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Repeatability and agreement of total corneal astigmatism measured in keratoconic eyes using four current devices

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Abstract

Background: To evaluate repeatability and agreement in measurements of total corneal astigmatism (TCA) in keratoconic eyes, using four optical coherence tomography (OCT)-based devices: Anterion, Casia SS-1000, IOLMaster 700, and MS-39.

Methods: Three consecutive measurements were taken with each device in 136 eyes. TCA values were converted into components J_0 and J_{45}. The Anterion and the IOLMaster 700 also provided axial length (AL) measurements. The repeatability was calculated using pooled within-subject standard deviation (S_w). The agreement among the four devices was assessed by pairwise comparisons and Bland–Altman plots.

Results: For all devices, the repeatability of TCA measurements showed S_w ≤0.23 D for TCA magnitude, ≤0.14 D for J_0, and ≤0.12 D for J_{45}. There were statistically significant differences in TCA magnitude for each pair, except for IOLMaster 700 with MS-39, and Anterion with MS-39. The repeatability (S_w) of axis measurements had a statistically significant negative correlation with the TCA magnitude ($p < 0.001$ for all devices). Both Anterion and IOLMaster 700 had high repeatability in AL measurements (S_w: 0.007 mm for Anterion and 0.009 mm for IOLMaster 700). The difference in AL between the two was 0.015 ± 0.033 mm ($p < 0.001$).

Conclusions: All four devices showed good repeatability in TCA measurements in keratoconic eyes, the agreement for TCA measurements between the tested devices was generally low. Anterion and IOLMaster 700 showed good repeatability and agreement in AL measurements.

KEYWORDS

axial length, keratoconus, optical coherence tomography, total corneal astigmatism

1 | INTRODUCTION

Keratoconus (KC) is characterised by a local corneal biomechanical failure, which results in progressive corneal steepening and thinning that cause optical irregularity leading to decreased visual quality and acuity.[1,2]

Corneal topography and tomography have been the basic diagnostic methods for keratoconus detection,[3] with a recent addition of corneal epithelial mapping[4] and biomechanical assessment.[5,6] KC treatment varies depending on its severity and progression. Mild non-progressive cases are typically only observed and corrected for their refractive error by spectacles or contact lenses. In moderate cases with pronounced irregular optics, hard contact lenses have been used, while the advanced and severe cases that could not be visually managed with scleral contact lenses, corneal transplantation has been required. Since its introduction at the beginning of this century, corneal cross-linking (CXL)[7] has been used to provide biomechanical stabilisation and halt the progression in mild to moderate cases of KC.[8] To improve the eye optics, CXL has often been combined with laser ablation[9] or intracorneal rings,[10] while in stabilised KC, implantation of phakic intraocular lenses (IOL), or refractive exchange of crystalline lens, has been used.[11] Treatments aiming to improve the irregular optics of KC may benefit from a better precision of corneal refractive analysis. Measuring the total corneal astigmatism (TCA) involves the optics of the posterior corneal surface and the corneal thickness, rather than only the anterior corneal surface. TCA can be determined by ray tracing or by utilising real measured data of the anterior and posterior corneal curvatures and corneal thickness.

In KC, where the optics of the posterior corneal surface may be dominant and in cases with previous post-laser vision correction (LVC), the determination of total corneal power (TCP) and TCA are crucial.[12–14] The Simulated Keratometry (SimK), which is based solely on anterior corneal measurements, has been used to assess the corneal optics in most traditional IOL calculations,[15] although lack of data from the posterior cornea has been identified as the most important source of error in toric IOLs calculations.[16,17] Indeed, a study showed that an IOL formula, using direct measurements of both anterior and posterior corneal power, had a higher predictive accuracy for spherical equivalent refractive outcome in LVC cataract surgery, than the regression-based formulas based on the SimK.[18–20] In virgin eyes, the contribution of the posterior corneal astigmatism is not nearly as important as the contribution of the anterior corneal astigmatism.[21] An ever-increasing demand for high precision in refractive predictability in lens exchange procedures relies on the correct power of the implanted IOL, which in turn depends on precise measurements of AL, corneal power, and corneal astigmatism.

Previous studies[22–25] have shown good repeatability and agreement for some of the four devices used in the current study. However, these four devices have not been compared when measuring patients with KC. The current study assesses the repeatability and agreement of TCA measurements of the four current devices: Anterion (Heidelberg Engineering, Heidelberg, Germany), Casia SS-1000 (Tomey Corporation, Nagoya, Aichi, Japan), IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany), and MS-39 (CSO, Firenze, Italy). Two of these devices (Anterion and IOLMaster 700) provide AL measurements as well, within the same examination, and the repeatability and agreement of those measurements were assessed as well.

2 | METHODS

This prospective study included 136 keratoconic eyes of 136 consecutive patients who satisfied our inclusion and exclusion criteria. All examinations were performed between March 2021 and December 2021 at Øyelegesenteret clinic in Tromsø, Norway. Inclusion criteria were: (1) Age ≥16 years; (2) confirmed diagnosis of KC; and (3) TCA ≤8 diopters (D). Exclusion criteria were: (1) History of previous ocular surgery (except CXL); (2) presence of eye diseases (except KC); (3) poor fixation or inability to complete the examination; and (4) use of contact lenses within 2 weeks before the examination day (the period of 2 weeks was considered sufficient since we knew in advance that only the soft- or mini-scleral contact lenses, and no rigid gas permeable lenses, are used in our KC population).

The patients were diagnosed as KC according to the following standard: (1) Topographic maps showing irregular astigmatism with localised steepening on curvature maps and with coinciding protrusion on the elevation maps; (2) corneal tomography showing more pronounced protrusion on the posterior compared with the anterior cornea, and both stromal and epithelial thinning in the area of protrusion.

Refraction, visual acuity, and standard ophthalmological slit lamp examination were performed before the corneal measurements.

The study was approved by the Norwegian Regional Committee for Medical & Health Research Ethics (REK Nord 72 084) and complied with the tenets of the Declaration of Helsinki. All patients provided informed consent for the anonymous use of their data in scientific analyses and publications, following a detailed explanation of the study.

2.1 | The measurements

Only one eye of each patient who met the inclusion criteria was selected for measurement according to a randomization generated by Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA). Three consecutive measurements were taken with each device and each measurement took about 20 s. All measurements were achieved within 15 min and were performed in an undilated state by the same experienced examiner (YF) between 10 AM and 2 PM.

All the measurements were performed according to the operating instructions for the devices. The measurements with the four devices were obtained in a random order according to a randomised list generated by Microsoft Excel 2019. The subjects were asked to place their chin on the chin rest and press their forehead against the forehead strap, to look at the fixation target of the relevant device, and to blink before each measurement to ensure that the tear film spread out evenly, and to keep their eyes wide open during the measurement. Between each measurement, to ensure that the measurements were independent of one another, the patients were asked to sit back, look away from the fixation light, and blink normally. The measurements were considered acceptable if they satisfied the quality criteria for the devices as defined by the manufacturers.

2.2 | Device description

The specifications of the four devices are shown in Table 1.

2.3 | Anterion

The Anterion SS-OCT (software version 2.5.2) generates images using a laser light source of 1300 nm wavelength to obtain B-scans with an axial resolution of <10 μm and a transversal resolution of 45 μm. The corneal measurements are acquired using the 'Cataract APP' mode of the device, which additionally provides eye biometry data. Sixty-five radial B-scans are performed, with 256 A-scan lines centred on the corneal vertex within a 9 mm diameter. The acquisition time with the Cataract APP is <2 s.

2.4 | Casia SS-1000

The Casia SS-1000 (Tomey, Japan; software version 6Q.2) is also an SS-OCT, using a 1310 nm light source. Its axial and transverse resolution is 10 and 30 μm, respectively. It performs 16 radial scans with 512 A-scan lines centred on the corneal vertex within 10 mm diameter. The device performs 30 000 A-scans per second and uses auto alignment to focus on the examined eye. Acquisition time is about 0.3 s.

2.5 | IOLMaster 700

The IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany) is an SS-OCT device combined with telecentric keratometry. The OCT uses a laser with a tunable wavelength from 1035 to 1080 nm centred on 1055 nm, while the keratometer uses a 950 nm light source. The SS-OCT generates B-scans with an acquisition speed of 2000 A-scans per second and a penetration depth of 44 mm, providing 6-line scans with 22 μm axial resolution. These B-scans are displayed as full-length OCT images showing

TABLE 1 Specifications of the four devices for TCA.

Device	Anterion	Casia SS-1000	IOLMaster 700	MS-39
Light source wavelength (nm)	1300	1310	OCT: 1055; keratometer: 950	OCT: 845; Placido: 635
A-scan speed (scan/s)	50 000	30 000	2000	102 400
Axial resolution (μm)	<10	10	22	3.6
Transverse resolution (μm)	<45	30	24	35
A-scan depth (mm)	14 ± 0.5	6	44	7.5
Maximum Scan width (mm)	16.5	10	6	6
Number of B-scans	65 × 1	16	6 × 3	12 × 5[a]
Number of A-scans per B-scan	256	512	128	1024[b]
Acquisition time (s)	0.33	0.3	1.2	2

Abbreviations: OCT, optical coherence tomography; TCA, total corneal astigmatism.
[a]Customised in this study as recommended by the manufacturer.
[b]1600 A-scan on 16 mm and 800 A-scan on 8 mm.

anatomical details on a longitudinal section through the entire eye. The telecentric keratometer measures 18 points arranged on three rings radially from the corneal centre. The optical axes of the SS-OCT and the keratometer are identical. This ensures that the B-scan passes through the measuring points. The anterior and the posterior corneal curvatures are measured by telecentric keratometry and by the SS-OCT, respectively. Measurements can be done in Auto/Manual mode. In the current study, the auto mode was selected. The Keratometry readings are calculated by analysing the anterior corneal curvature at 18 reference points in hexagonal patterns at 1.5-, 2.5-, and 3.5-mm optical zones. The keratometry readings analysed in the current study were at the 2.5-mm zone.

2.6 | MS-39

The MS-39 (CSO, Firenze, Italy; software Phoenix v.4.1.1.5) combines SD-OCT- and Placido disk imaging technology. A superluminescent diode (SLed) at 845 nm is used as a light source for the OCT, while a SLed at 635 nm is used for Placido disk illumination. The device provides an axial resolution of 3.6 μm, a transversal resolution of 35 μm, and a maximum depth of 7.5 mm. The 'Corneal topography' mode '12 × 5 @10 mm'[26] was used in this study as recommended by the manufacturer, as it provides a higher resolution than the '25 × 1 @16 mm' mode, which has been used in previous studies.[27–29] In the '12 × 5 @10 mm' mode, the measurement consists of 12 radial B-scans repeated five times for each of the 12 meridians, with 800 A-scan lines per B-scan over an 8 mm diameter. The acquisition time is about 2 s.

For the anterior corneal topography, ring edges are detected on the Placido image, providing native curvature data, while the height and slope data are calculated using the arc-step method. Profiles of both the anterior and the posterior cornea are provided from the SD-OCT scans. Data representing the anterior corneal surface are provided by merging the Placido imaging and the SD-OCT, using the manufacturer's proprietary method, while the data for the posterior cornea is derived solely from the SD-OCT.

2.7 | Statistical analysis

The TCA values were measured in a central 3.0 mm zone for all devices except for IOLMaster 700, where we used the values for a 2.5 mm zone. Data were analysed using the statistical package SPSS (IBM SPSS Statistics for Windows, Version 20.0. IBM Corp.). Descriptive statistics were done for continuous variables. Visual inspections of P–P plots and Kolmogorov–Smirnov tests were used to confirm that the data were normally distributed. The level of statistical significance was set at $p < 0.05$.

The TCA values were decomposed into two components by using the following equations[30]:

$$J_0 = \frac{C}{2} \times \cos 2\alpha$$

$$J_{45} = \frac{C}{2} \times \sin 2\alpha$$

where c is the negative cylindrical power and α is the cylindrical axis. J_0 refers to a Jackson cross-cylinder power set orthogonally at 90° and 180° meridians. Positive values of J_0 indicate with-the-rule (WTR) astigmatism, and negative values of J_0 indicate against-the-rule (ATR) astigmatism. J_{45} refers to a Jackson cross-cylinder power set orthogonally at 45° and 135°, representing oblique astigmatism.

To assess the repeatability, we calculated the pooled within-subject standard deviation (S_w) (lower values of S_w indicate better repeatability).[31] The repeatability limit (r), defined as $1.96\sqrt{2} \times S_w$ ($=2.77 \times S_w$), gives the value below which the absolute difference between two measurements of S_w would lie with 0.95 probability.[31,32] The Pearson correlation coefficient was calculated to assess the linear relationship between TCA axis (°) and magnitude.

To assess the agreement, we used the results only from the first measurement obtained by each device, and the following analysis was performed: (1) Differences in TCA magnitude, J_0, and J_{45}; (2) the 95% limits of agreement (LoA), defined as the mean difference for each pair of devices ±1.96 × standard deviations; and (3) pairwise comparisons of TCA measurements with Bonferroni adjustment.

To visualise the differences in the TCA magnitude of each pair of devices, Bland-Altman plots were generated.

To achieve 90% confidence in the estimate for repeatability analysis, we needed a sample size of 96 eyes for three repeated measurements.[33] In this study, we included 136 eyes which gives 91.6% confidence in the estimate.

3 | RESULTS

This study included 136 eyes (OD/OS: 81/55) of 136 patients [41.66 years ±15.15 (SD), range 16–75 years; male/female: 87/49]. According to Amsler-Krumeich KC classification,[34] the 136 eyes included in this study were Grade I: 103 eyes, Grade II: 30 eyes, Grade III: 3 eyes, and Grade IV: 0 eyes.

3.1 | Repeatability

Table 2 shows the S_w and repeatability limit r ($2.77*S_w$) for the TCA magnitude and its components J_0 and J_{45}. Anterion had the best S_w for TCA magnitude, J_0 and J_{45}, followed by Casia SS-1000, IOLMaster 700 and MS-39.

Table 3 shows the repeatability of the TCA axis (°) and its correlation with TCA magnitude (D). Anterion had the best S_w for TCA axis, followed by IOLMaster 700, MS-39 and Casia SS-1000. All of them had a S_w statistically significant ($p < 0.001$) negative correlation with the TCA magnitude, which means, that as the magnitude increases, the S_w tends to decrease (better repeatability).

3.2 | Agreement

Table 4 shows the mean of TCA measurements of all the 136 eyes obtained by the four devices. Casia SS-1000 had the lowest mean TCA magnitude with 1.52 ± 1.31 D, while IOLMaster 700 had the highest with 2.15 ± 1.81 D. The means of J_{45} values were similar for all four devices, while the mean of J_0 for Anterion and Casia SS-1000 was higher than for IOLMaster 700 and MS-39.

Table 5 shows the agreement of TCA magnitude and the components J_0 and J_{45} for each pair of devices. There were statistically significant differences in TCA magnitude in all pairs except for Anterion versus MS-39 and IOLMaster 700 versus MS-39, but only the difference between Casia SS-1000 and IOLMaster 700 was clinically significant by exceeding 0.50 D (0.631 D, $p = 0.000$). There were no statistically significant differences in TCA components in any pairs except in J_0 for IOLMaster 700 versus Anterion with a mean difference of −0.191 D ($p = 0.000$), and in Anterion versus MS-39 with a mean difference of 0.196 D ($p = 0.004$).

Bland–Altman plots for the agreement in TCA magnitude for all pairs of devices are shown in Figure 1.

3.3 | Axial length

Table 6 shows the repeatability and agreement of AL measurements of Anterion and IOLMaster 700.

Figure 2 shows the Bland–Altman plots for the agreement in AL measurements between Anterion and IOLMaster 700.

4 | DISCUSSION

In this prospective study, we tested the repeatability of TCA measurements in four devices (Table 2) in a group of eyes with KC. This analysis was performed by calculating the pooled within-subject SD (S_w), which represents the level of variability of three consecutive measurements, where lower values of S_w represent better repeatability.

Among the four devices, the Anterion had the best repeatability in measuring TCA magnitude and J_0 and J_{45} components. Previous studies[24,35,36] of TCA measurements in healthy eyes by Anterion reported a S_w for TCA magnitude varying from 0.07 D to 0.13 D, while Shajari et al.[37] reported a S_w of 0.15 D for IOLMaster 700. The worse repeatability in our study is presumably due to our population of KC corneas with irregular corneal optics. Gjerdrum et al.[25] evaluated the repeatability of Anterion and Casia SS-1000 in patients with hyperosmolar ($n = 31$) and normal ($n = 63$) tear film, showing a S_w for TCA mag-

TABLE 3 The repeatability of TCA axis (°) and its correlation with TCA magnitude (D).

Devices	Repeatability S_w	Pearson correlation r	Pearson correlation p
Anterion	4.26	−0.491	<0.001
Casia SS-1000	9.23	−0.478	<0.001
IOLMaster 700	7.21	−0.359	<0.001
MS-39	8.73	−0.370	<0.001

Note: TCA, total corneal astigmatism; S_w, pooled within-subject standard deviation; r, the correlation coefficient.

TABLE 2 Repeatability of TCA measurements of the four devices.

	Repeatability, S_w (repeatability limit, r)			
	Anterion	Casia SS-1000	IOLMaster 700	MS-39
TCA magnitude (D)	0.12 (0.34)	0.18 (0.50)	0.19 (0.53)	0.23 (0.64)
J_0 (D)	0.07 (0.20)	0.10 (0.26)	0.10 (0.27)	0.14 (0.39)
J_{45} (D)	0.06 (0.15)	0.10 (0.26)	0.09 (0.25)	0.12 (0.33)

Note: TCA, total corneal astigmatism; S_w, pooled within-subject standard deviation; r (repeatability limit), $2.77 \times S_w$; J_0, cylinder at 0-degree meridian; J_{45}, cylinder at 45-degree meridian.

TABLE 4 The mean of TCA measurements obtained by each device.

	Mean ± SD			
	Anterion	Casia SS-1000	IOLMaster 700	MS-39
TCA magnitude (D)	1.89 ± 1.52	1.52 ± 1.31	2.15 ± 1.81	1.99 ± 1.73
J_0 (D)	0.258 ± 0.969	0.242 ± 0.916	0.067 ± 1.103	0.062 ± 1.067
J_{45} (D)	0.124 ± 0.677	0.127 ± 0.635	0.131 ± 0.859	0.189 ± 0.753

Abbreviations: SD, standard deviation; TCA, total corneal astigmatism.

nitude varying from 0.15 D to 0.16 D for the Anterion and from 0.18 D to 0.28 D for the Casia. Schiano-Lomoriello et al.[28] assessed the repeatability of MS-39 in KC eyes ($n = 44$), giving a S_w of 0.55 D for TCA magnitude, which is more than twice our results.

Concerning the TCA components J_0 and J_{45}, Piñero et al.[38] found a S_w of 0.09 D for J_0 and 0.07 D for J_{45} in healthy eyes ($n = 35$), using the Cassini system (i-Optics, The Hague, Netherlands, distributed by Ophthec). The Cassini system is a topographer based on the specular reflection of 679 coloured light-emitting diodes (LEDs) to construct topographic maps of the anterior corneal surface and seven additional infrared LEDs to measure the curvature of the posterior corneal surface. Their results with the Cassini showed superior repeatability to ours with MS-39 (S_w: 0.14 D for J_0 and 0.12 D for J_{45}), similar to ours with Casia SS-1000 (S_w: 0.10 D for J_0 and 0.10 D for J_{45}) and IOLMaster 700 (S_w: 0.10 D for J_0 and 0.09 D for J_{45}), but inferior to ours with Anterion (S_w: 0.07 D for J_0 and 0.06 D for J_{45}).

We assessed the repeatability of TCA axis (°) in the four devices. Our results had the best repeatability in Anterion with S_w 4.26° and the worst in Casia SS-1000 with S_w of 9.23°. So far, there are no publications about the repeatability of TCA axis measurements in KC eyes with the current four devices. de Luis Eguileor et al.[39,40] found a S_w range from 7.70° to 11.78° for astigmatism axis in KC eyes using Scheimpflug-based tomographer, Pentacam HR (Oculus; Optikgeräte GmbH, Wetzlar, Germany). Their results were close to ours with Casia SS-1000 (S_w: 9.23°), IOLMaster 700 (S_w: 7.21°), and MS-39 (S_w: 8.73°), while far worse than ours with Anterion. The different findings between the studies may be due to both the precision of the devices and the corneal irregularities of different grades in KC eyes.

We also correlated the repeatability of TCA axis (°) with TCA magnitude (D). We found the repeatability of the TCA axis measurement improved with increasing TCA magnitude across all four devices, possibly because the magnitude dominates the measurement despite irregularities. Similarly, Kanellopoulos and Asimellis,[41] using Cassini in normal eyes, reported that the greater the cylinder magnitude, the better the repeatability of the axis measurements. In our study, Anterion and Casia SS-1000 had a moderate correlation, while, IOLMaster 700 and MS-39 had a weak correlation (Table 3). The low cylinder measurements are generally more likely than high cylinder to be influenced by general noise in the readings, such as tear film surface irregularities,[42] which can obscure the precise detection of the axis.

Regarding the agreement in TCA measurements for any pair of devices in our study, most of them had statistically significant differences in TCA magnitude (Table 5). The mean difference between Casia SS-1000 and IOLMaster 700 was 0.631 D ($p < 0.001$), while the mean difference for the other pairs did not exceed 0.50 D. It should be noted that a difference of 0.50 D in the estimation of corneal power results in an error of IOL power calculations below 0.50 D at the corneal plane, while 0.50 D is the minimum IOL power step provided by most manufacturers.[43] Accordingly, only the TCA magnitude difference between Casia SS-1000 and IOLMaster 700 was clinically significant.

The Bland–Altman plots in Figure 1 showed that the mean difference was smallest between Anterion and MS-39 with 0.099 D ($p = 1.00$, adjusted by multiple comparisons by Bonferroni). However, the 95% LoA range for these two devices was wide, (−2.620, 2.422) D. The narrowest 95% LoA range was for Anterion and Casia SS-1000, (−0.469, 1.217) D. It is interesting to notice from the Bland–Altman plots when comparing MS-39 to any of the other three devices that the distribution of the points becomes much more scattered as their mean value increases (Figure 1C,E,F). This phenomenon was not observed for the other pairs. This might be due to the MS-39's technology, which combines Placido technology with the SD-OCT for the anterior corneal measurement. In addition, from the plots related to the IOLMaster 700 (Figure 1B,D), we can see an apparent bias towards a more negative difference (greater magnitude measured by IOLMaster 700) as the mean increases. We speculate that this might be due to the IOLMaster 700 combining telecentric keratometry and SS-OCT, while the Anterion and Casia SS-1000 utilise only SS-OCT technology. Furthermore, this changing bias could also be partly caused by differences in the diameters used for measurements.

TABLE 5 Agreement of TCA measurements for each pair of devices.

	Anterion vs. Casia SS-1000			Anterion vs. IOLMaster 700			Anterion vs. MS-39		
	Difference			Difference			Difference		
	Mean ± SD	p	95% LoA range	Mean ± SD (D)	p	95% LoA range	Mean ± SD	p	95% LoA range
TCA magnitude (D)	0.374 ± 0.430	0.000	−0.469 to 1.217	−0.258 ± 0.748	0.001	−1.724 to 1.208	−0.099 ± 1.286	1.000	−2.620 to 2.422
J_0 (D)	0.016 ± 1.156	1.000	−2.25 to 2.282	0.191 ± 0.424	0.000	−0.640 to 1.022	0.196 ± 0.653	0.004	−1.084 to 1.476
J_{45} (D)	−0.002 ± 0.786	1.000	−1.543 to 1.539	−0.007 ± 0.336	1.000	−0.666 to 0.652	−0.064 ± 0.658	1.000	−1.356 to 1.228

	Casia SS-1000 vs. IOLMaster 700			Casia SS-1000 vs. MS-39			IOLMaster 700 vs. MS-39		
	Difference			Difference			Difference		
	Mean ± SD	p	95% LoA range	Mean ± SD	p	95% LoA range	Mean ± SD	p	95% LoA range
TCA magnitude (D)	−0.631 ± 0.936	0.000	−2.462 to 1.204	−0.473 ± 1.381	0.001	−3.180 to 2.234	0.158 ± 1.171	0.705	−2.137 to 2.453
J_0 (D)	0.175 ± 1.222	0.584	−2.220 to 2.570	0.180 ± 1.300	0.657	−2.366 to 2.726	0.005 ± 0.574	1.000	−1.120 to 1.130
J_{45} (D)	−0.005 ± 0.927	1.000	−1.822 to 1.812	−0.062 ± 1.018	1.000	−2.057 to 1.933	−0.057 ± 0.735	1.000	−1.498 to 1.384

Note: TCA, total corneal astigmatism; SD, standard deviation; J_0, cylinder at 0-degree meridian; J_{45}, cylinder at 45-degree meridian; *p*, the mean difference is significant at the 0.05 level. Adjustment for multiple comparisons: Bonferroni.

Specifically, the IOLMaster 700 uses a 2.5 mm diameter, whereas the others use 3.0 mm. Therefore, consistent use of the same device is recommended for accurate and reliable monitoring of keratoconus progression.

We also assessed the repeatability and agreement of AL measurements acquired by Anterion and IOLMaster 700. Both devices had very high repeatability with a S_w of 0.007 mm for Anterion and 0.009 mm for IOLMaster 700. The difference in AL between the two was statistically significant (0.015 ± 0.033 mm, $p < 0.001$), but it would be clinically irrelevant and would produce a very negligible difference (less than 0.1 D) in postoperative refractive errors, the AL measured by the two instruments may be used interchangeably for IOL power calculation.[44] Panda et al.[23] reported a difference in AL of −0.02 ± 0.09 mm ($p = 0.001$, $n = 203$) between Anterion and IOLMaster 700. Schiano-Lomoriello et al.[24] found a S_w of 0.01 mm for Anterion, similar to our results. The latter group also compared the AL measured by Anterion and IOLMaster 500 (Carl Zeiss Meditec, Jena, Germany), which is an older generation of optical biometer than the IOLMaster 700 and reported a 95%LoA (−0.06, 0.05) mm for Anterion and IOLMaster 500, which was comparable to our results of 95%LoA (−0.08, 0.05) mm for Anterion and IOLMaster 700.

Differences in the measured diameter (2.5 mm used for IOLMaster 700 and 3.0 mm for the others), may have influenced the results. In our decision between utilising the 2.5 or 3.5 mm diameter for IOLMaster 700 (3.0 mm not being available), we were aware of the recent findings by Alpins et al.[45] advocating for larger zones in keratoconic eyes, but we chose 2.5 mm diameter since it has been widely used in clinical practice, as well as referred in the literature.[46–48] Additionally, Fredriksson et al.,[49] recommended a smaller zone to mitigate the influence of the cone on the measurement.

The eyes in this study had a confirmed keratoconus with 75.7% diagnosed as Grade I. As more corneal irregularities in higher grade KC lead to variable repeatability and agreement, the results in studies with KC eyes may be challenging to interpret.[50] Therefore, even if higher TCA magnitudes may improve repeatability, the presence of more irregularities in severer KC will always reduce the repeatability.[51]

Our study focused on keratoconic eyes, where the typical anterior/posterior curvature ratios observed in regular eyes may not be applicable. Using the ray-tracing type IOL-calculation, used in formulas, such as Okulix[52] and Olsen[53] may give better results since it involve the exact Snell's law and ray-tracing calculated TCA, not relying on any assumptions in the calculation. For more accurate IOL power calculation and astigmatism correction in keratoconic eyes, it is essential to employ

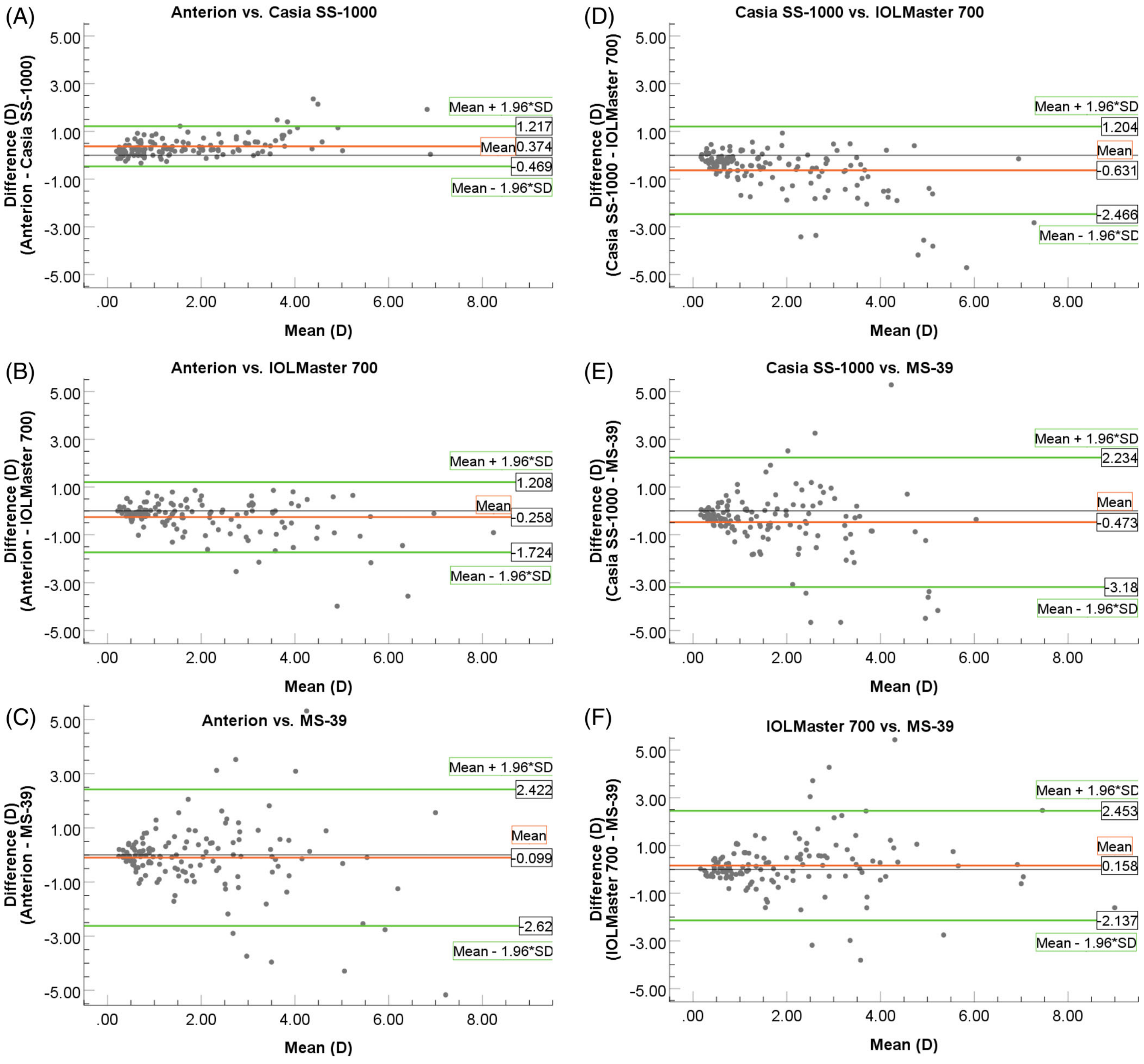

FIGURE 1 Bland–Altman plots showing agreement between total corneal astigmatism magnitude measured by (A) Anterion and Casia SS-1000, (B) Anterion and IOLMaster 700, (C) Anterion and MS-39, (D) Casia SS-1000 and IOLMaster 700, (E) Casia SS-1000 and MS-39, (F) IOLMaster 700 and MS-39. The red lines show the mean differences and the green lines show the lower and upper 95% limit of agreement.

TABLE 6 Repeatability and agreement of AL measurements of Anterion and IOLMaster 700.

			Difference (Anterion—IOLMaster 700)		
	Anterion	**IOLMaster 700**	**Mean ± SD**	***p***	**95% LoA range**
S_w (mm)	0.007	0.009	-	-	-
r (mm)	0.020	0.024	-	-	-
AL (mm)	24.120 ± 1.17	24.135 ± 1.17	−0.015 ± 0.033	<0.001	−0.080 to 0.049

Note: AL, axial length; S_w, pooled within-subject standard deviation; r (repeatability limit), 2.77 × S_w; LoA, limit of agreement; SD, standard deviation.

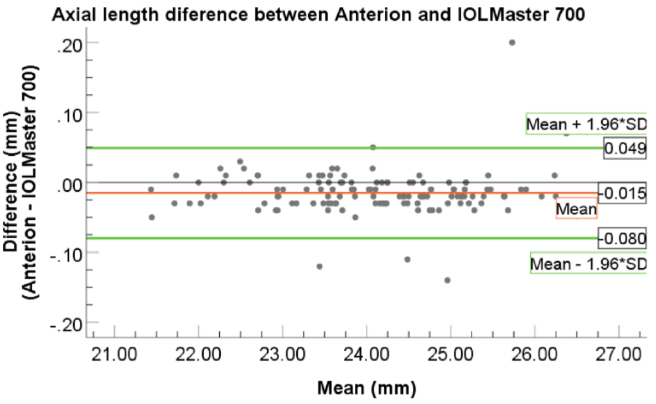

FIGURE 2 Bland–Altman plot showing the means plotted against the differences in axial length between Anterion and IOLMaster 700. The red line shows the mean differences and the green lines show the lower and upper 95% limit of agreement.

keratoconus-specific formulas. In addition to ray-tracing-based formulas, non-ray tracing formulas are used in keratoconic eyes, including the Barrett True-K for keratoconus, the Kane formula for keratoconus, the Holladay II keratoconus mode, the Toric Barrett True-K (for toric IOL), all utilising keratometry measurements. Commonly-used options based on TCP include the Barrett True-K keratoconus formula with total K (TK) for all severities of KC and Emmetropia Verifying Optical (EVO) formula with TK or K in eyes with non-severe disease ($K \leq 50.00$ D).[54] These specialised formulas take into account the unique corneal characteristics associated with keratoconus, providing more accurate and tailored results for IOL power and astigmatism correction. Thus, the use of personalised, device-specific A-constants is crucial to minimise systematic prediction errors.

Limitations of the current study: The cases were not divided into subgroups according to the grade of the KC due to the relatively small sample size. In addition, our sample included a few cases with severe keratoconus, where the quality of measurements is reduced.

4.1 | Conclusions

All four devices had good repeatability in the measurements of TCA in KC eyes, Anterion being the best. The agreement between the tested devices was generally low, and from this we identified two important consequences: a consistent use of the same device for accurate and reliable monitoring of keratoconus progression, and a use of personalised, device-specific A-constants, to minimise systematic prediction errors. We found that the larger the difference in the basic technology between the devices, the more disagreement in the results. For this reason, for the measurements of TCA, the SS-OCT-technology-only devices should not be used interchangeably with SS-OCT combined with telecentric keratometry (Anterion and Casia SS-1000 vs. IOLMaster 700) or with SD-OCT combined with Placido devices (Anterion and Casia SS-1000 vs. MS-39). Furthermore, devices using different hybrid technologies (IOLMaster 700 and MS-39) should not be used interchangeably. For AL measurements, Anterion and IOLMaster 700 had good repeatability and agreement and may be used interchangeably.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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