacam AXL device were compared with the ACD and WTW values provided by the IOLMaster 700, respectively. Bland–Altman plots were used to graphically present the agreement between the two devices. The mean difference and 95% limits of agreement (LoA) were calculated by mean difference ± 1.96 SD of the differences,

Table 1. Number of eyes in each element of the ABCD keratoconus classification system ($n = 30$).

Stage	Parameter 'A', ARC 3-mm zone at TP	Parameter 'B', PRC 3-mm zone at TP	Parameter 'C', thinnest pachymetry	Parameter 'D', DCVA
0	11	3	13	11
1	2	5	9	13
2	11	6	6	6
3	3	3	2	0
4	3	13	0	0

ARC, anterior radius of curvature (mm) at the 3-mm zone; DCVA, distance corrected visual acuity; PRC, posterior radius of curvature (mm) at the 3-mm zone; TP, corneal thickness at the thinnest point (μm).

which provides an interval within which 95% of the differences between the measurements were expected to lie.[14] A p-value less than 0.05 was considered statistically significant.

Results

A total of 30 eyes of 15 individuals who had been diagnosed with keratoconus bilaterally were included in our study. According to the Pentacam SimK measurements, 26 eyes (i.e. 86.7%) had a maximum K value of less than 50.0 D, 3 eyes had a maximum K value between 50.0 D and 55.0 D, and 1 eye had a maximum K value of 58.7 D. Of these, 22 eyes (i.e. 73.3%) showed mean keratometry readings < 47.0 D, 5 eyes had mean keratometry readings between ⩾ 47.0 D and < 52.0 D, and 3 eyes showed mean keratometry readings ⩾ 52.0 D. The number of eyes in each stage for each element of the ABCD keratoconus classification system is presented in Table 1. The mean age of the patients was 35.07 ± 12.07 years (range: 19–52 years); 14 patients were men and 1 patient was a woman. The mean best corrected visual acuity was 0.78 ± 0.22 (range: 0.3–1.0).

Table 2 shows the mean measurements, the p-value and the LoA of the comparisons between K1 and K2 obtained with IOLMaster 700, and the keratometric variables obtained with Pentacam AXL. The Pentacam AXL exhibited statistically significantly lower keratometry values than the corresponding variables of the IOLMaster 700 for all the variables studied, except for the comparison between the SimK and the standard K of the flat axis, between the EKR along 1- and 2-mm zones and the standard K of the flat axis, as well as between the TCRP and the standard K of the flat axis. Table 2 also shows the comparison between the K1 and TK1 values, as well as the K2 and TK2 of the IOLMaster 700. The standard K of the flat corneal axis did not significantly differ from the corresponding TK1 ($p = 0.4$), while the standard K of the steep axis was significantly higher than the corresponding TK2 ($p = 0.04$) of the IOLMaster 700.

Figure 1 shows the Bland–Altman plots for the Pentacam AXL SimK1, SimK2, EKR K1-1 mm, EKR K2-1 mm, EKR K1-2 mm, EKR K2-2 mm, TCRP K1, and TCRP K2 and the corresponding standard K values of the IOLMaster 700. The mean difference was the lowest for the comparison between the Pentacam TCRP K1 and the IOLMaster 700 K1, with −0.1 D and relatively wide 95% LoA of 3.472 and −3.689, and the greatest for the comparison between the Pentacam EKR K2-1 mm and the IOLMaster 700 K2, with −2.81 D and 95% LoA of 1.871 and −7.492.

Table 3 demonstrates the mean measurements, the p-value, and the LoA of the comparisons between the TK1 and TK2 obtained with IOLMaster 700 and their corresponding keratometric variables obtained with Pentacam AXL. The mean Pentacam SimK of the flat axis did not differ significantly from the TK1 ($p = 0.2$), whereas the mean SimK of the steep axis was significantly lower than the TK2 ($p = 0.02$) of the IOLMaster 700. The Pentacam AXL exhibited significantly lower keratometry values than the corresponding variables of the IOLMaster 700 for all the other variables studied, except for the comparison between the EKR-1-mm and the TK of the flat axis, as well as between the TCRP and the TK1 of the flat axis. In addition, Table 3 shows the comparison between the two devices for the ACD and WTW distance. The Pentacam AXL

Table 2. Comparison of standard keratometry values of the flattest and the steepest axes of the IOLMaster 700 with the keratometric variables obtained from Pentacam AXL.

Parameters	Pentacam AXL (mean ± SD)	IOLMaster 700 (mean ± SD)	Difference (mean ± SD)	*p*-value	Upper LoA	Lower LoA
K1 (IOLMaster) *versus* TK1		43.70 ± 2.89 (K1) 43.74 ± 2.72 (TK1)	−0.03 ± 0.28	0.4[a]	0.175	−0.954
K2 (IOLMaster) *versus* TK2		47.45 ± 3.62 (K2) 47.33 ± 3.47 (TK2)	0.11 ± 0.30	**0.04**[a]	0.706	−0.472
SimK1 *versus* K1 (IOLMaster)	43.91 ± 2.74	43.70 ± 2.89	0.20 ± 0.79	0.1[a]	1.768	−1.351
SimK2 *versus* K2 (IOLMaster)	46.88 ± 3.03	47.45 ± 3.62	−0.56 ± 1.02	**0.001**[b]	1.450	−2.575
EKR K1-1 mm *versus* K1 (IOLMaster)	43.82 ± 3.59	43.70 ± 2.89	0.12 ± 1.37	0.6[a]	2.819	−2.572
EKR K2-1 mm *versus* K2 (IOLMaster)	44.64 ± 3.57	47.45 ± 3.62	−2.81 ± 2.38	< **0.001**[b]	1.871	−7.492
EKR K1-2 mm *versus* K1 (IOLMaster)	43.32 ± 2.91	43.70 ± 2.89	−0.38 ± 1.20	0.1[b]	1.973	−2.735
EKR K2-2 mm *versus* K2 (IOLMaster)	44.90 ± 3.04	47.45 ± 3.62	−2.54 ± 2.33	< **0.001**[b]	2.030	−7.123
EKR K1-3 mm *versus* K1 (IOLMaster)	42.91 ± 2.76	43.70 ± 2.89	−0.79 ± 1.57	**0.01**[a]	2.284	−3.869
EKR K2-3 mm *versus* K2 (IOLMaster)	44.99 ± 2.67	47.45 ± 3.62	−2.45 ± 2.02	< **0.001**[a]	1.506	−6.417
EKR K1-4 mm *versus* K1 (IOLMaster)	42.68 ± 2.54	43.70 ± 2.89	−1.01 ± 2.04	**0.01**[a]	2.982	−5.021
EKR K2-4 mm *versus* K2 (IOLMaster)	45.03 ± 2.37	47.45 ± 3.62	−2.41 ± 1.98	< **0.001**[a]	1.469	−6.302
EKR K1-4.5 mm *versus* K1 (IOLMaster)	42.50 ± 2.11	43.70 ± 2.89	−1.20 ± 2.38	**0.01**[a]	3.477	−5.884
EKR K2-4.5 mm *versus* K2 (IOLMaster)	44.94 ± 2.01	47.45 ± 3.62	−2.50 ± 2.58	< **0.001**[a]	2.561	−7.576
TCRP K1 *versus* K1 (IOLMaster)	43.59 ± 1.88	43.70 ± 2.89	−0.10 ± 1.82	0.7[b]	3.472	−3.689
TCRP K2 *versus* K2 (IOLMaster)	46.22 ± 2.32	47.45 ± 3.62	−1.23 ± 1.87	< **0.001**[b]	2.445	−4.907
TNP K1-3 mm *versus* K1 (IOLMaster)	42.82 ± 2.98	43.70 ± 2.89	−0.88 ± 1.06	< **0.001**[a]	1.196	−2.965
TNP K2-3 mm *versus* K2 (IOLMaster)	45.81 ± 3.38	47.45 ± 3.62	−1.63 ± 1.05	< **0.001**[a]	0.432	−3.702
TNP K1-4 mm *versus* K1 (IOLMaster)	42.72 ± 2.56	43.70 ± 2.89	−0.97 ± 1.10	< **0.001**[a]	1.196	−3.151
TNP K2-4 mm *versus* K2 (IOLMaster)	45.50 ± 2.93	47.45 ± 3.62	−1.94 ± 1.17	< **0.001**[b]	0.367	−4.257

EKR, equivalent keratometer readings; IOL, intraocular lens; K1, corneal power of the flat axis; K2, corneal power of the steep axis; LoA, limits of agreement; SimK, simulated K; TCRP, total corneal refractive power; TK, total keratometry obtained with IOLMaster 700; TNP, true net power.
[a]Paired-samples *t*-test.
[b]Wilcoxon signed-rank test.

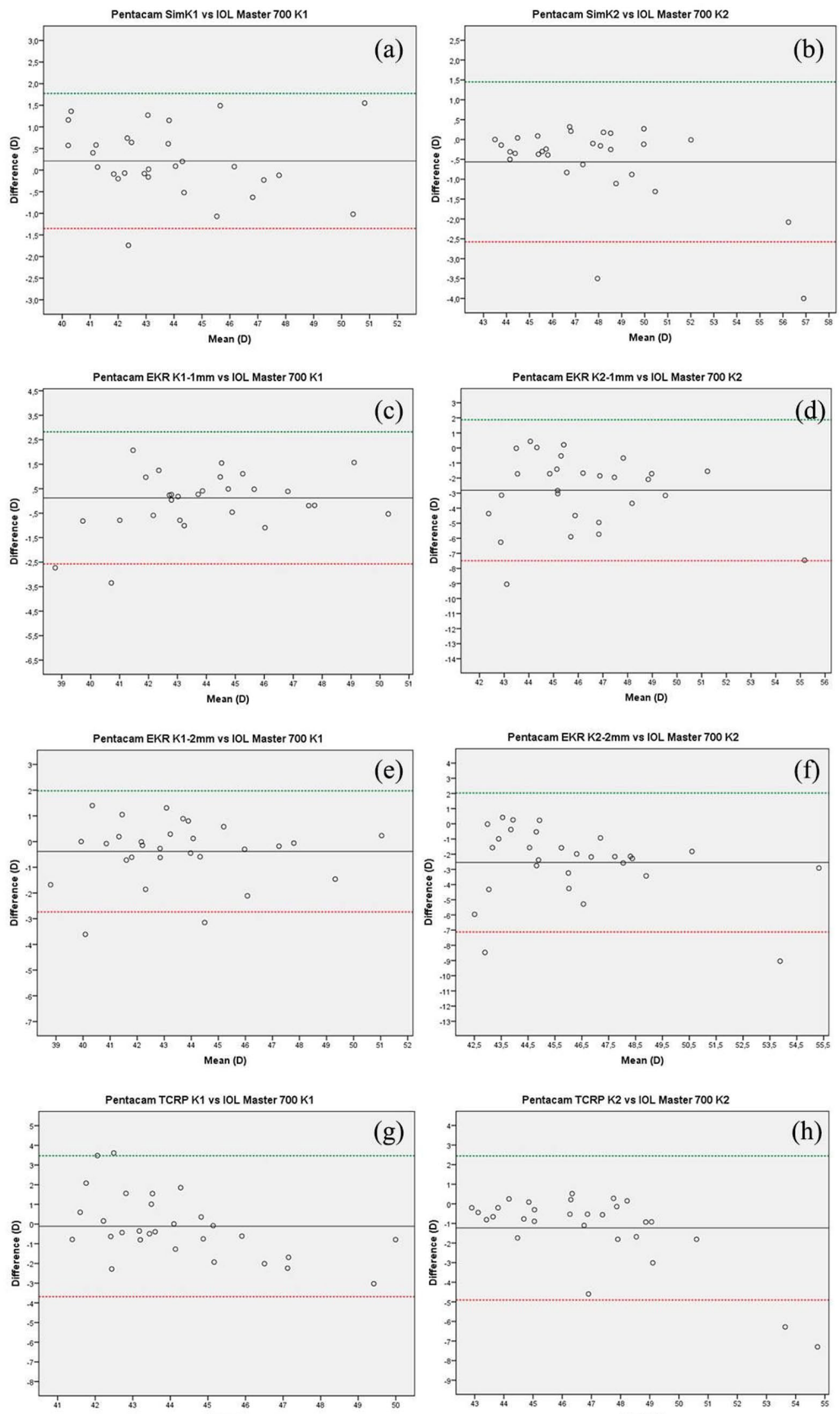


Figure 1. Evaluation of agreement between standard keratometry values (K) of swept-source optical biometry and Scheimpflug-based topography measurements of anterior segment parameters. Bland–Altman plots for the (a) Pentacam AXL SimK1 and IOLMaster 700 K1, (b) Pentacam AXL SimK2 and IOLMaster 700 K2, (c) Pentacam AXL EKR K1-1 mm and IOLMaster 700 K1, (d) Pentacam AXL EKR K2-1 mm and IOLMaster 700 K2, (e) Pentacam AXL EKR K1-2 mm and IOLMaster 700 K1, (f) Pentacam AXL EKR K2-2 mm and IOLMaster 700 K2, (g) Pentacam AXL TCRP K1 and IOLMaster 700 K1, and (h) Pentacam AXL TCRP K2 and IOLMaster 700 K2. The middle line shows the mean difference, while the top, dashed, green line and the bottom, dashed, red line show the upper and lower 95% limits of agreement, respectively. The Bland–Altman graphs of (a), (c), (e), and (g) show a mean difference near 0, implying that the measurements are somewhat comparable. The mean difference was the lowest for the comparison in (g), with −0.1 D and relatively wide 95% LoA of 3.472 and −3.689, and the greatest for the comparison in (d), with −2.81 D and 95% LoA of 1.871 and −7.492.

Table 3. Comparison of the ACD, WTW distance, and the TK readings of the flattest and the steepest axes of the IOLMaster 700 with their corresponding variables obtained from Pentacam AXL.

Parameters	Pentacam AXL (mean ± SD)	IOLMaster 700 (mean ± SD)	Difference (mean ± SD)	*p*-value	Upper LoA	Lower LoA
SimK1 *versus* TK1	43.91 ± 2.74	43.74 ± 2.72	0.16 ± 0.71	0.2[a]	0.169	0.714
SimK2 *versus* TK2	46.88 ± 3.03	47.33 ± 3.47	−0.44 ± 0.99	**0.02**[b]	1.499	−2.389
EKR K1-1 mm *versus* TK1	43.82 ± 3.59	43.74 ± 2.72	0.08 ± 1.41	0.7[a]	2.864	−2.695
EKR K2-1 mm *versus* TK2	44.64 ± 3.57	47.33 ± 3.47	−2.69 ± 2.41	**< 0.001**[a]	2.035	−7.421
EKR K1-2 mm *versus* TK1	43.32 ± 2.91	43.74 ± 2.72	−0.42 ± 1.08	**0.04**[a]	1.710	−2.550
EKR K2-2 mm *versus* TK2	44.90 ± 3.04	47.33 ± 3.47	−2.42 ± 2.29	**< 0.001**[b]	2.067	−6.925
EKR K1-3 mm *versus* TK1	42.91 ± 2.76	43.74 ± 2.72	−0.83 ± 1.37	**0.003**[a]	1.872	−3.534
EKR K2-3 mm *versus* TK2	44.99 ± 2.67	47.33 ± 3.47	−2.33 ± 1.90	**< 0.001**[b]	1.387	−6.064
EKR K1-4 mm *versus* TK1	42.68 ± 2.54	43.74 ± 2.72	−1.05 ± 1.82	**0.004**[a]	2.527	−4.644
EKR K2-4 mm *versus* TK2	45.03 ± 2.37	47.33 ± 3.47	−2.29 ± 1.80	**< 0.001**[a]	1.244	−5.842
EKR K1-4.5 mm *versus* TK1	42.50 ± 2.11	43.74 ± 2.72	−1.24 ± 2.17	**0.005**[a]	3.014	−5.499
EKR K2-4.5 mm *versus* TK2	44.94 ± 2.01	47.33 ± 3.47	−2.39 ± 2.42	**< 0.001**[b]	2.365	−7.147
TCRP K1 *versus* TK1	43.59 ± 1.88	43.74 ± 2.72	−0.14 ± 1.62	0.6[a]	3.042	−3.337
TCRP K2 *versus* TK2	46.22 ± 2.32	47.33 ± 3.47	−1.11 ± 1.73	**< 0.001**[b]	2.288	−4.516
TNP K1-3 mm *versus* TK1	42.82 ± 2.98	43.74 ± 2.72	−0.92 ± 1.00	**< 0.001**[b]	1.041	−2.887
TNP K2-3 mm *versus* TK2	45.81 ± 3.38	47.33 ± 3.47	−1.51 ± 1.00	**< 0.001**[b]	0.458	−3.493
TNP K1-4 mm *versus* TK1	42.72 ± 2.56	43.74 ± 2.72	−1.01 ± 0.96	**< 0.001**[a]	0.874	−2.907
TNP K2-4 mm *versus* TK2	45.50 ± 2.93	47.33 ± 3.47	−1.82 ± 1.07	**< 0.001**[b]	0.288	−3.944
ACD (mm)	3.74 ± 0.23	3.74 ± 0.24	0.0006 ± 0.03	0.9[a]	0.077	−0.076
WTW (mm)	12.06 ± 0.36	12.38 ± 0.39	−0.31 ± 0.11	**< 0.001**[b]	−0.088	−0.545

ACD, anterior chamber depth; EKR, equivalent keratometer readings; IOL, intraocular lens; K1, corneal power of the flat axis; K2, corneal power of the steep axis; LoA, limits of agreement; SimK, simulated K; TK, total keratometry obtained with IOLMaster 700; TCRP, total corneal refractive power; TNP, true net power; WTW, white-to-white.
[a]Paired-samples *t*-test.
[b]Wilcoxon signed-rank test.

yielded statistically significantly lower mean values for the WTW distance ($p < 0.001$), while our analysis showed no significant difference in terms of ACD values ($p = 0.9$).

Figure 2 shows the corresponding Bland–Altman plots for the Pentacam AXL SimK1, SimK2, EKR K1-1 mm, EKR K2-1 mm, TCRP K1, and TCRP K2 and the corresponding TK values of the IOLMaster 700. The plots showed high agreement and narrow 95% LoA only for the comparison between the Pentacam SimK1, EKR K1-1 mm, and TCRP K1 and their corresponding TK values of the IOLMaster 700. The mean difference in the keratometry values was the lowest for the comparison between the Pentacam EKR K1-1 mm and the IOLMaster 700 TK1, with 0.08 D and 95% LoA of 2.864 and −2.695, and the greatest for the comparison between the Pentacam EKR K2-1 mm and the IOLMaster 700 TK2, with −2.69 D and 95% LoA of 2.035 and −7.421.

Figures 3 and 4 demonstrate the mean keratometry values of the two devices for the flattest and the steepest corneal axes, respectively. Figure 4 clearly delineates that the K2 of IOLMaster 700 was higher than any of the other keratometry values obtained from the two devices.

Discussion

This study was designed to assess the comparability of one widely used instrument, the Pentacam AXL, and a newer optical biometer, the IOLMaster 700, in eyes with keratoconus. We concluded that all the Pentacam keratometry measurements were flatter than the IOLMaster 700 readings in the steep axis measurements, fairly significant for keratoconic eyes. For the differences between the keratometry values obtained by the IOLMaster 700 and EKR measurements in the flattest axis, we also observed that, as the diameter of the corneal zone increased, the 95% LoA values were extended. This can be explained by the asymmetrical peripheral placement of the corneal apex in keratoconic eyes. To our knowledge, this is the first study to examine the comparability of these two devices in measuring the corneal power in keratoconic eyes.

From the results of this pilot study, it would appear that the K1 value of the IOLMaster 700 did not differ significantly from TK1, SimK1, EKR K1-1 mm, EKR K1-2 mm, and TCRP K1, while it was significantly higher from EKR K1-3 mm, EKR K1-4 mm, EKR K1-4,5 mm, TNP K1-3 mm, and TNP K1-4 mm (Figure 3(a)). The TK1 value did not differ significantly from SimK1, EKR K1-1 mm, and TCRP K1, while it was significantly higher from EKR K1-2 mm, EKR K1-3 mm, EKR K1-4 mm, EKR K1-4,5 mm, TNP K1-3 mm, and TNP K1-4 mm (Figure 3(b)). The K2 value of the IOLMaster 700 was significantly higher from TK2 and all the corresponding variables of the Pentacam device (Figure 4(a)). The TK2 value was significantly higher from all the corresponding variables of the Pentacam device (Figure 4(b)). The two devices were in agreement with the ACD values, while the Pentacam AXL yielded significantly lower mean values for the WTW distance.

The agreement between the Scheimpflug camera and the various other devices in measuring the corneal curvature in keratoconic eyes has been studied by many researchers. Viswanathan *et al.*[15] studied the agreement between Pentacam and Visante OMNI which is a Placido-OCT device and showed that the Pentacam measured significantly greater SimK readings in keratoconic eyes. Shetty *et al.*[16] assessed the agreement between three Scheimpflug cameras – Pentacam, Galilei, and Sirius – in keratoconus and concluded that they cannot be used interchangeably. Mirzajani *et al.*[17] compared the curvature measurements of five corneal rings in keratoconus patients using Orbscan and Pentacam and observed that the Pentacam measurements were steeper than the Orbscan measurements for all the corneal rings except for the 5-mm ring. Ortiz-Toquero *et al.*[18] suggested that the Placido-based topography underestimated the mean simulated keratometry, flat K, and steep K when compared with the dual-Scheimpflug topography in keratoconic eyes. Ghoreishi *et al.*,[19] who assessed the agreement of the corneal measurements between Scheimpflug imaging and SS-OCT, showed good agreement for the cornea keratometry indices except for the steep K of the posterior corneal surface in eyes with keratoconus. Szalai *et al.*[20] found significant differences in keratoconus patients between the anterior segment Fourier-domain AS-OCT and the Pentacam HR for the anterior and posterior keratometry readings, except for the posterior steep K results. However, no study in the literature has studied the keratometry values obtained with IOLMaster 700 in keratoconus in comparison with the Pentacam AXL.

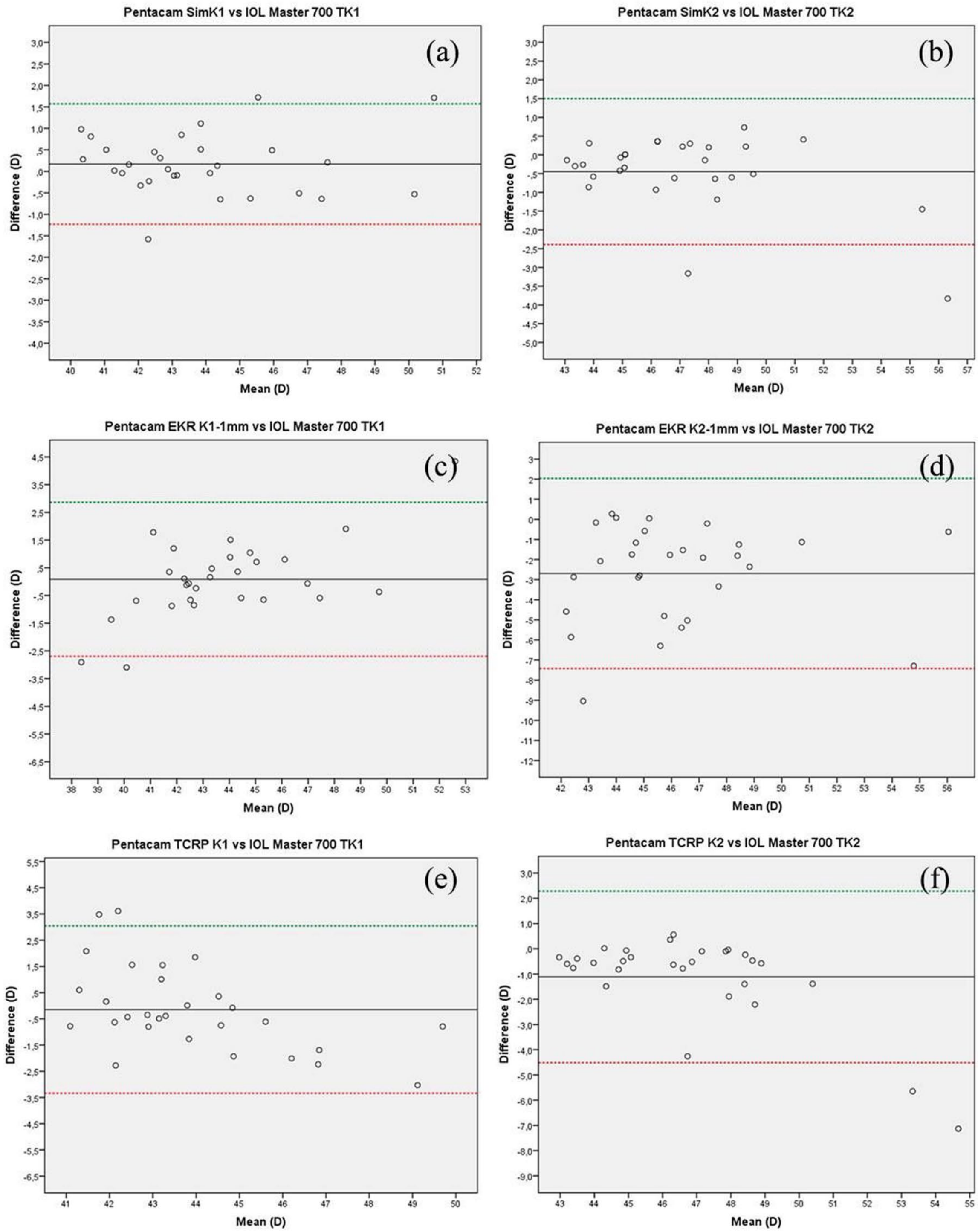


Figure 2. Evaluation of agreement between the total keratometry values (TK) of swept-source optical biometry and the Scheimpflug-based topography measurements of anterior segment parameters. Bland–Altman plots for the (a) Pentacam AXL SimK1 and IOLMaster 700 TK1, (b) Pentacam AXL SimK2 and IOLMaster 700 TK2, (c) Pentacam AXL EKR K1-1 mm and IOLMaster 700 TK1, (d) Pentacam AXL EKR K2-1 mm and IOLMaster 700 TK2, (e) Pentacam AXL TCRP K1 and IOLMaster 700 TK1, and (f) Pentacam AXL TCRP K2 and IOLMaster 700 TK2. The middle line shows the mean difference, while the top, dashed, green line and the bottom, dashed, red line show the upper and lower 95% limits of agreement, respectively. The Bland–Altman graphs of (a), (c), and (e) show a mean difference near 0, implying that the measurements are somewhat comparable. The mean difference was the lowest for the comparison in (c), with 0.08 D and 95% LoA of 2.864 and −2.695, and the greatest for the comparison in (d), with −2.69 D and 95% LoA of 2.035 and −7.421.

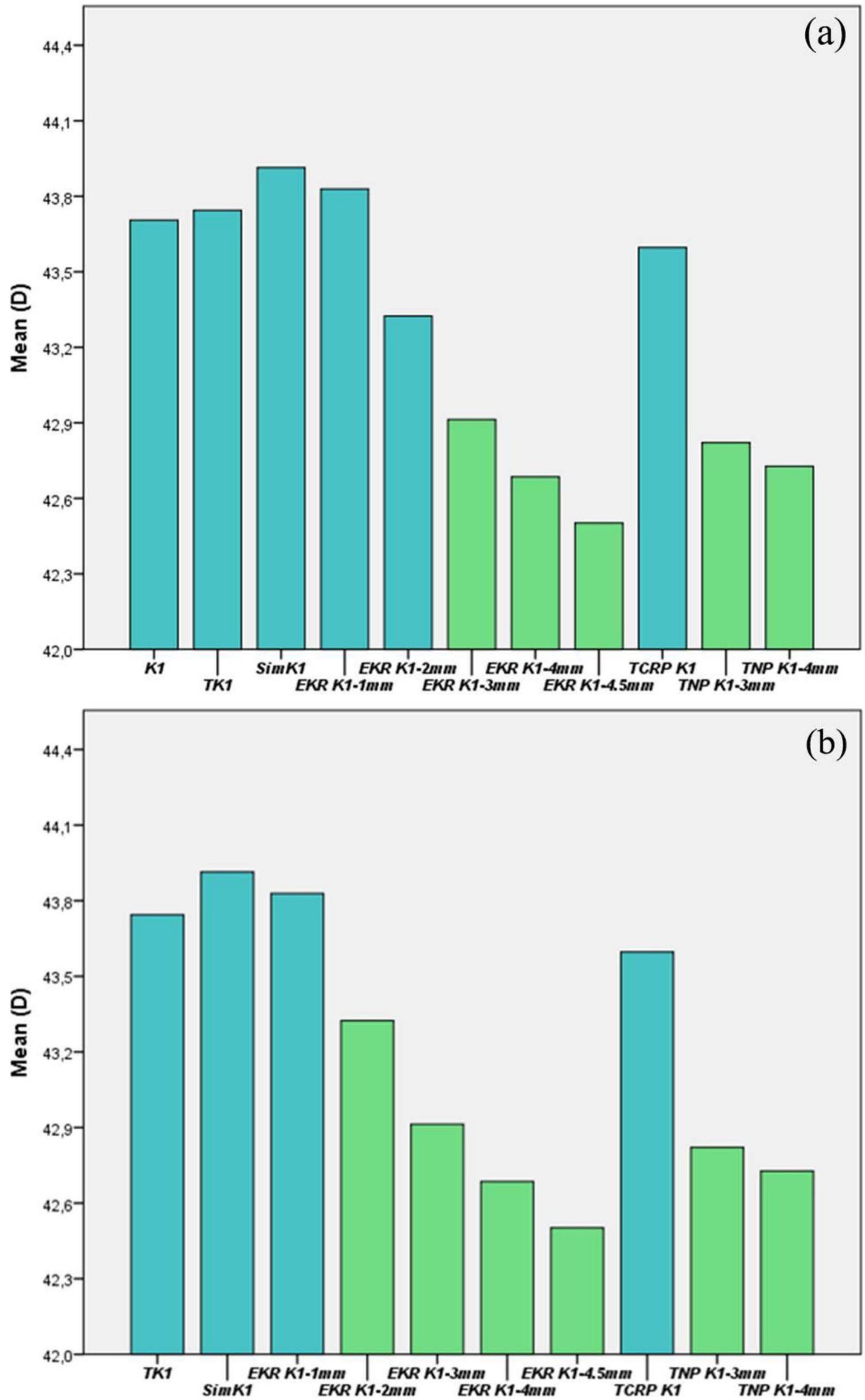
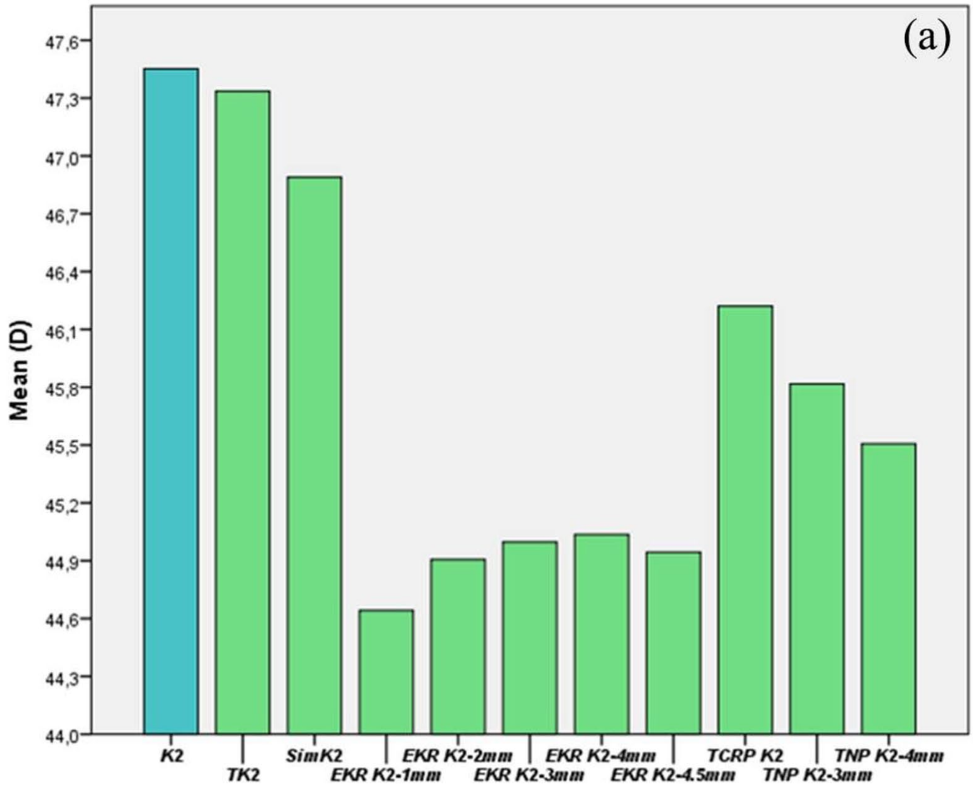


Figure 3. The mean keratometry values of the IOLMaster 700 and the Pentacam AXL for the flattest corneal axis. (a) The K1 value of the IOLMaster 700 did not differ significantly from the variables in the blue bars (i.e. TK1, SimK1, EKR K1-1 mm, EKR K1-2 mm, and TCRP K1), while it was significantly higher from all the variables in the green bars (i.e. EKR K1-3 mm, EKR K1- 4 mm, EKR K1-4.5 mm, TNP K1-3 mm, and TNP K1-4 mm). (b) The TK1 value did not differ significantly from the variables in the blue bars (i.e. SimK1, EKR K1-1 mm, and TCRP K1), while it was significantly higher from all the variables in the green bars (i.e. EKR K1-2 mm, EKR K1-3 mm, EKR K1-4 mm, EKR K1-4.5 mm, TNP K1-3 mm, and TNP K1-4 mm).



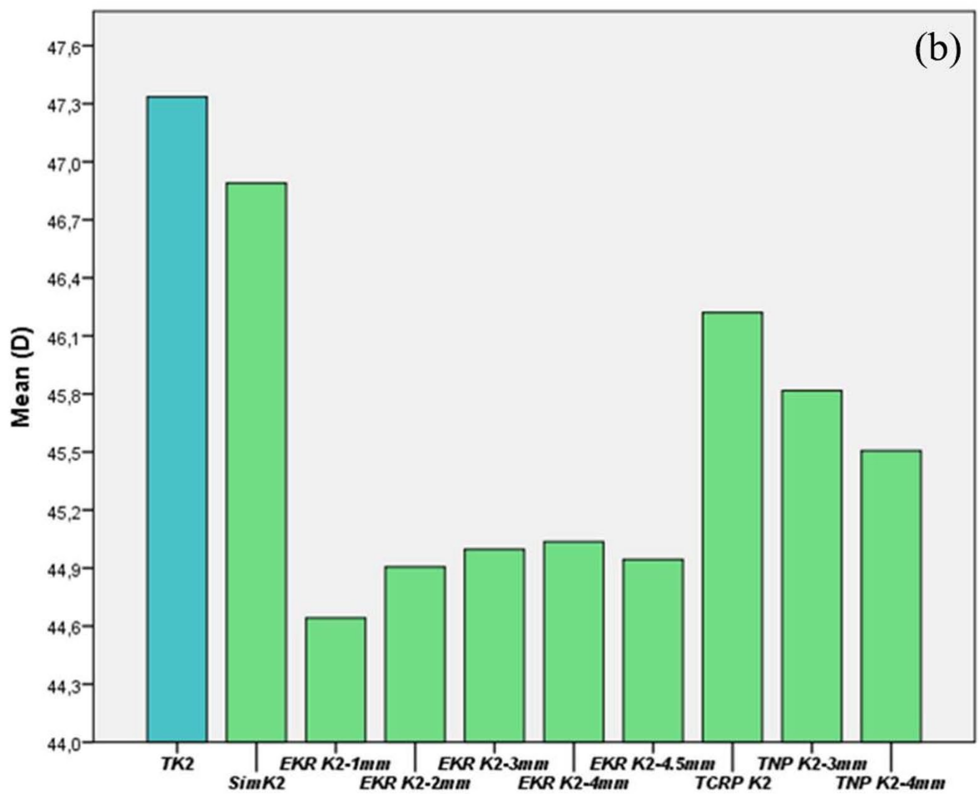


Figure 4. The mean keratometry values of the IOLMaster 700 and the Pentacam AXL for the steepest corneal axis. (a) The K2 value of the IOLMaster 700 was significantly higher from all the variables in the green bars (i.e. TK2, SimK2, EKR K2-1 mm, EKR K2-2 mm, EKR K2-3 mm, EKR K2-4 mm, EKR K2-4.5 mm, TCRP K2-4 mm, TNP K2-3 mm, and TNP K2-4 mm). (b) The TK2 value was significantly higher from all the variables in the green bars (i.e. SimK2, EKR K2-1 mm, EKR K2-2 mm, EKR K2-3 mm, EKR K2-4 mm, EKR K2-4.5 mm, TCRP K2, TNP K2-3 mm, and TNP K2-4 mm).

However, there is a limited number of studies[11,21–23] which have studied the agreement between the Pentacam device and the IOLMaster 700 in healthy corneas for the anterior segment characteristics, with contradictory outcomes. In line with our results, Özyol and Özyol,[21] who studied healthy patients, suggested that the IOLMaster 700 exhibited higher keratometry values than the Pentacam HR, but no significant differences in the ACD values. Sel *et al.*,[22] who also evaluated healthy corneas, concluded that the IOLMaster 700 exhibited significantly higher mean keratometry values and lower ACD measurements than the Pentacam AXL. Asena *et al.*[11] compared the keratometry values obtained with IOLMaster 700, IOLMaster 500, and WaveLight Oculyzer II, which has a rotating Scheimpflug camera and is based on the Pentacam technology, in a cataractous population. They concluded that the keratometry values of the flat axis were similar between the devices, while the keratometry values of the steep axis and the mean keratometry values of the IOLMaster 700 were higher than the corresponding variables obtained by Scheimpflug imaging. However, Shajari *et al.*[23] compared the keratometry and ACD values between the Pentacam AXL, IOLMaster 700, and IOLMaster 500 in healthy patients and found no significant differences between the devices in any of the variables they studied.

The overestimation of the keratometry values we observed with the IOLMaster 700 measurements could be related to the smaller diameter of the region measured with the IOLMaster 700 and the difference in the number of data points used to make the calculation. IOLMaster 700 provides the corneal curvature data obtained from 18 reference points in hexagonal patterns at approximately 1.5-, 2.4-, and 3.2-mm optical zones around the center of the cornea,[24] whereas the rotating Scheimpflug camera of Pentacam AXL, after detecting the first Purkinje image, captures 138,000 data points from the whole cornea and calculates the conventional keratometric values from the central 3-mm zone.[7,23] The posterior curvature of the cornea is directly considered in the algorithm of Scheimpflug imaging[23]; however, the IOLMaster 700 calculates the TK value, which combines the telecentric three-zone keratometry and the corneal thickness derived by the swept-source optical coherence tomography technology in order to determine the anterior and posterior corneal surfaces.[25] Standard keratometry relies purely on the measurements of the anterior corneal surface,[26] while both the anterior and posterior curvatures and the corneal thickness contribute to the TK of the human cornea.[25–27] It is also worth noting that the corneal apex in keratoconic eyes is off-center and the visual axis might not pass through the steepest part of the cornea. Hence, the K readings could be less precise, especially in cases where the corneal surface is distorted. In addition, the irregularity of tear film reflex secretion in such patients makes it difficult to identify the reliable and repeatable K values.[28]

As highlighted above, we also observed that the standard K of the flat corneal axis obtained with IOLMaster 700 was comparable with its corresponding TK value with a mean difference of 0.03 D and 95% LoA of 0.175 and −0.954. However, the standard K of the steep corneal axis obtained with IOLMaster 700 was statistically greater than its corresponding TK value, with a 0.11 D difference and a wider span of 95% LoA (1.178 D). This is partly in discordance with the study of Shajari *et al.*[29] who compared the TK values with the standard K values of IOLMaster 700 in healthy eyes and found no statistically significant difference between the two variables in any of the flattest and steepest axes. Taking into account that the main problem in keratoconus is identified in the steep axis of the cornea, a dispute between these results could be expected. Similarly, Srivannaboon *et al.*[27] compared the refractive outcomes following cataract surgery using conventional keratometry (K) and total keratometry (TK) for IOL calculation in 60 normal eyes and concluded that K and TK showed excellent agreement in both axes. They also claimed that the postoperative refractive outcomes using the TK value appeared to be slightly better than the outcomes obtained using the K value. However, being that TK is derived by combining the telecentric keratometry and SS-OCT technology,[25–27] the confidence of its application to current IOL formulas requires validation.

In addition, we observed a statistically significant difference in the WTW distance between the two devices. According to our results, the mean WTW distance measured with the IOLMaster 700 was 0.31 mm greater than that measured with the Pentacam AXL. The agreement between the measurements of the two devices was not clinically acceptable (95% LoA of −0.088 and −0.545 mm). Our data are in accordance with two previous studies[30,31] which concluded that the

IOLMaster 700 overestimates the WTW distance compared with the Pentacam device in healthy corneas. This finding was expected because keratoconus does not affect the corneal diameter. The difference that we observed could be attributed to the method that each device uses to define the limbus, as well as the quality of the anterior segment images obtained.[30]

Keratoconic eyes tend to have larger axial lengths and deeper anterior chambers, and the IOL is assumed to have a more posterior effective lens position.[32] Therefore, accurate preoperative ACD measurements for these eyes are really important for better postoperative refractive outcome. We found no statistical difference between the two devices in terms of ACD. This finding is in accordance with previous studies describing that the ACD distance measured in normal corneas did not statistically differ between Pentacam and IOLMaster 700.[11,21] Interestingly, Hashemi *et al.*[33] who assessed ACD measurements with Orbscan and Pentacam in keratoconus patients showed good agreement between them.

There are several possible limitations to this study. The findings of our study may not be applicable to other cohorts of keratoconic eyes with more or less severe disease, as the measurements may vary more with more severe keratoconus.[34,35] Though we can possibly expect different results, in this study, we did not compare the two devices in different grades of keratoconus. In addition, the sample size we studied was relatively small and the vast majority of our patients were men. Another significant limitation to this study is related to the use of both eyes for the statistical analysis of the results. However, this is a pilot study with a small sample size to begin with and we analyzed both eyes because keratoconus is an asymmetric disease and the inter-eye correlation between the two eyes of each participant of our cohort indicated poor consistency. Further studies with larger sample sizes and less gender imbalance are needed. Our report also lacks a repeatability analysis which has been frequently examined and discussed in the majority of corresponding reports. Finally, we did not do any adjustment for the p-value in the multiple tests that we included in our analysis as we preferred not to miss important findings; however, only two of the comparisons that we have made (the K2 value of the IOLMaster 700 *versus* TK2 and EKR K1-2 mm *versus* TK1) reached borderline significance ($p = 0.04$).

To summarize, the results of this limited size pilot study indicate that the IOLMaster 700 measured a significantly greater corneal curvature compared to Pentacam AXL for all the values of the steep corneal axis and some of the values of the flat axis in keratoconic eyes. Therefore, these two devices do not seem to be interchangeable in a clinical setting, probably because of the irregular corneal surface associated with keratoconus. Further studies with larger sample sizes of both normal and abnormal corneas including keratoconus suspect and post refractive surgery are justified. Taking into consideration that patients with both cataract and keratoconus present unique challenges to surgeons, the gold standard keratometry method for keratoconic eyes should be determined by future studies and the potential clinical significance of IOLMaster 700 in the preoperative assessment of keratoconus should be clarified.

Author contributions

Evangelia Chalkiadaki: Conceptualization; Formal analysis; Investigation; Methodology; Supervision; Writing-original draft; Writing-review & editing.

Panos S. Gartaganis: Data curation; Investigation; Methodology.

Thomas Ntravalias: Data curation; Investigation; Software.

Ioannis Giannakis: Project administration; Resources; Software.

Evangelos Manousakis: Conceptualization; Project administration; Software.

Efthymios Karmiris: Conceptualization; Formal analysis; Investigation; Project administration; Supervision; Validation; Visualization; Writing-review & editing.

Conflict of interest statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethics statement

This study was conducted in accordance with the Declaration of Helsinki and the local legal regulations. The study protocol was approved by the Institutional Review Board and the Ethics Committee of the Hellenic Airforce General Hospital (6231/30-04-2020). All participants signed a written informed consent form after the explanation of the study protocol.

Availability of data and material

The data that support the findings of this study are available from the corresponding author (E.C.) on request.

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