Agreement of total corneal power measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in normal and keratoconic patients

Miss Rusaporn Yodying

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ความสอดคล้องกันของค่าความโค้งรวมของกระจกตาจากการวัดด้วย CASIA 2, Pentacam AXL, และ IOLMaster 700 ในคนปกติและผู้ป่วยโรคกระจกตาโก่ง

น.ส.รสพร ยอดยิ่ง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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Thesis Advisor	Associate Professor KRIT PONGPIRUL, Ph.D.

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รสพร ยอดยิ่ง : ความสอดคล้องกันของค่าความโค้งรวมของกระจกตาจากการวัดด้วย CASIA 2, Pentacam AXL, และ IOLMaster 700 ในคนปกติและผู้ป่วยโรคกระจกตาโก่ง. (Agreement of total corneal power measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in normal and keratoconic patients) อ.ที่ปรึกษาหลัก : รศ. นพ.กฤษณ์ พงศ์พิรุฬห์

วัตถุประสงค์: เพื่อศึกษาความสอดคล้องกันของค่าความโค้งรวมของกระจกตา, ค่าชีวมิติของลูกตาอื่นๆ, และค่าเลนส์แก้วตาเทียม จากการวัดด้วย CASIA 2, Pentacam AXL, และIOLMaster 700 ในคนปกติ และผู้ป่วยโรคกระจกตาโก่ง

รูปแบบการวิจัย: การวิจัยเชิงพรรณนา Prospective observational study

วิธีการวิจัย: อาสาสมัคร 134 คน ประกอบด้วย คนปกติ 100 คน และผู้ป่วยโรคกระจกตาโก่ง 34 คน ได้เข้าร่วมวิจัย ที่โรงพยาบาลจุฬาลงกรณ์ คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย โดยอาสาสมัครจะถูกวัดค่าชีวมิติของลูกตาด้วยเครื่องมือ 3 เครื่อง เครื่องละ 3 ครั้ง โดยผู้วัด 2 คน เพื่อศึกษาความแม่นยำของการวัด และความสอดคล้องกันของเครื่องมือ 3 เครื่อง โดยค่าชีวมิติของลูกตาที่วัด ได้แก่ ค่าความโค้งรวมของกระจกตา, ค่าความเอียงรวมของกระจกตา, ค่าความโค้งกระจกตาด้านหน้า, ค่าความเอียงของกระจกตาส่วนหน้า, ค่าความโค้งกระจกตาด้านหลัง, ค่าความเอียงของกระจกตาส่วนหลัง, ค่าความลึกของช่องหน้าม่านตา, ค่าความกว้างกระจกตาในแนวนอน, ค่าความหนากระจกตาส่วนกลาง, และค่าเลนส์แก้วตาเทียม สถิติที่ใช้วิเคราะห์ คือ Intraclass correlation coefficient และ Bland-Altman plot

ผลการวิจัย: ความแม่นยำของการวัดค่าชีวมิติของลูกตาทุกค่า ยกเว้นค่าความกว้างกระจกตาในแนวนอน อยู่ในระดับดีเยี่ยม ทั้ง 3 เครื่อง (ICC > 0.9) ความสอดคล้องกันของการวัดค่าความโค้งรวมของกระจกตาของ 3 เครื่องมือ อยู่ในระดับดีเยี่ยม (ICC > 0.9) ในคนปกติและผู้ป่วยโรคกระจกตาโก่ง อย่างไรก็ตามเมื่อเปรียบเทียบ CASIA 2 และ IOLMaster 700 มีค่าความสอดคล้องกันของการวัดค่าความโค้งรวมของกระจกตาอยู่ในระดับดี ในคนปกติ (ICC = 0.867) และผู้ป่วยโรคกระจกตาโก่ง (ICC = 0.852) และค่าความแตกต่างเฉลี่ยของค่าความโค้งรวมของกระจกตา ใน 2 เครื่องมือข้างต้นนั้น > 1.0 diopter ซึ่งมีนัยสำคัญทางคลินิก และยังพบว่าคนไข้โรคกระจกตาโก่ง มี 95% limit of agreement ที่กว้างกว่าคนปกติ นอกจากนี้ความสอดคล้องของการวัดค่าชีวมิติของลูกตาอื่นๆและค่าเลนส์แก้วตาเทียมของ 3 เครื่องมือนั้นมีความสอดคล้องกันอยู่ในระดับดี ถึง ดีเยี่ยม ยกเว้นค่าความกว้างกระจกตาในแนวนอนมีความสอดคล้องอยู่ในระดับต่ำ ถึง ปานกลางในกลุ่มอาสาสมัครทั้ง 2 กลุ่ม

สรุป: ความสอดคล้องกันของค่าความโค้งรวมของกระจกตาจากการวัดด้วย CASIA 2, Pentacam AXL, และ IOLMaster 700 นั้นดีเยี่ยม ทั้งในคนปกติและผู้ป่วยโรคกระจกตาโก่งอย่างไรก็ตามไม่สามารถใช้ค่าความโค้งรวมกระจกตาจากแต่ละเครื่องแทนกันได้

สาขาวิชา	เวชศาสตร์คลินิก	ลายมือชื่อนิสิต ....
ปีการศึกษา	2563	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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KEYWORD: Total corneal power, IOL power calculation, CASIA 2, Pentacam AXL, IOLMaster 700, Keratoconus

Rusaporn Yodying : Agreement of total corneal power measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in normal and keratoconic patients. Advisor: Assoc. Prof. KRIT PONGPIRUL, Ph.D.

Purpose: To evaluate agreement of total corneal power (TCP), ocular biometry and IOL power calculation measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in normal and keratoconic patients

Setting: King Chulalongkorn Memorial Hospital, Chulalongkorn University, Bangkok, Thailand

Design: Prospective observational study

Methods: One-hundred normal eyes and 34 keratoconic eyes were enrolled. Biometric values were measured by each device for three times by two operators to evaluate repeatability and reproducibility of TCP and other parameters. The agreement of TCP and other parameters including total corneal astigmatism, anterior keratometry, anterior corneal astigmatism, posterior keratometry, posterior corneal astigmatism, anterior chamber depth, white-to-white (WTW) corneal diameter, central corneal thickness, and intraocular power were evaluated. Intraclass correlation coefficient and Bland Altman plot was used to analyze.

Results: The repeatability and reproducibility of TCP and other biometry were high in all devices except WTW (ICC > 0.9). The agreement of TCP was excellent among three devices in both groups (ICC > 0.9). However, the agreement of TCP between CASIA 2 and IOLMaster 700 was slightly lower in normal eyes (ICC = 0.867) and keratoconic eyes (ICC = 0.852) with mean differences more than 1.0 diopter, might be considered clinically significant. Wider 95% limit of agreement were found in keratoconus group. Most of the other parameters and IOL power showed good to excellent agreement except WTW showing poor to moderate agreement in both groups.

Conclusions: The agreement of TCP by CASIA 2, Pentacam AXL, and IOLMaster 700 was excellent in normal and keratoconic eyes. However, TCP cannot be used interchangeably.

Field of Study:	Clinical Sciences	Student's Signature ....
Academic Year:	2020	Advisor's Signature ....

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Rusaporn Yodying

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Chapter 1: Introduction

Background and rationale

Cataract is the leading cause of blindness worldwide. Cataract surgery with intraocular lens (IOL) implantation is the most common surgery in ophthalmology field. One of the keys to achieving a favorable refractive outcome after cataract surgery is the precise ocular biometer values. Residual refractive error can be experienced owing to inappropriate IOL calculation, and results in patient's dissatisfaction, poor vision and impaired quality of life. To achieve precise IOL power calculation, the measurement of biometric data of the eye is crucial due to the fact that each parameter will be used to calculate the IOL power and effects surgical planning, such as incision wound location and length of incisional correction.

Ocular biometry parameters include axial length (AL), keratometry (K), anterior chamber depth (ACD), lens thickness (LT), central corneal thickness (CCT), white-to-white (WTW) corneal diameter, and pupil size (PS). In the past, the standard method to measure ocular biometry parameters is ultrasound biometry using sound wave. In the present optical biometry becomes standard ocular biometry for IOL calculation instead of ultrasound biometry.[1] Several optical biometry devices have been developed in these recent decades with different principles. There are three principles and techniques of optical biometry have been used in the present.

Partial coherence interferometry (PCI) is a laser interferometry, measuring solely axial length with multimode laser diode (MMLD) 780 nm. Dual beam is set up and reflection from cornea to retina is assessed in parallel.

Optical low coherence reflectometry (OLCR) is a laser interferometry which can axial measure of entire eye with superluminescent diode (SLD) 820 nm. Using standard interferometer set up with rotating glass cube system is used to change optical path length in the reference arm.

Swept source optical coherence tomography (SS-OCT), the latest technology, is full length eye tomography using laser interferometry with light emitting diode (LED) 1055 nm. SS-OCT uses tunable laser source and analyzing the interference signal based on wavelength of light. It provides better image quality and penetration.[2-4]

The keratometry (K) is one of the most important parameters for IOL power calculation. It determines corneal curvature by measuring the size of mire reflected on corneal surface which can be acquired by several methods. The manual keratometry, automated keratometry, and Placido-disk system can measure only anterior corneal curvature. A Recently developed slit image system including slit scan camera, Scheimpflug camera, and optical coherence tomography (OCT) image can measure both anterior and posterior corneal curvature.

For standard IOL calculation, the estimation of total refractive power of cornea can be calculated from anterior corneal curvature and keratometric index (KI) of 1.3375, which is a standardized ratio of normal anterior and posterior corneal curvature.[5] This corneal refractive power from anterior corneal curvature and KI of 1.3375 have been widely used in IOL formula in normal eyes. Nevertheless, total refractive power of cornea can be derived from total corneal power (TCP) that determine direct measurement of anterior and posterior corneal curvature. The assessment of posterior corneal curvature showed to reduced systematic measurement errors and provided benefits in refractive accuracy outcome after cataract surgery, especially in astigmatic correction.[6-9] In addition, posterior corneal curvature measurement should not be neglected in complex cornea surface which the relationship between anterior and posterior corneal curvature is altered such as keratoconus, post refractive surgery, post corneal transplantation, and corneal scar. TCP may serve the advantages for IOL calculation and provide benefits in refractive outcomes in these group of patients.

In some patients with corneal disease the biometric measurement for IOL calculation is more difficult than normal. Keratoconus is bilateral noninflammatory corneal thinning with abnormal posterior ectasia, and abnormal corneal thickness distribution.[10] It results in bulging and distortion of the corneal surface, leading to irregular astigmatism and progressive myopia. IOL calculation in eyes with keratoconus is still challenging and different from that in normal eyes because of the altered relationship between anterior and posterior corneal curvature, deeper anterior chamber and elongation of the eye.[11-13] In keratoconic patients, using standard keratometry usually overestimates corneal power from underestimating negative power of posterior corneal surface which results in underestimation of IOL power and postoperative hyperopia.[14, 15]

Modern generation optical biometry devices can measure TCP by direct measurement of anterior corneal curvature and posterior corneal curvature. These three biometric devices of interest are available in our institution. IOLMaster 700 is mainly an optical biometry device, while Pentacam AXL is a corneal topography and tomography with an addition feature for IOL calculation. CASIA 2 is an anterior segment OCT with a new feature for IOL calculation.

IOLMaster 700, a SS-OCT based optical biometry device, is one of the most widely used and acknowledged for IOL power calculation worldwide. IOLMaster 700 provides high accuracy in IOL power calculation. It can measure all the conventional ocular biometric data and also posterior corneal curvature.

Pentacam AXL is a rotating Scheimpflug camera combined with partial coherence interferometry (PCI). It mainly developed for corneal topography and tomography by using a rotating Scheimpflug camera. It is commonly used for keratoconus or corneal ectasia detection and progression, and also used for preoperative plan for toric IOL or refractive surgery. Pentacam AXL is newly developed with additional features for AL measurement and IOL calculation by using PCI. It determines TCP by measuring anterior and posterior corneal surface with difference techniques. Pentacam AXL provide high reliability and accuracy of ocular biometry measurement but only few studies have assessed TCP and IOL calculation. The limitation of Scheimpflug imaging is that it has low resolution and poor quality of the image.[9]

CASIA 2, a latterly introduced anterior segment OCT, is a SS-OCT based device specifically designed cross-sectional imaging of the anterior segment structure of the eye. It provides high resolution and high scan speed of up to 30000 A-scan per second. CASIA is commonly used for diagnosis of corneal or ocular surface disease, and surgical planning of anterior segment surgery. CASIA 2 added a new feature for IOL power calculation. Anterior and posterior corneal curvature can be obtained from it. There are few studies about biometric data measurement by CASIA 2 and no study that evaluate IOL calculation. According to its advantages CASIA 2 might be a device of choice for ocular biometry and IOL power calculation.

Research questions

Does CASIA 2 provide excellent agreement of TCP to Pentacam AXL and IOLMaster 700 in normal eyes and keratoconic eyes?

Does CASIA 2 provide excellent agreement of other ocular biometry including total corneal astigmatism (TCA), anterior keratometry (anterior K), anterior corneal astigmatism (ACA), posterior keratometry (posterior K), posterior corneal astigmatism (PCA), ACD, WTW, CCT, and IOL power calculation to Pentacam AXL and IOLMaster 700 in normal eyes and keratoconic eyes?

Objectives of the study

There are two main objectives of this study. The first objective is to evaluate repeatability, reproducibility and agreement of TCP measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in normal eyes and in keratoconic eyes.

The second objective is to evaluate repeatability, reproducibility and agreement of other ocular biometry including TCA, anterior K, ACA, posterior K, PCA, ACD, WTW, CCT, and IOL power calculation measured by three devices in normal eyes and in keratoconic eyes.

Research hypothesis

CASIA 2 provides excellent repeatability and reproducibility of TCP in both normal eyes and keratoconic eyes which comparable to Pentacam AXL and IOLMaster 700 and provides excellent agreement compared to Pentacam AXL and IOLMaster 700.

There are excellent repeatability and reproducibility of CASIA 2, and excellent agreement of other ocular biometry and IOL power calculation between CASIA 2, Pentacam AXL, and IOLMaster 700 in normal eyes and keratoconic eyes.

Less repeatability, reproducibility, and agreement may be observed in keratoconic eyes than in normal eyes.

Scope of study

This is a prospective descriptive study that mainly interested in the ocular biometric parameters of the eye including TCP, TCA, anterior K, ACA, posterior K, PCA, ACD, WTW, CCT, and IOL powers in healthy participants and keratoconic patients. These values were measured by three devices – CASIA 2, Pentacam AXL, and IOLMaster 700 – in the outpatient unit of the Department of Ophthalmology, King Chulalongkorn Memorial Hospital, Faculty of Medicine, Chulalongkorn University from July 2020 to March 2021.

Significance of research

CASIA 2 is a high-resolution swept source-based AS-OCT that commonly used for cross-sectional imaging of the anterior segment structure of the eye. It also provides a new feature for IOL power calculation.

This is the first study that evaluate the repeatability and the reproducibility of the ocular biometry and IOL power calculation measured by CASIA 2 compared to Pentacam AXL and IOLMaster 700 and provides the agreement of CASIA 2 in the ocular biometry measurement and IOL power calculation compared to Pentacam AXL and IOLMaster 700 in normal eyes.

Furthermore, this study evaluated the repeatability and the reproducibility of the ocular biometry and IOL power calculation measured by CASIA 2, Pentacam AXL and IOLMaster 700 and also the agreement between devices in keratoconic eyes.

The ocular biometric parameters that have been evaluated in this study include conventional biometric parameters including anterior K, ACD, WTW, CCT and IOL powers. In addition, this study also evaluated TCP, the focus parameter of this study, and the other parameters including posterior K, TCA, ACA, PCA, and also the vector analysis of the astigmatism.

The results of the study will express new information about the accuracy of CASIA 2 in measuring the ocular biometric parameters and IOL power calculation in both normal and keratoconic eyes. Furthermore, this study provides the agreement of CASIA 2 compared with Pentacam AXL, and IOLMaster 700 in measuring the ocular biometric parameters and IOL power calculation. This information will confirm the accuracy of CASIA 2 that used for the ocular biometry measurement and IOL power calculation in normal eyes and keratoconic eyes. Therefore, CASIA 2 may be considered one of the devices of choice for IOL power calculation

Operational definitions

- Accuracy

  The accuracy of the measurement method consists of trueness, and precision based on International Organization for Standardization.[27]

- Trueness

  The trueness is determined as the closeness of the agreement between the mean of the measurement results and the true or accepted reference value. In measurement such as in ophthalmology field, the trueness possibly compares to accepted reference value.

- Precision

  The precision or reliability is determined as the closeness of the agreement between measurement results or the variability between repeated measurement. The precision or reliability consists of the repeatability and the reproducibility.

- Repeatability

  The repeatability is determined as the closeness among the independent measurement results within the same method, same equipment, same device, same laboratory, when the same operator repeats the measurement in short interval of time.

- Reproducibility

  The reproducibility is determined as the closeness among the independent measurement results within the same method, same equipment, same devices, same laboratory, when the different operator repeats the measurement.

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Chapter 2: Review of related literature

Measurement of ocular biometric data

The accuracy of ocular biometric parameters of each device has been widely studied in this decade.

IOLMaster 700, a SS-OCT based optical biometry device, becomes one of the most widely used optical biometry device for IOL power calculation. Several studies showed excellent repeatability of IOLMaster 700 in measuring biometric parameters and excellent agreement compared with other PCI and OLCR based devices.[3, 4, 16] Srivannaboon et al.[2] showed excellent repeatability and reproducibility, and very high agreement of IOLMaster 700 in measuring ocular biometric values and IOL power calculation compared to the previous standard device which was time domain-OCT (IOLMaster 500). Moreover, IOLMaster 700 provides better penetration through opaque media and is significantly faster.

Pentacam AXL is a rotating Scheimpflug camera combined with PCI based biometer. There are several studies evaluated the accuracy between Pentacam AXL and IOLMaster in measuring different ocular biometric parameters. Sel et al.[17] showed that the repeatability and reproducibility of Pentacam AXL was excellent and comparable to IOLMaster 700 in measurement of mean keratometry, astigmatism, ACD and AL. Shajari et al.[18] and Wang et al.[19] reported no statistical difference in the measurement of biometric values measured by Pentacam AXL, IOLMaster 500 and IOLMaster 700. In addition, Haddad et al.[20] and Muzyka-Wozniak et al.[21] compared the measurement of biometric values which keratometry showed statistically significant between devices measured by Pentacam AXL with IOLMaster 500. Pentacam AXL provided higher IOL power using Haigis and SRK/T.[21]

CASIA 2 is a recently introduced SS-OCT based AS-OCT device, therefore, few studies that evaluated the reliability and the accuracy of CASIA 2 in measurement of the ocular biometric parameters. Schroder et al.[22] showed higher repeatability of pachymetry by CASIA 2 than Pentacam AXL. Wylegala et al.[23] demonstrated significant difference of posterior keratometry and pachymetry measured by CASIA 2, Reve NX, and Galilei G6. Until now, no study was evaluated the IOL power calculation of CASIA 2. However, CASIA SS-1000, an earlier version swept source AS-OCT, has been studied in ocular biometric parameters measurement in various reports.[24-28] Szalai et al.[27] and Chan et al.[28] showed similar results that CASIA SS-1000 was better repeatability than Scheimpflug camera in measuring pachymetry and showed significant difference between two devices in keratometry, pachymetry and ACD. Chen et al.[24] compared ACD and CCT measured by CASIA SS-1000 and TD-OCT (Visante) which showed high repeatability and high agreement between devices. Moreover, CASIA SS-1000 provided higher repeatability than TD-OCT.

There are many ocular biometric parameters that have been studied to compare the accuracy of each device.

There are a small number of published reports about the measurement of TCP, which is the most interesting parameter in this study, and TCA. Shajari et al.[29] studied the repeatability and the accuracy of TCP measured by IOLMaster 700 and Pentacam in normal subjects. The results showed high repeatability of both devices and no significant differences between TCP measured by IOLMaster 700 which called total keratometry (TK) and by Pentacam which is total corneal refractive power (TCRP). However, TCP measured from IOLMaster 700 and Pentacam cannot be used interchangeably. Furthermore, the results from this study showed high repeatability of TCA but varied values of meridian of TCA. Savini et al.[30] recently demonstrated that TCP measured by IOLMaster 700 (TK) had high repeatability and was comparable to the standard K in normal and post refractive surgery eye. In addition, TCA between IOLMaster 700 and Pentacam AXL showed significant difference. Another study from Savini et al.[31] evaluated the repeatability and the agreement of TCP measured by AS-OCT (MS-39) and two rotating Scheimpflug cameras (Pentacam HR and Sirius). The results showed high repeatability of TCP and moderate repeatability of TCA. The agreement of TCP between devices were moderate and statistically significant differences were observed in both normal and post refractive surgery eyes. Lomoriello et al.[32] showed high repeatability of TCP but lower repeatability of TCA measured by AS-OCT (MS-39) and a rotating Scheimpflug camera combined with Placido-disk topography (Sirius, CSO) in eyes with keratoconus. Guler et al.[33] and Kim et al.[34] studied the repeatability and reproducibility of TCP measured by dual Scheimpflug analyzer (Galilei). Both studied showed similar results with high repeatability and reproducibility in normal and post refractive surgery eyes. In addition, Guler et al. demonstrated that wider 95% LoA of TCP was observed in keratoconic eyes than in normal and post refractive surgery eyes.

For other keratometry, there are several reports compared Pentacam AXL and IOLMaster 700 in measurement of the anterior K which demonstrated high repeatability and reproducibility as mentioned. Two studies from Shajari et al.[18] and Wang et al.[19] showed no statistically significant difference in mean anterior K measured by Pentacam AXL, IOLMaster 500, and IOLMaster 700. Conversely, the studies from Sel et al.,[17] Muzyka-Woz'niak et al.,[21] and Haddad et al.[20] showed statistical difference in the mean of anterior K between these devices, which IOLMaster 700 provided higher value of mean keratometry than Pentacam AXL did. Few studies compared the measurement of keratometry by CASIA 2 with other devices. A recent study compared corneal elevation and pachymetry between CASIA 2 and Pentacam AXL in normal eyes. The results showed that Pentacam AXL provided better repeatability of anterior corneal elevation, but CASIA 2 provided better repeatability of pachymetry and good repeatability for posterior corneal curvature.[22] The ACA showed high repeatability and no statistically significant difference measured by CASIA and Pentacam,[27] or Pentacam AXL and IOLMaster 700.[17]

Posterior K was evaluated in many studies which demonstrated high repeatability;[31, 32, 34] however, some showed statistically significant difference between devices.[31, 32] The repeatability of PCA showed moderate agreement, and statistically significant difference was found between CASIA and Pentacam.[27]

For ACD, the repeatability and reproducibility were excellent by Pentacam AXL and IOLMaster 700. Some studies reported no statistically significant difference in ACD measured by Pentacam AXL and IOLMaster 500 or IOLMaster 700.[18, 19, 21]By contrast, other studies showed statistically significant difference in ACD measured from Pentacam AXL and IOLMaster 700, and Pentacam AXL provided higher value of ACD than IOLMaster 700 did.[17, 20]

The repeatability and reproducibility of WTW measured by Pentacam AXL[35] and IOLMaster 700[2] determined high. Some studies showed statistically significant difference in WTW between Pentacam AXL, IOLMaster 500, and IOLMaster 700.[19, 21]

For CCT, the repeatability of CCT measured by IOLMaster 700[2], Pentacam AXL[36] were excellent. A recent study showed that CASIA 2 provided better repeatability of pachymetry than Pentacam AXL did.[22]

There are previous studies reported no statistically significant difference in AL measured by Pentacam AXL and IOLMaster 500 or IOLMaster 700.[18-20] Conversely, some studies showed significantly higher value of AL from IOLMaster 700 than Pentacam AXL.[17, 21]

For IOL power calculation, there is a study that mentioned about IOL power calculation using Pentacam AXL and IOLMaster 500. Pentacam AXL showed flatter mean keratometry and lower AL, and thus Pentacam AXL provided higher IOL power calculated by both Haigis and SRK/T formula.[21] There has been no study about the accuracy of CASIA 2 in IOL power calculation.

Ocular biometry and IOL calculation in keratoconus

Ocular biometry measurement and IOL power calculation in keratoconic eyes are challenging and different from normal eyes due to unreliable biometric measurement and IOL power calculation methods and formula.

There are several studies evaluated the ocular biometry measurement in patient with keratoconus measured by many different devices. Most of the studies showed less repeatability of biometric values in keratoconic eye than in normal eye. Szalia et al.[27] evaluated the repeatability and reproducibility in measuring keratometry, pachymetry and ACD by CASIA SS-1000 and Pentacam HR in normal and keratoconic patients. The results showed less repeatability of keratometry, and higher mean difference of most parameters measured by both devices in keratoconic eyes than in normal eyes. Furthermore, CASIA ss-1000 provided less difference in repeatability than Pentacam HR in keratoconic eye. Tang et al.[37] compared keratometry measurement by AS-OCT (RTVue) with IOLMaster 500 in three groups of participants: normal eyes, post refractive surgery eyes, and keratoconic eyes. The results showed good repeatability of anterior and posterior keratometry in all groups, and net corneal power by AS-OCT was significantly lower than IOLMaster 500. The different values from the measurement between devices were observed higher in keratoconic eyes than in other group of participants. Lomoriello et al.[32] demonstrated lower repeatability and reproducibility in the measurement of biometric values including TCP by AS-OCT (MS-39) and rotating Scheimpflug camera combined with Placido-disk topography (Sirius, CSO) in eyes with keratoconus than in normal and post refractive surgery eyes. Wider 95% Limit of Agreement (LoA) of most parameters were observed in eyes with keratoconus. Guler et al.[33] also showed wider 95% LoA of TCP in keratoconic eyes measured by dual schiempflug analyzer (Galiei) than in normal or post refractive surgery eyes. Yagci et al.[38] demonstrated that Nidek AL-Scan which was an optical biometer showed less repeatability of steep keratometry in keratoconus eyes than in normal eyes. Hashemi et al.[39] compared the repeatability of keratometry measured by 5 different devices – Scheimpflug camera (Pentacam), Placido topographer (Eyesys), scanning-slit corneal topographer (Orbscan), PCI device (IOLMaster 500), and Javal manual keratometer – with different grades of keratoconus. The results showed good repeatability in mild keratoconus; however, reduced repeatability was observed in advanced kereatoconic eyes.

IOL power calculation in patients with keratoconus is challenging issue. As aforementioned, eyes with keratoconus usually have steeper corneal curvature, abnormal relationship of anterior and posterior corneal curvature, deeper ACD or more posterior effective lens position (ELP), and longer AL than normal eyes. Many studies showed postoperative refractive error, especially postoperative hyperopia in eye with keratoconus which were greater in advanced stage than in mild or moderate stage of keratoconus.[40, 41] Kamiya et al.[14] and Tamaoki et al.[15] showed that using total corneal power in IOL calculation resulted in less postoperative hyperopia. At present, common IOL formulae have been developed for normal eyes. There is no consensus of IOL formula for keratoconic eyes. Several formulae were adopted in many studies for IOL power calculation in keratoconic patients, and SRK/T seemed to yield most preferable outcome after cataract surgery. Savini et al.[42] observed large serie of keratoconic eyes that undergone cataract surgery and demonstrated hyperopic refractive outcome in every IOL formula, and SRK/T was the most accurate one. Worse refractive outcome was found in cases with advanced keratoconus. However, the study from Wang et al.[43] reported that Barrett Universal II provided the most accuracy in IOL power calculation in patients with mild to moderate keratoconus.

Chapter 3: Research methodology

Study design

This is a prospective observational study. This study was approved by Institutional Review Board, Faculty of Medicine, Chulalongkorn University, Bangkok (IRB No.169/63 and COA No. 708/2020). The study has been registered to Thai Clinical Trial Registry and the identification number is TCTR20210608001. This work was supported by Ratchadapiseksompotch Fund, Chulalongkorn University : CU_GR_63_146_30_53.

Population and samples

Population

This study enrolled two different groups of participants including

- Healthy participants (Normal group)
- Patients with keratoconus (Keratoconus group)

Venue of the study

This study performed at an outpatient unit of ophthalmology department at King Chulalongkorn Memorial Hospital, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand.

Approach to participants

The researcher approached potential study participants by direct recruitment and referral from non-investigator physicians. In addition, the researcher provided posters, flyers and notices of the research information at an outpatient unit of ophthalmology department, King Chulalongkorn Memorial Hospital to recruit participants joining the study.

Inclusion criteria and exclusion criteria

- Normal group

  Inclusion criteria

  - Healthy participants
  - Age 18 years old or more
  - Able to read, understand and sign an informed consent form

  Exclusion criteria

  - Participants who have ocular pathology
    - Corneal disease including severe dry eye and pterygium
    - Retina or macular disease
    - Strabismus or nystagmus or unable to hold gaze or fix target
  - Previous intraocular surgery, ocular surface surgery, or refractive surgery
  - Previous ocular trauma

- Keratoconus group

  Inclusion criteria

  - Participants with diagnosed keratoconus by corneal specialist based on both
    - Topography/tomography pattern characteristic; abnormal posterior elevation, abnormal corneal thickness[10]
    - At least one keratoconus clinical findings on slit-lamp examination; corneal stromal thinning, Fleischer ring, and Vogt's striae[44]
  - Subclinical keratoconus or forme fruste keratoconus based on corneal topography pattern characteristic without clinical findings
  - Mild to moderate severity of keratoconus stage 1-3 by Amsler-Krumeich keratoconus classification

- Amlers-Krumeich keratoconus classification[45]
  - Stage 1: Eccentric steeping
    Myopia & astigmatism < 5.00 D
    Mean K < 48.0 D
  - Stage 2: Myopia & astigmatism 5.00 – 8.00 D
    Mean K < 53.0 D
    Absence of scarring
    Minimum corneal thickness > 400 µm
  - Stage 3: Myopia & astigmatism 8.00 – 10.00 D
    Mean K > 53.0 D
    Absence of scarring
    Minimum corneal thickness 300 - 400 µm
  - Stage 4: Refraction cannot be measured
    Mean K > 55.0 D
    Central scarring
    Minimum corneal thickness 200 µm

Exclusion criteria

- Participants who have ocular pathology
  - Other corneal disease including severe dry eye and pterygium
  - History of acute hydrops and corneal scarring
  - Retina or macular disease
  - Strabismus or nystagmus or unable to hold gaze or fix target
- Previous intraocular surgery, ocular surface surgery, or refractive surgery
- Previous ocular trauma

Informed consent process

The researcher explained the research process and hand a research information sheet to the participants. Participants could ask the researcher any questions about the research process. Each participant had time to decide without pressure and might take their information sheet and informed consent back home and decide later. All participants willing to join the research must sign their name in written informed consent before enrolled.

Research methods

Measured instruments

Three interesting optical biometry devices were evaluated in this study including CASIA 2, Pentacam AXL, and IOLMaster 700.

- **CASIA 2**

  CASIA 2 (Tomey Corp., Japan) is an anterior segment OCT using swept-light source. CASIA 2 is not US Food and Drug Administration (FDA) approved but approved by many other countries including Japan. Its wavelength is 1310 nm with 10 μm or less for axial resolution and 30 μm or less for transverse resolution. Its scan speed is 30000 A-scan per second. A 16-line radial B-scan with 512 A-scan/line is used for keratometry measurement. CASIA 2 can measure total corneal power, called real keratometry (real K), derived from measuring anterior corneal surface, posterior corneal surface and adding pachymetry into the sum of refractive power from anterior and posterior surface at 2.5 mm and 3.0 mm zone.[46] Anterior segment scans with SS-OCT are used for central corneal thickness and anterior chamber depth measurement. CASIA 2 cannot measure axial length itself; however, axial length value from other devices can be input to calculate IOL power. The cataract preoperative protocol, which is a new feature, is used in an automatic capture mode of biometric parameters measurement and IOL power calculation. In each measurement the scans will be recorded using the auto-alignment function by moving the aiming circle on the touch screen to the corneal vertex until the focus is properly aligned.

- **Pentacam AXL**

  Pentacam AXL (Oculus Optikgerate GmbH, Germany) is a rotating Scheimpflug camera combined with PCI based optical biometer that US Food and Drug Administration (FDA) approved. Pentacam AXL uses a single Scheimpflug camera that rotates along the optical axis of the eyes. A 475 nm monochromatic blue light-emitting diode (LED) is emanated and reflected the corneal surface with different refractive indices. The camera can capture 25, 50, 100 picture scans in 2 seconds with 2760 measuring points. The measurement with Pentacam AXL has 2 steps as follows. First, axial length is measured with PCI technology with automatic captured mode. Second, anterior segment biometry, including anterior corneal surface, posterior corneal surface, TCP, pachymetry, and ACD are measured with a high-resolution rotating Scheimpflug camera in automatic technique. The TCP that measured from Scheimpflug tomography includes total corneal refractive power (TCRP) using ray tracing method with snell's law to calculate refractive power at any point of cornea which stated by the manufacturer that may represent actual refractive power[47]. Nevertheless, it can also measure true net power (TNP) which is incorporated anterior and posterior surface of the cornea. [46]

- **IOLMaster 700**

  IOLMaster 700 (Carl Zeiss Meditec AG, Germany) is a SS-OCT based optical biometer that can measure all ranges in the eye along the visual axis including CCT, ACD, LT and AL. It is a US Food and Drug Administration (FDA) approved device. Its wavelength is 1055 nm, with scan speed of 2000 A-scans per second and 44 μm scan depth with 22 μm resolution in tissue. Keratometry measurement in IOLMaster 700 uses eighteen points telecentric keratometry in 3 zones (1.5, 2.5, 3.5 mm) for anterior corneal surface and uses SS-OCT for posterior corneal surface. Total keratometry (total K) is determined TCP that measured by IOLMaster 700 which derived from calculated anterior corneal surface, posterior corneal surface, pachymetry combine with thick lens formula.[48] IOLMaster 700 utilizes optical B-scan to determine the optical biometric data. The advantage of optical b-scan technology is to allow cross-sectional visualization of structure along visual axis such as decentration of crystaline lens and location of the fovea. So that it could detect poor fixation of the eye. The automatic mode is used in each measurement.

Measurement procedures

One eye of the participants was measured the ocular biometric parameters with three devices: IOLMaster 700, Pentacam AXL, and CASIA 2 with random order. The randomization is performed by a block of three method.

All devices were calibrated every day before the first measurement in accordance with the manufacturers' instructions.

For each device, three consecutive measurements were taken. Two measurements were taken by an experienced operator to evaluate repeatability or intra-observer reliability. Another measurement was taken by another experienced operator. The first measurement from the first operator and the measurement from the second operator were used to evaluate a reproducibility or inter-observer reliability.

During the measurement, all participants were instructed to keep their chin and forehead in place and look at the fixation light in the devices. Each device was brought into the focus, and the participants' eye was aligned along with the visual axis. All participants were instructed to blink completely before each capture. In this study, all devices are non-invasive, non-contact, and no wind flow to the eyes. There was only slight flashlight from the devices for a second during measurement After completing each measurement, a short break was taken, and the participants were asked to sit back and close their eyes for few seconds. At that time each device was realigned to the beginning position before subsequent measurement. Figure 1-3 demonstrated the measurement of the ocular biometric parameters by each device.

All measurements were performed continuously in individual participants with a short resting interval between each device measurement. The overall time to measure with all devices was less than 30 minutes. The participants were measured the ocular biometric parameters with three devices in the same day during 10 am to 4 pm to minimize diurnal change. No eyedrop was allowed to instill before measurement.

Only one eye of each participant was enrolled to avoid any bias, which was always right eye. In case of right eye met the exclusion criteria, left eye was enrolled instead.

The measurements were accepted for analysis if image quality status “OK” showed on device’s screen. Otherwise, the measurements were repeated until good quality image was acquired.

The participants who had eye discomfort after finished multiple measurement were advice to close their eyes for a short period or instillation of artificial tears and then the symptom was resolved.

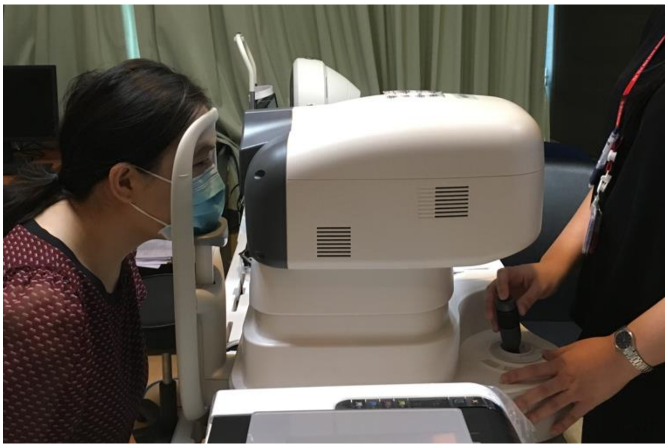

Figure 1. Demonstration of ocular biometry measurement by CASIA 2

Figure 2. Demonstration of ocular biometry measurement by Pentacam AXL

Figure 3. Demonstration of ocular biometry measurement by IOLMaster 700

Measured parameters

There are several ocular biometric parameters were evaluated in this study which can measured in all devices.

- **Total corneal power (TCP)**

  The principle of TCP is determined as the total refractive power of cornea through anterior and posterior corneal surface, calculated from refractive index of the air, which is 1.0, the refractive index of cornea which is 1.376 and the refractive index of aqueous humor which is 1.336. However, there are many different techniques to determine the TCP which depends on each device.

- **Total corneal astigmatism (TCA)**

  TCA was defined as the difference in degree of refraction in different meridians of total corneal surface including anterior and posterior corneal surface. It calculated in term of vector analysis for the valid astigmatism comparison, which are J0 vector and J45) vector. J0 is the Jackson cross-cylinder, axes at 90 degrees and 180 degrees; J45 is the Jackson cross-cylinder, axes at 45 degrees and 135 degrees. It is calculated by using J0 and J45 equation.[49]

$$J0 = (- C/2) \cos (2\alpha)$$

$$J45 = (- C/2) \sin (2\alpha)$$

- **Anterior keratometry (anterior K)**

  This parameter is the mean of the corneal curvature in millimeter from flattest and steepest meridians of the anterior corneal surface. The curvature is converted to keratometric diopter using the standard keratometric index of 1.3375.

- **Anterior corneal astigmatism (ACA)**

ACA is the difference in degree of refraction in different meridians from anterior surface of the cornea. It also calculated to vector analysis which are J0 and J45 as mentioned in TCA.

- **Posterior keratometry (posterior K)**

This parameter is the mean of the corneal curvature in millimeter from flattest and steepest meridian of the posterior corneal surface. The curvature is converted to keratometric diopter using the refractive index of cornea which is 1.376 and the refractive index of aqueous humor which is 1.336.

- **Posterior corneal astigmatism (PCA)**

PCA is the difference in degree of refraction in different meridians from posterior surface of the cornea. It also calculated to vector analysis which are J0 and J45 as mentioned in TCA.

- **Anterior chamber depth (ACD)**

ACD represents the axial depth between central anterior corneal epithelium and anterior surface of crystalline lens.

- **White-to-white (WTW)**

WTW or corneal diameter is defined as the widest horizontal distance between the border of corneal limbus.

- **Central corneal thickness (CCT)**

CCT is the thickness or pachymetry of cornea which determines the axial distance from anterior to posterior corneal surface at central cornea.

- **IOL power calculation**

The IOL power were calculated with IOL model Acrysof SN60WF (Alcon Laboratories, Inc.) which is one of the most commonly used IOL models in practice and in former research.

The IOL formulae that used to calculate IOL power were SRK/T and Barrett universal II in both normal group and keratoconus group.

  - **SRK/T**

    SRK/T is the third generation IOL formula that is commonly used. To calculate IOL power with SRK/T formula, keratometry and axial length are required.

  - **Barrett Universal II**

    Barrett Universal II is the fourth generation IOL formula. This formula requires many parameters including keratometry, AL, ACD, LT, and WTW.

The User Group for Laser Interference Biometry (ULIB) IOL constant for IOLMaster were used for IOL power calculation in three devices with SRK/T formula, which A constant is 119.0. For Barrett Universal II, lens factor of SN60WF model is 1.88 based on Asia-Pacific Association of Cataract and Refractive Surgeons website for Barrett Universal II calculation.

The IOL formulae that used for IOL power calculation in this study are SRK/T and Barrette universal II which using anterior corneal power and keratometric index (KI) = 1.3375 to calculate IOL power in both normal and keratoconus group.

There are limited literature and no consensus about IOL calculation for keratoconus. Some studies showed that using SRK/T formula is the best method to calculate IOL power in mild keratoconus.[40, 42, 50] In theory, modern or fourth generation formula might improve the outcome in abnormal eyes such as variable of ELP in keratoconic eyes. And recently study showed that Barrett universal II is the most accuracy formula for keratoconic eyes.[40, 43]

Axial length (AL) is the distance from anterior surface of cornea to retina through the visual axis of the eye. Optical biometry measures AL by detecting the signal that reflects from the cornea and the retinal pigment epithelium.

Due to CASIA 2's inability to measure AL, this parameter was not considered as an outcome of this study. For IOL calculation with CASIA 2 we used axial length value from IOLMaster 700 instead.

Sample size

- The total sample size is approximated 134 eyes of participants. The number is calculated from
    - Intraclass Correlation of Coefficient (ICC)
    - Bland-Altman plot
- Sample size calculated from Intraclass Correlation of Coefficient (ICC) is 134.

$$n = 1 + \frac{2(Z_\alpha + Z_\beta)^2 k}{(\ln C_0)^2 (k-1)}$$

Where $C_0 = \frac{1+k\theta_0}{1+k\theta_1}$

$$\theta_0 = \frac{R_0}{1-R_0} \; ; \; \theta_1 = \frac{R_1}{1-R_1}$$

P1 = 0.90

P2 = 0.85

Number of replications = 2

Alpha = 0.05

Power = 0.80

- Sample size calculated from Bland-Altman plot is 128.

  95% Confidence Interval = +/- 1.96 $\sqrt{(3S^2/N)}$

  S = Standard deviation of differences between measurement by 2 methods

  N = Sample size

  Acceptable 95% Confidence Interval = 0.3 S

- In this study the 134 participants were separated into 2 groups: normal group and keratoconus group. The sample size for normal group were 100 eyes and keratoconus group were 34 eyes.

Data collection

The data were completely collected in a case record form after measurement in one visit. There is a case record form for normal group and for keratoconus group separately. The case record form consists of two parts. Part 1 is the patient assessment which includes demographic data, age, sex, ophthalmic history, visual aquity, and ophthalmic examination. The spherical equivalence from auto-refraction is also included. For keratoconus group, the history of diagnosis, clinical signs, stage of keratoconus and previous treatment are included in the case record form. Part 2 is the ocular biometry measurement. Three-time repeated results of the ocular biometry measurements and IOL power calculation from IOLMaster 700, Pentacam AXL, and CASIA 2 were collected in all biometric parameters. The first two-time measurements were performed by the first operator and the last time measurement by the second operator.

The digit numbers were used for research participant identification instead of the real name of participants so that the participants were not identifiable.

Adverse events were included in the case record form. No Adverse event was reported from the research process.

Data analysis and statistics

The accuracy of the measurement method consists of trueness, and precision based on International Organization for Standardization.[51] As mentioned before, trueness is defined as the closeness of agreement between the mean of the measurement results and the true value or accepted reference value. Precision is defined as the closeness of agreement between repeated measurement results.

There are several factors that contribute the variability of the measurement including the operator, the instrument used, the calibration of the instrument, the environment, and the time elapsed between measurement.

Precision or reliability is determined as the variability between repeated measurement, consisted of repeatability and reproducibility. In the repeatability, all of the aforementioned factors are constant and do not contribute the variability. On the other hand, the factors are varied and contribute variability in the reproducibility.

Some measurement methods, the true value cannot be exactly demonstrated. Trueness can be possibly obtained from accepted reference value.

In this study, the repeatability or intra-observer reliability were analyzed by twice measurement by the first operator. The reproducibility or inter-observer reliability were analyzed by the first measurement from the first operator and the measurement from the second operator. The repeatability and the reproducibility were used to evaluate the precision or reliability of ocular biometric parameter measurements and IOL power calculation in each device. Intraclass correlation coefficient (ICC) and Bland-Altman plot were used for statistical analysis.

The agreement of ocular biometry measurement and IOL power calculation among three devices and the agreement between CASIA 2 and IOLMaster 700, and CASIA 2 and Pentacam AXL, and Pentacam AXL and IOLMaster 700 were analyzed. The biometric values measured by IOLMaster 700 and Penatacam AXL were considered reference values. The agreement of Pentacam AXL and IOLMaster 700 were also analyzed. Intraclass correlation coefficient (ICC) and Bland-Altman plot were used for statistical analysis.

Statistical analysis

- **Intraclass correlation coefficient (ICC)**

An index of reliability commonly used to evaluate repeatability and reproducibility between pairs of measurement. The ICC is the proportion of the variability in the measurement which is due to difference between pairs.

The ICC ranges from 0 to 1 and is commonly classified as follows: ICC of less than 0.5 is considered poor agreement; ICC of 0.5 to less than 0.75 is considered moderate agreement; ICC of 0.75 to less than 0.90 is considered good agreement; ICC of 0.90 or more is considered excellent agreement, and ICC of 0.90 or more is considered excellent agreement.[52]

- **Bland-Altman plot**

Bland-Altman plot is used to measure level of agreement between measurement. The plot using the differences between method measurement in y-axis and the means in x-axis. The 95% limits of agreement (LoA), interval between upper and lower limits, is defined as mean +/- 1.96 SD of the differences between two measurement. Bland-Altman plot can show the systematic difference or bias between measurement when it is existed.[53]

Ethical consideration

The study was performed following the tenets of the Declaration of Helsinki and was approved by Institutional Review Board, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand. Written informed consents were obtained from all participants.

The researcher followed three ethical principles of Belmont report.

- **Respect for person**

First, respect for person, the participants were explained the research objective, research process, research method, and possible adverse events by the researcher and have time to decide without pressure before signing the informed consent. If the participants had any questions, they could ask the researcher directly. The participants could refuse to join the research whenever along the process, and they would be received a standard treatment.

- **Beneficence**

For beneficence principle, the participants were screened for any abnormal ocular biometry and corneal abnormalities and if there were any abnormalities the participants were investigated and treated properly.

All devices used in this study are a non-contact instrument, therefore the participants might only feel eye discomfort after multiple measurement.

All participants' data were kept confidentially without identification.

- **Justice**

For justice principle, each participant was measured and treated with the same protocol.

Risk and Investigator responsibility

The risk and the adverse events from this research process are very low. Because of all devices using in this study is non-invasive, non-contact, and no wind flow to the eyes. The overall time to measure with all devices is less than 30 minutes and the participants have time to rest between the device measurement.

The participants might have eye discomfort after multiple measurement due to decrease blinking during the measurement without serious adverse effects. And the symptoms resolved after close the eyes or instillation of artificial tears.

The participants' information was kept confidential by the principal investigator.

Chapter 4: Results

One hundred and thirty-four eyes of 134 participants (100 normal participants and 34 participants with keratoconus) completed all of the measurements and were eligible for analysis. The mean (SD) age of the entire participants was 34.86 (13.34) years (range 18 to 71 years). Demographic data of the study population is shown in Table 1.

Table 1. Demographic data

Demographic data	Normal (n = 100)	Keratoconus (n = 34)
Age, mean ± SD (range, years)	36.72 ± 14.26 (18 - 71)	29.38 ± 8.10 (19 - 57)
Sex, female, n (%)	84 (84%)	13 (38.24%)
Right eye, n (%)	92 (92%)	21 (61.76%)
Uncorrected distance visual acuity, mean ± SD (LogMAR)	0.63 ± 0.58	0.75 ± 0.52
Manifest spherical equivalent, mean ± SD (diopters)	-3.57 ± 3.95	-6.11 ± 3.70
Sphere	-3.21 ± 3.83	-4.27 ± 3.33
Cylinder	-0.67 ± 0.56	-3.60 ± 2.38
Refraction		
Less than -5.00 D	57 (57%)	16 (47.1%)
-5.00 D or more	43 (43%)	18 (52.9%)
Amsler – Krumeich keratoconus stage, n (%)		
Stage 1		25 (73.53%)
Stage 2		6 (17.65%)
Stage 3		3 (8.82%)

Table 2 and 3 respectively show the mean ocular biometric parameters obtained from the three devices in normal eyes and in keratoconic eyes.

Table 2. The biometric measurements using CASIA 2, Pentacam AXL, IOLMaster 700 in normal eyes.

Parameters	CASIA 2 (1)		Pentacam AXL (2)		IOLMaster 700 (3)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
TCP (D)	43.09 ± 1.31	38.90, 46.10	43.49 ± 1.41	39.50, 47.00	44.11 ± 1.35	40.04, 47.35
TCA (D)						
Power (D)	-1.03 ± 0.62	-4.00, -0.20	-1.13 ± 0.69	-4.00, -0.10	-1.10 ± 0.59	-3.02, -0.14
J0	0.41 ± 0.37	-0.45, 1.66	0.46 ± 0.42	-0.58, 1.85	0.43 ± 0.38	-0.52, 1.49
J45	-0.10 ± 0.22	-0.56, 1.12	-0.08 ± 0.22	-0.58, 0.75	-0.09 ± 0.22	-0.63, 0.57
Anterior K (D)	44.15 ± 1.33	39.80, 47.10	44.05 ± 1.32	40.00, 47.30	44.13 ± 1.35	39.97, 47.36
ACA						
Power (D)	-1.17 ± 0.66	-4.30, -0.20	-1.18 ± 0.77	-3.60, 2.50	-1.15 ± 0.59	-2.94, -0.18
J0	0.50 ± 0.37	-0.39, 1.82	0.51 ± 0.42	-1.23, 1.67	0.48 ± 0.37	-0.49, 1.45
J45	-0.10 ± 0.23	-0.57, 1.14	-0.08 ± 0.21	-0.59, 0.67	-0.08 ± 0.21	-0.68, 0.58
Posterior K (D)	-6.24 ± 0.20	-6.80, -5,50	-6.38 ± 0.21	-7.00, -5.70	-5.95 ± 0.19	-6.46, -5.30
PCA						
Power (D)	-0.32 ± 0.12	-0.80, -0.10	-0.37 ± 0.14	-0.80, -0.10	-0.24 ± 0.11	-0.50, 0.00
J0	47.89 ± 0.06	-0.35, 0.01	-0.18 ± 0.07	-0.39, -0.01	-0.11 ± 0.06	-0.25, 0.05
J45	0.02 ± 0.04	-0.19, 0.11	0.01 ± 0.05	-0.10, 0.16	0.01 ± 0.05	-0.10, 0.16
ACD (mm)	3.53 ± 0.39	2.52. 4.24	3.46 ± 0.39	2.46, 4.18	3.43 ± 0.39	2.41, 4.14
WTW (mm)	11.76 ± 0.51	9.14, 12.64	11.71 ± 0.42	10.8, 13.5	11.91 ± 0.59	8.40, 12.80
CCT (μm)	528.21 ± 28.67	446, 621	539.55 ± 28.06	458, 632	534.1 ± 30.74	447, 627
IOL power (D)						
SRK/T	16.91 ± 5.17	5.0, 25.5	17.02 ± 5.08	5.0, 25.0	16.93 ± 5.17	4.5, 25.5
Barrette II	16.91 ± 5.17	6.0, 25.5	17.01 ± 5.12	5.5, 25.5	16.83 ± 5.15	5.5, 25.5

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D =diopters

Table 3. The biometric measurements using CASIA 2, Pentacam AXL, IOLMaster 700 in keratoconic eyes.

Parameters	CASIA 2 (1)		Pentacam AXL (2)		IOLMaster 700 (3)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
TCP (D)	45.39 ± 2.47	40.40, 52.40	45.98 ± 2.9	40.90, 53.20	47.27 ± 3.75	41.58, 56.33
TCA (D)						
Power (D)	-3.22 ± 1.74	-7.50, -0.80	-3.75 ± 2.14	-10.30, -0.90	-4.66 ± 2.79	-11.00, -0.25
J0	1.30 ± 1.09	-1.29, 3.74	1.55 ± 1.30	-0.71, 5.10	1.40 ± 2.04	-3.42, 5.47
J45	-0.28 ± 0.66	-1.57, 1.58	-0.01 ± 0.79	-1.82, 1.72	-0.12 ± 1.17	-2.72, 2.59
Anterior K (D)	46.66 ± 2.65	41.60, 53.90	47.08 ± 3.33	41.60, 54.60	47.39 ± 3.85	41.67, 56.49
ACA						
Power (D)	-3.47 ± 1.82	-7.80, -0.80	-3.95 ± 2.29	-11.5, -0.7	-4.73 ± 2.81	-12.00, -0.32
J0	1.44 ± 1.09	-1.00, 3.90	1.44 ± 1.54	-1.94, 5.62	1.44 ± 2.06	-3.30, 5.97
J45	-0.33 ± 0.69	-1.62, 1.64	-0.03 ± 0.92	-1.93, 1.58	-0.12 ± 1.17	-2.77, 2.60
Posterior K (D)	-6.77 ± 0.53	-7.90, -6.00	-6.95 ± 0.67	-8.30, -5.90	-6.49 ± 0.64	-7.85, -5.59
PCA						
Power (D)	-0.72 ± 0.29	-1.40, -0.10	-0.79 ± 0.47	-2.20, 0.00	-0.71 ± 0.39	-1.79, -0.11
J0	-0.32 ± 0.16	-0.67, 0.04	-0.32 ± 0.28	-1.09, 0.17	-0.23 ± 0.28	-0.89, 0.34
J45	0.09 ± 0.13	-0.22, 0.34	0.04 ± 0.19	-0.43, 0.45	0.03 ± 0.19	-0.37, 0.44
ACD (mm)	3.79 ± 0.28	3.12, 4.18	3.73 ± 0.29	3.11, 4.21	3.69 ± 0.28	3.01, 4.08
WTW (mm)	11.87 ± 0.49	10.93, 12.68	11.83 ± 0.38	11.20, 12.70	12.03 ± 0.71	8.80, 12.90
CCT (μm)	488.79 ± 31.13	414, 565	493.32 ± 31.88	422, 571	493.09 ± 33.33	416, 574
IOL power (D)						
SRK/T	13.84 ± 4.28	1.5, 21.5	12.88 ± 5.73	-5.5, 21.5	12.31 ± 6.71	-10.0, 21.5
Barrette II	13.37 ± 4.35	3. 21.5	12.65 ± 3.02	-2.0, 21.5	12.06 ± 5.97	-5.5, 21.5

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D =diopters

Repeatability and Reproducibility

The repeatability and the reproducibility of TCP and other biometric parameters measured by the three devices in healthy participants are demonstrated in Table 4 and 5 respectively. The repeatability and the reproducibility of all ocular biometric parameters in keratoconic eyes are demonstrated in Table 6 and 7.

If focus on TCP, both of the repeatability and the reproducibility of each device was high in both normal and keratoconic eyes. For the repeatability of the three devices, ICCs ranged from 0.996 to 0.997 in normal eyes, and 0.998 to 0.999 in keratoconic eyes. All of the three devices showed low mean differences between the measurements by the same operator and narrow 95% confidence limits of the ICCs and 95% LoAs in both groups of participants. The repeatability of IOLMaster 700 had a much higher mean difference than CASIA 2 and Pentacam AXL in normal eyes. Keratoconic eyes had higher mean differences between measurements by the same operator compared with normal eyes in all devices.

The ICCs for the reproducibility of TCP ranged from 0.995 to 0.998 in normal eyes, and 0.996 to 0.998 in keratoconic eyes. All devices showed low mean differences between the measurements by the different operators and narrow 95% confidence limits of the ICCs and 95% LoAs in both groups of participants. As with the repeatability analysis, the reproducibility of IOLMaster 700 had a much higher mean difference than the other devices. Using CASIA 2 and Pentacam AXL, keratoconic eyes had higher mean differences between TCP measured by the different operators compared with normal eyes, while IOLMaster 700 demonstrated comparable mean differences. Among 3 devices, CASIA 2 demonstrated the lowest mean difference in the repeatability and reproducibility analysis in both normal and keratoconic eyes.

For other biometric parameters, the ICCs of most parameters showed excellent repeatability in both groups. The repeatability of astigmatism values with vector analysis including TCA, ACA, and PCA were considered good repeatability in healthy participants. WTW measured by CASIA 2 and IOLMaster 700 showed moderate repeatability in normal eyes (ICC = 0.701, and ICC = 0.658 respectively) and showed highest mean difference by IOLMaster 700.

The reproducibility of other biometric parameters showed excellent in most of parameters in both groups. Similar to the repeatability, the reproducibility of astigmatisms values was good in healthy participants. WTW measured by CASIA 2 in normal eyes showed moderate reproducibility (ICC = 0.653). However, WTW by CASIA 2 did not show higher mean difference, but slightly wider 95% LoA was observed in normal eyes.

Table 4. Repeatability of all biometric parameters measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in healthy participants

N = 100		95% CL		Difference	95% LoA	
Parameters	ICC	Lower	Upper	Mean ± SD	Lower	Upper
TCP (D)						
CASIA 2	0.996	0.994	0.997	-0.007 ± 0.171	-0.342	0.328
Pentcam AXL	0.996	0.994	0.997	-0.006 ± 0.175	-0.349	0.337
IOLMaster700	0.997	0.995	0.998	0.056 ± 0.180	-0.297	0.409
TCA (D)						
CASIA 2	0.908	0.863	0.938	0.008 ± 0.362	-0.702	0.718
Pentcam AXL	0.865	0.799	0.909	0.038 ± 0.460	-0.864	0.940
IOLMaster700	0.945	0.919	0.963	-0.011 ± 0.275	-0.550	0.528
J0						
CASIA 2	0.947	0.921	0.964	-0.011 ± 0.165	-0.334	0.312
Pentcam AXL	0.894	0.842	0.929	-0.010 ± 0.247	-0.494	0.474
IOLMaster700	0.965	0.949	0.977	0.009 ± 0.138	-0.261	0.279
J45						
CASIA 2	0.916	0.875	0.943	0.000 ± 0.128	-0.251	0.251
Pentcam AXL	0.868	0.803	0.911	0.007 ± 0.151	-0.289	0.303
IOLMaster700	0.854	0.782	0.901	-0.010 ± 0.160	-0.324	0.304
Anterior K (D)						
CASIA 2	0.998	0.997	0.999	-0.013 ± 0.118	-0.244	0.218
Pentcam AXL	0.996	0.994	0.997	-0.004 ± 0.162	-0.322	0.314
IOLMaster700	0.996	0.995	0.998	0.022 ± 0.244	-0.456	0.500
ACA (D)						
CASIA 2	0.919	0.879	0.945	0.004 ± 0.363	-0.707	0.715
Pentcam AXL	0.795	0.696	0.862	-0.024 ± 0.585	-1.171	1.123
IOLMaster700	0.943	0.915	0.961	-0.15 ± 0.257	-0.654	0.354
J0						
CASIA 2	0.946	0.920	0.964	-0.009 ± 0.167	-0.336	0.318
Pentcam AXL	0.844	0.769	0.895	0.022 ± 0.289	-0.544	0.588
IOLMaster700	0.964	0.947	0.976	0.010 ± 0.128	-0.241	0.261
J45						
CASIA 2	0.923	0.885	0.948	-0.004 ± 0.128	-0.255	0.247
Pentcam AXL	0.871	0.809	0.913	0.015 ± 0.143	-0.265	0.295
IOLMaster700	0.873	0.811	0.914	-0.009 ± 0.153	-0.309	0.291
Posterior K (D)						

CASIA 2	0.996	0.994	0.997	0.002 ± 0.025	-0.047	0.051
Pentcam AXL	0.965	0.949	0.977	-0.015 ± 0.056	-0.125	0.095
IOLMaster700	0.985	0.978	0.990	0.002 ± 0.068	-0.131	0.135
PCA (D)						
CASIA 2	0.948	0.922	0.965	-0.002 ± 0.053	-0.106	0.102
Pentcam AXL	0.885	0.829	0.923	0.007 ± 0.084	-0.158	0.172
IOLMaster700	0.913	0.870	0.941	-0.010 ± 0.070	-0.147	0.127
J0						
CASIA 2	0.952	0.929	0.968	0.000 ± 0.025	-0.049	0.049
Pentcam AXL	0.891	0.837	0.926	0.002 ± 0.042	-0.080	0.084
IOLMaster700	0.930	0.896	0.953	-0.002 ± 0.034	-0.069	0.065
J45						
CASIA 2	0.964	0.947	0.976	0.003 ± 0.016	-0.028	0.034
Pentcam AXL	0.888	0.833	0.924	-0.003 ± 0.030	-0.062	0.056
IOLMaster700	0.818	0.729	0.878	0.001 ± 0.039	-0.075	0.077
ACD (mm)						
CASIA 2	0.999	0.999	1.000	0.006 ± 0.021	-0.035	0.047
Pentcam AXL	1.000	0.999	1.000	0.001 ± 0.016	-0.030	0.032
IOLMaster700	0.994	0.992	0.996	0.004 ± 0.021	-0.037	0.045
WTW (mm)						
CASIA 2	0.701	0.548	0.803	0.004 ± 0.447	-0.872	0.880
Pentcam AXL	0.940	0.911	0.960	-0.007 ± 0.185	-0.370	0.356
IOLMaster700	0.658	0.492	0.770	0.075 ± 0.400	-0.709	0.859
CCT (µm)						
CASIA 2	1.000	0.999	1.000	0.060 ± 1.278	-2.445	2.565
Pentcam AXL	0.997	0.996	0.998	0.620 ± 2.936	-5.135	6.375
IOLMaster700	0.997	0.996	0.998	0.990 ± 3.765	-6.389	8.369
IOL power						
SRK/T						
CASIA 2	1.000	1.000	1.000	0.030 ± 0.171	-0.305	0.365
Pentcam AXL	0.999	0.999	0.999	0.030 ± 0.308	-0.574	0.634
IOLMaster700	1.000	0.999	1.000	-0.035 ± 0.268	-0.560	0.490
Barrette II						
CASIA 2	0.999	0.999	1.000	0.030 ± 0.274	-0.507	0.567
Pentcam AXL	0.999	0.999	0.999	0.060 ± 0.312	-0.552	0.672
IOLMaster700	0.999	0.999	0.999	-0.040 ± 0.281	-0.591	0.511

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits

Table 5. Reproducibility of all biometric parameters measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in healthy participants

N = 100		95% CL		Difference	95% LoA	
Parameters	ICC	Lower	Upper	Mean ± SD	Lower	Upper
TCP (D)						
CASIA 2	0.998	0.997	0.998	0.000 ± 0.124	-0.243	0.243
Pentcam AXL	0.996	0.995	0.998	-0.003 ± 0.162	-0.321	0.315
IOLMaster700	0.995	0.992	0.997	0.056 ± 0.180	-0.297	0.409
TCA (D)						
CASIA 2	0.867	0.802	0.91	0.063 ± 0.386	-0.694	0.82
Pentcam AXL	0.851	0.778	0.899	0.018 ± 0.476	-0.915	0.951
IOLMaster700	0.948	0.923	0.965	-0.011 ± 0.275	-0.550	0.528
J0						
CASIA 2	0.930	0.895	0.953	-0.033 ± 0.177	-0.380	0.314
Pentcam AXL	0.904	0.858	0.936	-0.010 ± 0.241	-0.482	0.462
IOLMaster700	0.968	0.953	0.979	0.009 ± 0.138	-0.261	0.279
J45						
CASIA 2	0.781	0.675	0.853	-0.019 ± 0.174	-0.360	0.322
Pentcam AXL	0.878	0.818	0.918	-0.004 ± 0.137	-0.273	0.265
IOLMaster700	0.840	0.763	0.893	-0.010 ± 0.160	-0.324	0.304
Anterior K (D)						
CASIA 2	0.997	0.995	0.998	-0.002 ± 0.156	-0.308	0.304
Pentcam AXL	0.997	0.996	0.998	0.006 ± 0.135	-0.259	0.271
IOLMaster700	0.992	0.988	0.994	0.022 ± 0.244	-0.456	0.5
ACA (D)						
CASIA 2	0.876	0.815	0.916	0.055 ± 0.399	-0.727	0.837
Pentcam AXL	0.833	0.753	0.888	-0.049 ± 0.530	-1.088	0.99
IOLMaster700	0.955	0.932	0.969	-0.15 ± 0.257	-0.654	0.354
J0						
CASIA 2	0.925	0.889	0.95	-0.030 ± 0.182	-0.387	0.327
Pentcam AXL	0.882	0.824	0.92	0.022 ± 0.261	-0.49	0.534
IOLMaster700	0.971	0.957	0.98	0.010 ± 0.128	-0.241	0.261
CASIA 2	0.796	0.697	0.863	-0.026 ± 0.175	-0.369	0.317
Pentcam AXL	0.913	0.871	0.942	-0.003 ± 0.116	-0.230	0.224
IOLMaster700	0.857	0.788	0.904	-0.009 ± 0.153	-0.309	0.291
Posterior K (D)						

CASIA 2	0.996	0.994	0.997	0.001 ± 0.027	-0.052	0.054
Pentcam AXL	0.961	0.942	0.974	-0.012 ± 0.062	-0.134	0.11
IOLMaster700	0.967	0.95	0.977	0.002 ± 0.068	-0.131	0.135
PCA (D)						
CASIA 2	0.905	0.859	0.936	0.008 ± 0.066	-0.121	0.137
Pentcam AXL	0.882	0.824	0.92	0.012 ± 0.084	-0.153	0.177
IOLMaster700	0.896	0.846	0.93	-0.010 ± 0.070	-0.147	0.127
J0						
CASIA 2	0.92	0.881	0.946	0.004 ± 0.031	-0.057	0.065
Pentcam AXL	0.889	0.835	0.925	0.006 ± 0.042	-0.076	0.088
IOLMaster700	0.918	0.878	0.945	-0.002 ± 0.034	-0.069	0.065
J45						
CASIA 2	0.876	0.815	0.917	0.005 ± 0.027	-0.048	0.058
Pentcam AXL	0.853	0.781	0.901	0.000 ± 0.035	-0.069	0.069
IOLMaster700	0.83	0.747	0.885	0.001 ± 0.039	-0.075	0.077
ACD (mm)						
CASIA 2	0.999	0.999	0.999	0.005 ± 0.022	-0.038	0.048
Pentcam AXL	0.999	0.998	0.999	-0.002 ± 0.026	-0.053	0.049
IOLMaster700	0.999	0.999	1	0.004 ± 0.021	-0.037	0.045
WTW (mm)						
CASIA 2	0.653	0.476	0.771	-0.004 ± 0.496	-0.976	0.968
Pentcam AXL	0.948	0.922	0.965	-0.007 ± 0.174	-0.348	0.334
IOLMaster700	0.841	0.764	0.893	0.075 ± 0.400	-0.709	0.859
CCT (µm)						
CASIA 2	0.999	0.999	1	0.370 ± 1.315	-2.207	2.947
Pentcam AXL	0.998	0.997	0.999	0.310 ± 2.477	-0.348	0.334
IOLMaster700	0.996	0.994	0.997	0.990 ± 3.765	-6.389	8.369
SRK/T						
CASIA 2	1	1	1	0.000 ± 0.188	-0.368	0.368
Pentcam AXL	0.999	0.999	1	0.015 ± 0.251	-0.477	0.507
IOLMaster700	0.999	0.999	1	-0.035 ± 0.268	-0.560	0.49
Barrette II						
CASIA 2	0.999	0.999	0.999	-0.010 ± 0.284	-0.567	0.547
Pentcam AXL	0.999	0.999	0.999	0.000 ± 0.318	-0.623	0.623
IOLMaster700	0.999	0.999	0.999	-0.040 ± 0.281	-0.591	0.511

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits

Table 6. Repeatability of all biometric parameters measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in keratoconic patients

N = 34		95% CL		Difference	95% LoA	
Parameters	ICC	Lower	Upper	Mean ± SD	Lower	Upper
TCP (D)						
CASIA 2	0.998	0.997	0.999	-0.038 ± 0.202	-0.434	0.358
Pentcam AXL	0.999	0.997	0.999	-0.059 ± 0.205	-0.461	0.343
IOLMaster700	0.998	0.997	0.999	0.042 ± 0.312	-0.57	0.654
TCA (D)						
CASIA 2	0.994	0.988	0.997	0.021 ± 0.264	-0.496	0.538
Pentcam AXL	0.990	0.980	0.995	0.079 ± 0.415	-0.734	0.892
IOLMaster700	0.982	0.965	0.991	-0.113 ± 0.772	-1.626	1.4
J0						
CASIA 2	0.996	0.992	0.998	-0.010 ± 0.139	-0.282	0.262
Pentcam AXL	0.992	0.984	0.996	-0.064 ± 0.224	-0.503	0.375
IOLMaster700	0.991	0.982	0.995	0.055 ± 0.403	-0.735	0.845
J45						
CASIA 2	0.994	0.987	0.997	0.001 ± 0.107	-0.209	0.211
Pentcam AXL	0.980	0.959	0.990	-0.013 ± 0.226	-0.456	0.43
IOLMaster700	0.988	0.976	0.994	0.019 ± 0.253	-0.477	0.515
Anterior K (D)						
CASIA 2	0.999	0.997	0.999	0.003 ± 0.190	-0.369	0.375
Pentcam AXL	0.999	0.998	0.999	-0.050 ± 0.230	-0.501	0.401
IOLMaster700	0.999	0.997	0.999	0.029 ± 0.300	-0.559	0.617
ACA (D)						
CASIA 2	0.994	0.988	0.997	0.024 ± 0.279	-0.523	0.571
Pentcam AXL	0.990	0.981	0.995	-0.027 ± 0.447	-0.903	0.849
IOLMaster700	0.989	0.978	0.994	-0.108 ± 0.609	-1.302	1.086
J0						
CASIA 2	0.996	0.991	0.998	-0.015 ± 0.145	-0.299	0.269
Pentcam AXL	0.995	0.990	0.997	0.003 ± 0.224	-0.436	0.442
IOLMaster700	0.994	0.988	0.997	0.047 ± 0.325	-0.590	0.684
J45						
CASIA 2	0.992	0.984	0.996	-0.002 ± 0.124	-0.245	0.241
Pentcam AXL	0.987	0.975	0.994	-0.029 ± 0.203	-0.427	0.369
IOLMaster700	0.991	0.981	0.995	0.016 ± 0.228	-0.431	0.463
Posterior K (D)						

CASIA 2	0.998	0.997	0.999	0.000 ± 0.043	-0.084	0.084
Pentcam AXL	0.997	0.995	0.999	-0.009 ± 0.071	-0.148	0.13
IOLMaster700	0.998	0.996	0.999	0.006 ± 0.058	-0.108	0.12
PCA (D)						
CASIA 2	0.996	0.991	0.998	0.009 ± 0.038	-0.065	0.083
Pentcam AXL	0.987	0.975	0.994	-0.015 ± 0.099	-0.209	0.179
IOLMaster700	0.979	0.952	0.99	-0.048 ± 0.107	-0.258	0.162
J0						
CASIA 2	0.997	0.994	0.998	0.003 ± 0.018	-0.032	0.038
Pentcam AXL	0.984	0.969	0.992	0.014 ± 0.069	-0.121	0.149
IOLMaster700	0.988	0.976	0.994	-0.011 ± 0.063	-0.134	0.112
J45						
CASIA 2	0.991	0.983	0.996	-0.003 ± 0.024	-0.050	0.044
Pentcam AXL	0.984	0.968	0.992	-0.004 ± 0.048	-0.098	0.09
IOLMaster700	0.983	0.966	0.992	-0.010 ± 0.050	-0.108	0.088
ACD (mm)						
CASIA 2	0.998	0.997	0.999	-0.006 ± 0.021	-0.047	0.035
Pentcam AXL	0.996	0.991	0.998	0.003 ± 0.038	-0.071	0.077
IOLMaster700	0.999	0.998	0.999	0.000 ± 0.020	-0.039	0.039
WTW (mm)						
CASIA 2	0.903	0.803	0.952	-0.094 ± 0.287	-0.657	0.469
Pentcam AXL	0.992	0.984	0.996	0.016 ± 0.064	-0.109	0.141
IOLMaster700	0.951	0.902	0.975	-0.056 ± 0.349	-0.740	0.628
CCT (µm)						
CASIA 2	0.999	0.999	1	0.147 ± 1.635	-3.058	3.352
Pentcam AXL	0.998	0.996	0.999	-0.235 ± 3.006	-6.127	5.657
IOLMaster700	0.994	0.988	0.997	0.059 ± 5.187	-10.108	10.226
IOL power (D)						
SRK/T						
CASIA 2	0.998	0.997	0.999	0.059 ± 0.343	-0.613	0.731
Pentcam AXL	0.997	0.995	0.999	0.132 ± 0.581	-1.007	1.271
IOLMaster700	0.998	0.997	0.999	0.015 ± 0.571	-1.104	1.134
Barrette II						
CASIA 2	0.998	0.997	0.999	0.015 ± 0.359	-0.689	0.719
Pentcam AXL	0.998	0.996	0.999	0.132 ± 0.449	-0.748	1.012
IOLMaster700	0.998	0.997	0.999	-0.061 ± 0.480	-1.002	0.88

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits

*Table 7. Reproducibility of all **biometric** parameters measured by CASIA 2, Pentacam AXL, and IOLMaster 700 in keratoconic patients*

N = 34		95% CL		Difference	95% LoA	
Parameters	ICC	Lower	Upper	Mean ± SD	Lower	Upper
TCP (D)						
CASIA 2	0.996	0.991	0.998	0.012 ± 0.330	-0.635	0.659
Pentcam AXL	0.997	0.995	0.999	-0.103 ± 0.274	-0.64	0.434
IOLMaster700	0.998	0.997	0.999	0.052 ± 0.298	-0.532	0.636
TCA (D)						
CASIA 2	0.98	0.959	0.99	0.068 ± 0.471	-0.855	0.991
Pentcam AXL	0.983	0.967	0.992	0.109 ± 0.523	-0.916	1.134
IOLMaster700	0.993	0.986	0.997	-0.037 ± 0.455	-0.929	0.855
J0						
CASIA 2	0.985	0.97	0.993	-0.008 ± 0.256	-0.51	0.494
Pentcam AXL	0.991	0.982	0.996	-0.074 ± 0.229	-0.523	0.375
IOLMaster700	0.997	0.994	0.998	0.033 ± 0.232	-0.422	0.488
J45						
CASIA 2	0.983	0.965	0.991	-0.012 ± 0.171	-0.347	0.323
Pentcam AXL	0.964	0.929	0.982	0.023 ± 0.281	-0.528	0.574
IOLMaster700	0.992	0.983	0.996	-0.001 ± 0.209	-0.411	0.409
Anterior K (D)						
CASIA 2	0.996	0.992	0.998	0.029 ± 0.334	-0.626	0.684
Pentcam AXL	0.998	0.996	0.999	-0.106 ± 0.251	-0.598	0.386
IOLMaster700	0.999	0.997	0.999	0.042 ± 0.284	-0.515	0.599
ACA (D)						
CASIA 2	0.981	0.962	0.99	0.071 ± 0.476	-0.862	1.004
Pentcam AXL	0.989	0.978	0.995	0.053 ± 0.463	-0.854	0.96
IOLMaster700	0.993	0.987	0.997	-0.006 ± 0.454	-0.896	0.884
J0						
CASIA 2	0.986	0.972	0.993	-0.010 ± 0.252	-0.504	0.484
Pentcam AXL	0.994	0.989	0.997	-0.035 ± 0.231	-0.488	0.418
IOLMaster700	0.997	0.994	0.998	0.022 ± 0.231	-0.431	0.475
J45						
CASIA 2	0.978	0.956	0.989	-0.010 ± 0.199	-0.4	0.38
Pentcam AXL	0.979	0.958	0.989	0.042 ± 0.255	-0.458	0.542
IOLMaster700	0.992	0.984	0.996	0.005 ± 0.207	-0.401	0.411
Post K (D)						

CASIA 2	0.998	0.995	0.999	0.003 ± 0.052	-0.099	0.105
Pentcam AXL	0.997	0.993	0.998	0.003 ± 0.080	-0.154	0.16
IOLMaster700	0.996	0.992	0.998	-0.001 ± 0.079	-0.156	0.154
PCA (D)						
CASIA 2	0.989	0.978	0.995	0.012 ± 0.059	-0.104	0.128
Pentcam AXL	0.974	0.949	0.987	-0.009 ± 0.142	-0.287	0.269
IOLMaster700	0.98	0.96	0.99	-0.006 ± 0.110	-0.222	0.21
J0						
CASIA 2	0.989	0.978	0.994	0.004 ± 0.033	-0.061	0.069
Pentcam AXL	0.977	0.953	0.988	0.011 ± 0.086	-0.158	0.18
IOLMaster700	0.991	0.983	0.996	-0.006 ± 0.051	-0.106	0.094
J45						
CASIA 2	0.98	0.959	0.99	0.002 ± 0.036	-0.069	0.073
Pentcam AXL	0.971	0.942	0.986	-0.018 ± 0.059	-0.134	0.098
IOLMaster700	0.979	0.959	0.99	-0.003 ± 0.055	-0.111	0.105
ACD (mm)						
CASIA 2	0.997	0.995	0.999	-0.001 ± 0.030	-0.06	0.058
Pentcam AXL	0.999	0.998	1	0.003 ± 0.018	-0.032	0.038
IOLMaster700	0.999	0.997	0.999	-0.006 ± 0.020	-0.045	0.033
WTW (mm)						
CASIA 2	0.886	0.772	0.943	0.048 ± 0.304	-0.548	0.644
Pentcam AXL	0.988	0.975	0.994	0.022 ± 0.083	-0.141	0.185
IOLMaster700	0.972	0.944	0.986	-0.015 ± 0.254	-0.513	0.483
CCT (µm)						
CASIA 2	0.999	0.998	0.999	0.382 ± 2.075	-3.685	4.449
Pentcam AXL	0.998	0.995	0.999	0.382 ± 3.025	-5.547	6.311
IOLMaster700	0.993	0.986	0.997	0.294 ± 5.535	-10.555	11.143
IOL power (D)						
SRK/T						
CASIA 2	0.997	0.993	0.998	0.015 ± 0.515	-0.994	1.024
Pentcam AXL	0.998	0.996	0.999	0.147 ± 0.469	-0.772	1.066
IOLMaster700	0.999	0.998	0.999	0 ± 0.477	-0.935	0.935
Barrette II						
CASIA 2	0.996	0.993	0.998	-0.029 ± 0.521	-1.05	0.992
Pentcam AXL	0.999	0.997	0.999	0.147 ± 0.359	-0.557	0.851
IOLMaster700	0.998	0.997	0.999	-0.015 ± 0.468	-0.932	0.902

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits

Agreement between the devices

The agreement of TCP among the three devices were excellent in both normal eyes (ICC = 0.996) and keratoconic eyes (ICC = 0.970). The confidence limits of the ICCs were narrow. The other biometric parameters and IOL powers, except J45 vector of PCA and WTW, showed good to excellent agreement. (Table 8)

The comparison between any two devices in normal eyes is shown Tables 9 and 10 and in keratoconic eyes is shown in Table 11 and 12 respectively.

The agreement of TCP between Pentacam AXL and the other devices were excellent (ICCs ranged from 0.931 to 0.966) and between CASIA 2 and IOLMaster 700 was good (ICCs ranged from 0.851 to 0.867) in both groups of participants. The mean differences of TCP between Pentacam AXL and the other devices in normal eyes and Pentacam AXL and CASIA 2 in keratoconic eyes were less than 1 diopter while the other comparisons were more than 1 diopter. The 95% LoAs between the TCP from any two devices were narrow in normal eyes but the 95% LoAs showed a much wider in keratoconic eyes. Bland-Altman plot of TCP showed proportional bias among keratoconic eyes which the mean differences between any two devices increased with the mean TCP. (Figure 4)

TCA power and J0 and J45 vector of TCA between devices demonstrated varied agreement from moderate to excellent agreement (ICCs ranged from 0.743 to 0.914, 0.851 to 0.953, and 0.639 to 0.855 respectively). Moreover, TCA power, and J0 and J45 vector of TCA demonstrated lower mean differences and narrower 95% LoA in normal eyes than in keratoconic eyes. (Figure 5 – 7)

For anterior K, the ICCs showed excellent agreement between any two devices in both groups of participants (ICCs ranged from 0.934 to 0.996). The ICCs of ACA power and J0 vector of ACA showed good to excellent agreement in both groups of participants. J45 vector of ACA also showed good agreement, except the measurement between CASIA 2 and IOLMaster 700 in normal eyes which showed moderate agreement. (ICC = 0.680) The mean differences of anterior K and ACA were lower and 95% LoA were narrower in normal eyes than in keratoconic eyes. Bland-Altman plot showed proportional bias among keratoconic eyes. (Figure 8 – 11)

The agreement of posterior K and PCA were varied. Most of the comparisons of posterior K, PCA power, and J0 and J45 vector of PCA showed good to excellent agreement in both groups of participants. (ICCs ranged from 0.777 to 0.950), except the measurements of posterior keratometry, PCA power, and J0 and J45 vector of PCA between IOLMaster 700 and the other two devices in normal eyes (ICCs ranged from 0.422 to 0.721). However, wider 95% LoA were observed in keratoconic eyes than in normal eye and Bland-Altman plot showed proportional bias among keratoconic eyes. (Figure 12 – 15)

There was excellent agreement of ACD (ICCs range from 0.968 to 0.997), low mean differences, and narrow 95% LoA of ACD between each device in both groups. (Figure 16)

Accordingly, the repeatability and the reproducibility of WTW by each device were considered moderate. The WTW showed poor to moderate agreement between any two devices (ICCs ranged from 0.338 to 0.713). The mean differences of WTW were low between CASIA 2 and Pentacam AXL. Conversely, higher mean differences of WTW and wider 95% LoA were observed between the measurements of IOLMaster 700 and the other devices. (Figure 17)

There was excellent agreement of CCT between any two devices in both groups (ICCs ranged from 0.956 to 0.988). Similar to other parameters, mean differences were lower and 95% LoA were narrower in normal eyes. (Figure 18)

The agreement of IOL powers calculated by SRK/T and Barrett universal II formulas were excellent (ICCs ranged from 0.955 to 0.999) except between CASIA 2 and IOLMaster 700 in eyes with keratoconus, which showed good agreement (ICC = 0.898). The mean differences of the IOL powers from any two devices were lower than 0.5 diopters in normal eyes and were higher than 0.5 diopters in keratoconic eyes. Furthermore, Barrette universal II formula showed less proportional bias in IOL calculation in patient with keratoconus. (Figure 19 – 20)

In summary, most comparisons demonstrated good to excellent agreement, except J45 vectors of TCA and ACA between CASIA 2 and IOLMaster 700, posterior K and PCA between IOLMaster 700 and the other two devices, and WTW between any two devices in normal eyes. In eyes with keratoconus, most comparisons also displayed good to the excellent agreement, except TCA between CASIA 2 and IOLMaster 700, and WTW between any two devices.

Table 8. Agreement among CASIA 2, Pentacam AXL, and IOLMaster 700 in normal, and keratoconic eyes by ICC

Parameters	Normal (n = 100)			Keratoconus (n = 34)		
	ICC	95% CL		ICC	95% CL	
		Lower	Upper		Lower	Upper
TCP (D)	0.996	0.994	0.997	0.970	0.948	0.984
TCA (D)						
Power (D)	0.893	0.850	0.925	0.901	0.825	0.947
J0	0.938	0.913	0.956	0.926	0.869	0.960
J45	0.812	0.738	0.868	0.884	0.795	0.938
Anterior K (D)	0.996	0.995	0.997	0.980	0.964	0.989
ACA						
Power (D)	0.878	0.830	0.914	0.934	0.883	0.965
J0	0.919	0.887	0.943	0.945	0.902	0.971
J45	0.830	0.763	0.881	0.922	0.863	0.959
Posterior K (D)	0.982	0.975	0.988	0.990	0.982	0.995
PCA						
Power (D)	0.882	0.835	0.917	0.915	0.851	0.955
J0	0.903	0.865	0.932	0.903	0.828	0.948
J45	0.452	0.236	0.615	0.600	0.294	0.787
ACD (mm)	0.999	0.999	1.000	0.997	0.995	0.999
WTW (mm)	0.547	0.368	0.682	0.670	0.418	0.824
CCT (μm)	0.995	0.993	0.997	0.993	0.987	0.996
IOL power (D)						
SRK/T	0.999	0.999	1.000	0.971	0.948	0.984
Barrette II	0.999	0.999	0.999	0.983	0.970	0.991

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits

Table 9. Agreement between CASIA 2 and Pentacam AXL, CASIA 2 and IOLMaster 700, and Pentacam AXL and IOLMaster 700 in normal eyes by ICC

Parameters	CASIA 2 and Pentacam			CASIA 2 and IOLMaster 700			Pentacam AXL and		
	ICC	95% CL		ICC	95% CL		ICC	95% CL	
		Lower	Upper		Lower	Upper		Lower	Upper
TCP (D)	0.966	0.180	0.991	0.867	-0.019	0.970	0.947	-0.038	0.988
TCA (D)									
Power (D)	0.852	0.779	0.901	0.867	0.802	0.910	0.819	0.731	0.878
J0	0.909	0.864	0.939	0.929	0.894	0.952	0.889	0.836	0.925
J45	0.793	0.692	0.860	0.639	0.462	0.757	0.788	0.685	0.857
Anterior K (D)	0.992	0.984	0.996	0.996	0.994	0.997	0.993	0.988	0.996
ACA									
Power (D)	0.834	0.754	0.889	0.866	0.801	0.910	0.790	0.688	0.859
J0	0.880	0.821	0.919	0.923	0.886	0.948	0.849	0.776	0.899
J45	0.820	0.732	0.878	0.680	0.525	0.785	0.791	0.690	0.860
Posterior K (D)	0.843	-0.141	0.956	0.638	-0.037	0.898	0.422	-0.039	0.784
PCA									
Power (D)	0.851	0.655	0.923	0.684	0.134	0.853	0.602	-0.195	0.840
J0	0.860	0.686	0.926	0.721	-0.024	0.89	0.630	-0.211	0.862
J45	0.823	0.737	0.881	0.707	0.565	0.803	0.689	0.537	0.791
ACD (mm)	0.992	0.318	0.998	0.982	0.055	0.996	0.997	0.907	0.999
WTW (mm)	0.525	0.263	0.695	0.338	-0.005	0.566	0.492	0.241	0.661
CCT (μm)	0.956	-0.020	0.990	0.986	0.633	0.996	0.980	0.894	0.992
IOL power (D)									
SRK/T	0.999	0.998	0.999	0.999	0.999	1.000	0.999	0.998	0.999
Barrette II	0.999	0.998	0.999	0.999	0.998	0.999	0.998	0.997	0.999

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits; LoA = limits of agreement

Table 10. Agreement between CASIA 2 and Pentacam AXL, CASIA 2 and IOLMaster 700, and Pentacam AXL and IOLMaster 700 in normal eyes

Parameters	CASIA 2 and Pentacam AXL			CASIA 2 and IOLMaster 700			Pentacam AXL and IOLMaster		
	Difference	95% LoA		Difference	95% LoA		Difference	95% LoA	
	(Mean ± SD)	Lower	Upper	(Mean ± SD)	Lower	Upper	(Mean ± SD)	Lower	Upper
TCP (D)	-0.432 ± 0.242	-0.906	0.042	-1.025 ± 0.177	-1.372	-0.679	-0.593 ± 0.224	-1.032	-0.155
TCA (D)									
Power (D)	0.096 ± 0.467	-0.818	1.011	0.065 ± 0.412	-0.743	0.873	-0.031 ± 0.505	-1.020	0.958
J0	-0.049 ± 0.224	-0.488	0.389	-0.023 ± 0.193	-0.401	0.355	0.026 ± 0.252	-0.467	0.520
J45	-0.018 ± 0.182	-0.374	0.338	-0.006 ± 0.226	-0.448	0.436	0.012 ± 0.181	-0.344	0.367
Anterior K (D)	0.102 ± 0.208	-0.306	0.510	0.028 ± 0.172	-0.309	0.364	-0.074 ± 0.213	-0.492	0.343
ACA									
Power (D)	0.011 ± 0.540	-1.048	1.069	-0.022 ± 0.429	-0.862	0.818	-0.033 ± 0.570	-1.149	1.084
J0	-0.013 ± 0.261	-0.524	0.499	0.027 ± 0.196	-0.358	0.411	0.039 ± 0.286	-0.522	0.600
J45	-0.017 ± 0.173	-0.355	0.322	-0.012 ± 0.218	-0.439	0.414	0.004 ± 0.178	-0.345	0.354
Posterior K (D)	0.141 ± 0.062	0.019	0.263	-0.287 ± 0.058	-0.401	-0.172	-0.428 ± 0.074	-0.573	-0.283
PCA									
Power (D)	0.049 ± 0.080	-0.107	0.205	-0.084 ± 0.095	-0.269	0.102	-0.133 ± 0.100	-0.328	0.063
J0	0.024 ± 0.040	-0.055	0.102	-0.047 ± 0.043	-0.131	0.037	-0.071 ± 0.049	-0.166	0.024
J45	0.007 ± 0.036	-0.064	0.077	0.009 ± 0.043	-0.074	0.093	0.003 ± 0.046	-0.088	0.094
ACD (mm)	0.064 ± 0.024	0.017	0.110	0.101 ± 0.025	0.053	0.149	0.037 ± 0.026	-0.014	0.088
WTW (mm)	0.062 ± 0.533	-0.984	1.107	-0.147 ± 0.707	-1.532	1.238	-0.204 ± 0.594	-1.369	0.961
CCT (μm)	-11.340 ±	-19.694	-2.986	-5.890 ± 3.923	-13.579	1.799	5.450 ± 6.315	-6.928	17.828
IOL power (D)									
SRK/T	-0.110 ± 0.345	-0.786	0.566	-0.015 ± 0.261	-0.526	0.496	0.095 ± 0.324	-0.539	0.729
Barrette II	-0.095 ± 0.374	-0.828	0.638	0.085 ± 0.326	-0.554	0.724	0.180 ± 0.373	-0.551	0.911

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits; LoA = limits of agreement

Table 11. Agreement between CASIA 2 and Pentacam AXL, CASIA 2 and IOLMaster 700, and Pentacam AXL and IOLMaster 700 in keratoconic eyes by ICC

Parameters	CASIA 2 and Pentacam			CASIA 2 and IOLMaster 700			Pentacam AXL and		
	ICC	95% CL		ICC	95% CL		ICC	95% CL	
		Lower	Upper		Lower	Upper		Lower	Upper
TCP (D)	0.966	0.864	0.987	0.851	0.107	0.953	0.931	0.486	0.979
TCA (D)									
Power (D)	0.914	0.786	0.961	0.743	0.240	0.894	0.813	0.585	0.911
J0	0.953	0.875	0.979	0.851	0.702	0.926	0.896	0.793	0.948
J45	0.855	0.629	0.935	0.855	0.712	0.927	0.787	0.575	0.893
Anterior K (D)	0.970	0.931	0.986	0.934	0.844	0.969	0.986	0.970	0.993
ACA									
Power (D)	0.928	0.830	0.967	0.767	0.372	0.899	0.919	0.755	0.966
J0	0.948	0.896	0.974	0.848	0.695	0.924	0.961	0.922	0.981
J45	0.863	0.639	0.940	0.850	0.699	0.925	0.908	0.816	0.954
Posterior K (D)	0.957	0.653	0.987	0.931	-0.025	0.984	0.883	-0.044	0.975
PCA									
Power (D)	0.828	0.658	0.913	0.846	0.691	0.923	0.927	0.845	0.964
J0	0.860	0.719	0.930	0.794	0.547	0.902	0.950	0.686	0.983
J45	0.781	0.553	0.892	0.777	0.508	0.894	0.942	0.885	0.971
ACD (mm)	0.986	0.729	0.996	0.968	0.006	0.994	0.991	0.846	0.998
WTW (mm)	0.713	0.407	0.861	0.512	0.035	0.756	0.559	0.135	0.779
CCT (μm)	0.983	0.942	0.993	0.987	0.948	0.995	0.988	0.976	0.994
IOL power (D)									
SRK/T	0.955	0.891	0.980	0.898	0.765	0.952	0.983	0.964	0.992
Barrette II	0.973	0.932	0.988	0.939	0.828	0.974	0.987	0.966	0.994

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits; LoA = limits of agreement

Table 12. Agreement between CASIA 2 and Pentacam AXL, CASIA 2 and IOLMaster 700, and Pentacam AXL and IOLMaster 700 in keratoconic eyes

Parameters	CASIA 2 and Pentacam AXL			CASIA 2 and IOLMaster 700			Pentacam AXL and IOLMaster		
	Difference	95% LoA		Difference	95% LoA		Difference	95% LoA	
	(Mean ± SD)	Lower	Upper	(Mean ± SD)	Lower	Upper	(Mean ± SD)	Lower	Upper
TCP (D)	-0.591 ± 0.806	-2.171	0.988	-1.881 ± 1.633	-5.082	1.321	-1.289 ± 1.218	-3.676	1.097
TCA (D)									
Power (D)	0.529 ± 0.998	-1.427	2.486	1.439 ± 1.809	-2.106	4.985	0.910 ± 1.841	-2.698	4.518
J0	-0.251 ± 0.457	-1.147	0.645	-0.099 ± 1.188	-2.426	2.229	0.152 ± 1.054	-1.915	2.218
J45	-0.272 ± 0.466	-1.185	0.640	-0.156 ± 0.669	-1.467	1.155	0.116 ± 0.836	-1.523	1.755
Anterior K (D)	-0.426 ± 0.953	-2.295	1.442	-0.734 ± 1.516	-3.705	2.237	-0.307 ± 0.791	-1.857	1.242
ACA									
Power (D)	0.479 ± 0.989	-1.458	2.417	1.263 ± 1.817	-2.299	4.824	0.783 ± 1.224	-1.616	3.183
J0	0.005 ± 0.599	-1.170	1.179	0.005 ± 1.209	-2.365	2.374	0 ± 0.714	-1.399	1.399
J45	-0.303 ± 0.504	-1.291	0.684	-0.213 ± 0.676	-1.537	1.112	0.091 ± 0.615	-1.114	1.295
Posterior K (D)	0.182 ± 0.177	-0.164	0.529	-0.276 ± 0.152	-0.573	0.021	-0.459 ± 0.115	-0.684	-0.234
PCA									
Power (D)	0.074 ± 0.296	-0.506	0.653	-0.008 ± 0.253	-0.504	0.488	-0.082 ± 0.215	-0.503	0.339
J0	-0.001 ± 0.159	-0.313	0.311	-0.086 ± 0.175	-0.429	0.256	-0.086 ± 0.091	-0.265	0.093
J45	0.052 ± 0.132	-0.207	0.310	0.065 ± 0.128	-0.186	0.316	0.013 ± 0.088	-0.159	0.185
ACD (mm)	0.054 ± 0.042	-0.027	0.136	0.096 ± 0.032	0.034	0.158	0.041 ± 0.033	-0.023	0.106
WTW (mm)	0.009 ± 0.415	-0.804	0.823	-0.175 ± 0.695	-1.537	1.188	-0.197 ± 0.625	-1.422	1.028
CCT (μm)	-4.529 ± 6.890	-18.033	8.974	-4.294 ± 5.865	-15.789	7.201	0.235 ± 7.237	-13.948	14.419
IOL power (D)									
SRK/T	0.956 ± 1.904	-2.777	4.688	1.529 ± 3.169	-4.682	7.741	0.574 ± 1.523	-2.412	3.559
Barrette II	0.721 ± 1.394	-2.011	3.452	1.309 ± 2.202	-3.007	5.625	0.588 ± 1.171	-1.706	2.883

TCP = total corneal power; TCA = total corneal astigmatism; Anterior K = anterior keratometry; ACA = anterior corneal astigmatism; Posterior K = posterior keratometry; PCA = posterior corneal astigmatism; ACD = anterior chamber depth; WTW = white-to-white; CCT = central corneal thickness; IOL = intraocular lens; J0 = Jackson cross-cylinder, axes at 0 degrees and 90 degrees; J45 = Jackson cross-cylinder, axes at 45 degrees and 135 degrees; D = diopters; ICC = intraclass correlation coefficient; CL = confidence limits; LoA = limits of agreement

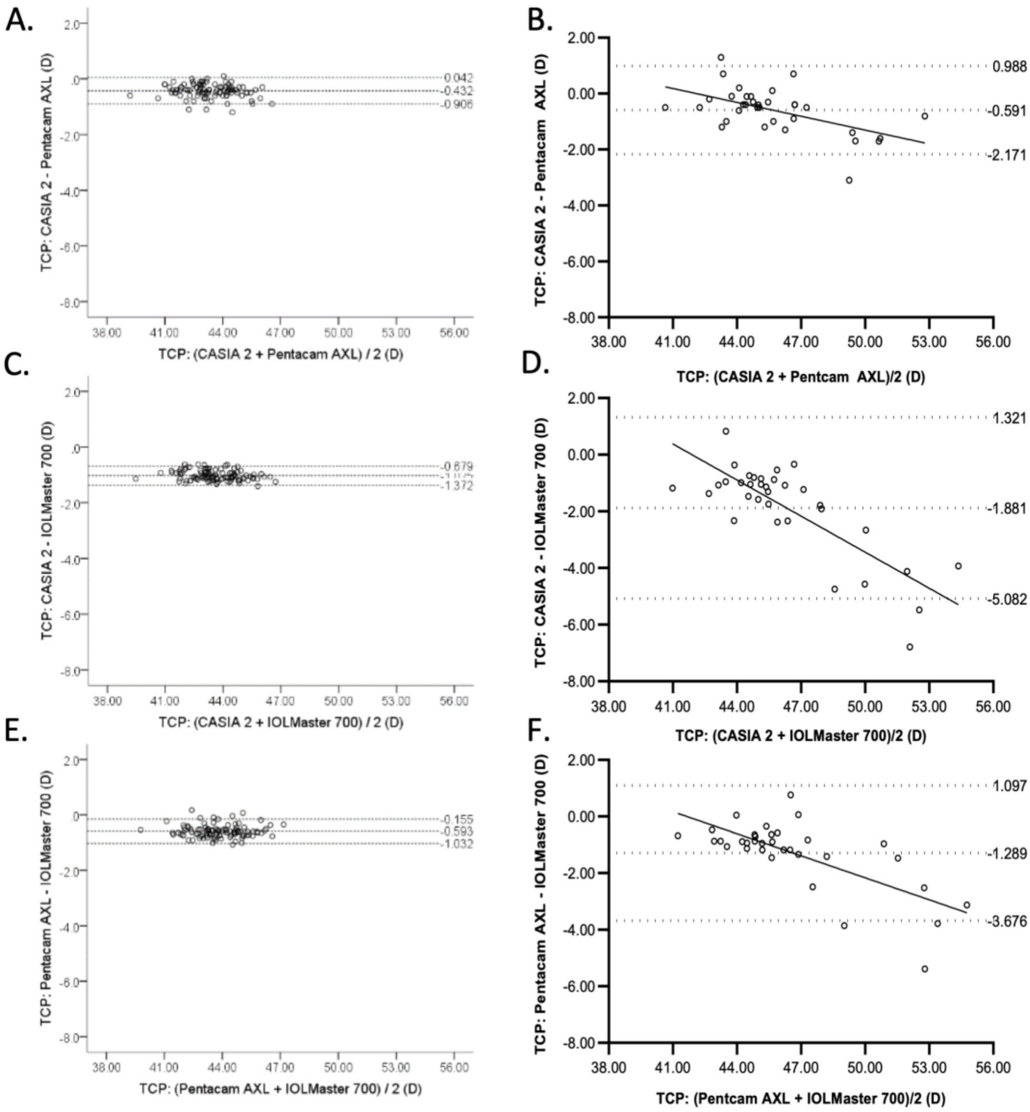

Figure 4. Bland-Altman plot of TCP

showing the agreement of TCP between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

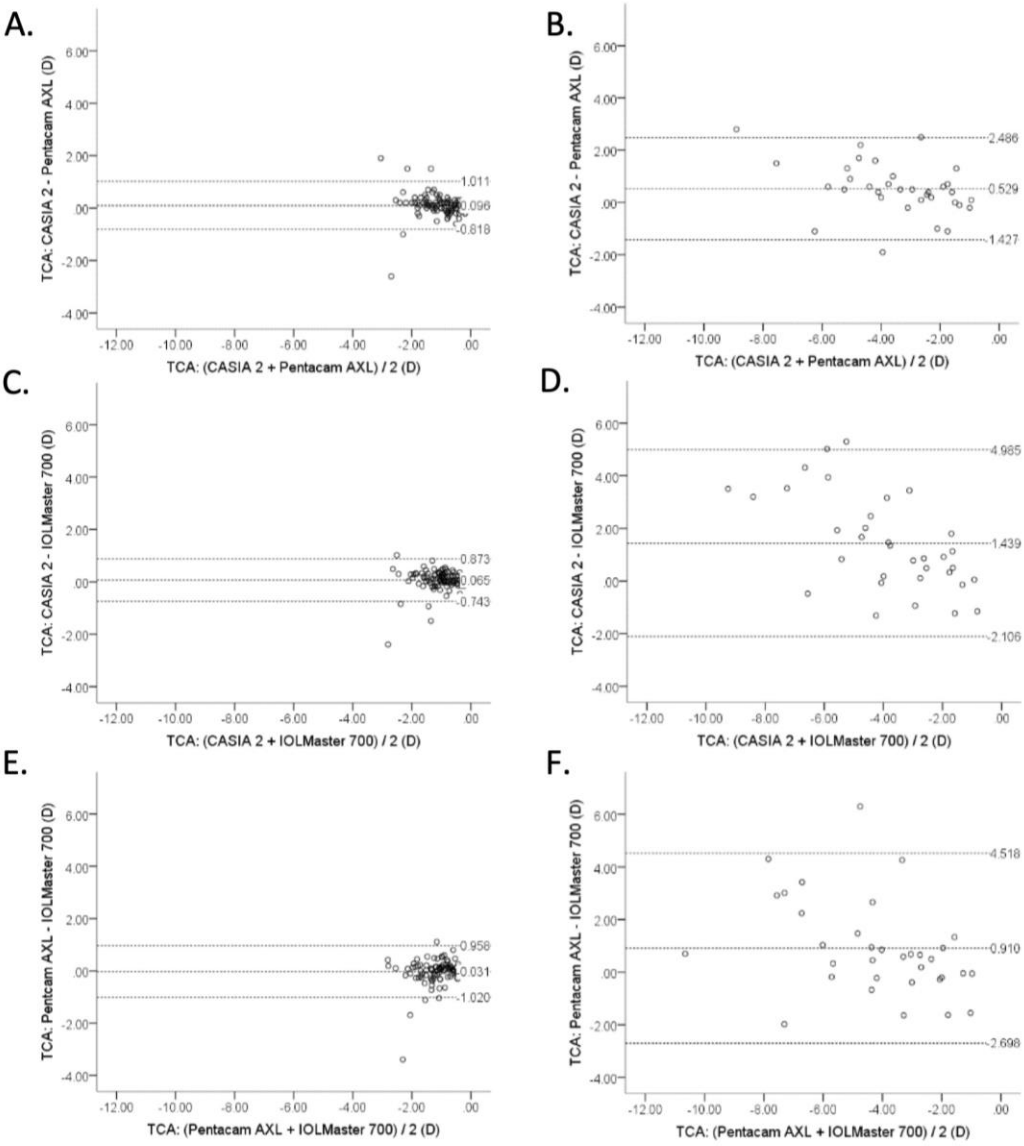

Figure 5. Bland-Altman plot of TCA

showing the agreement of TCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

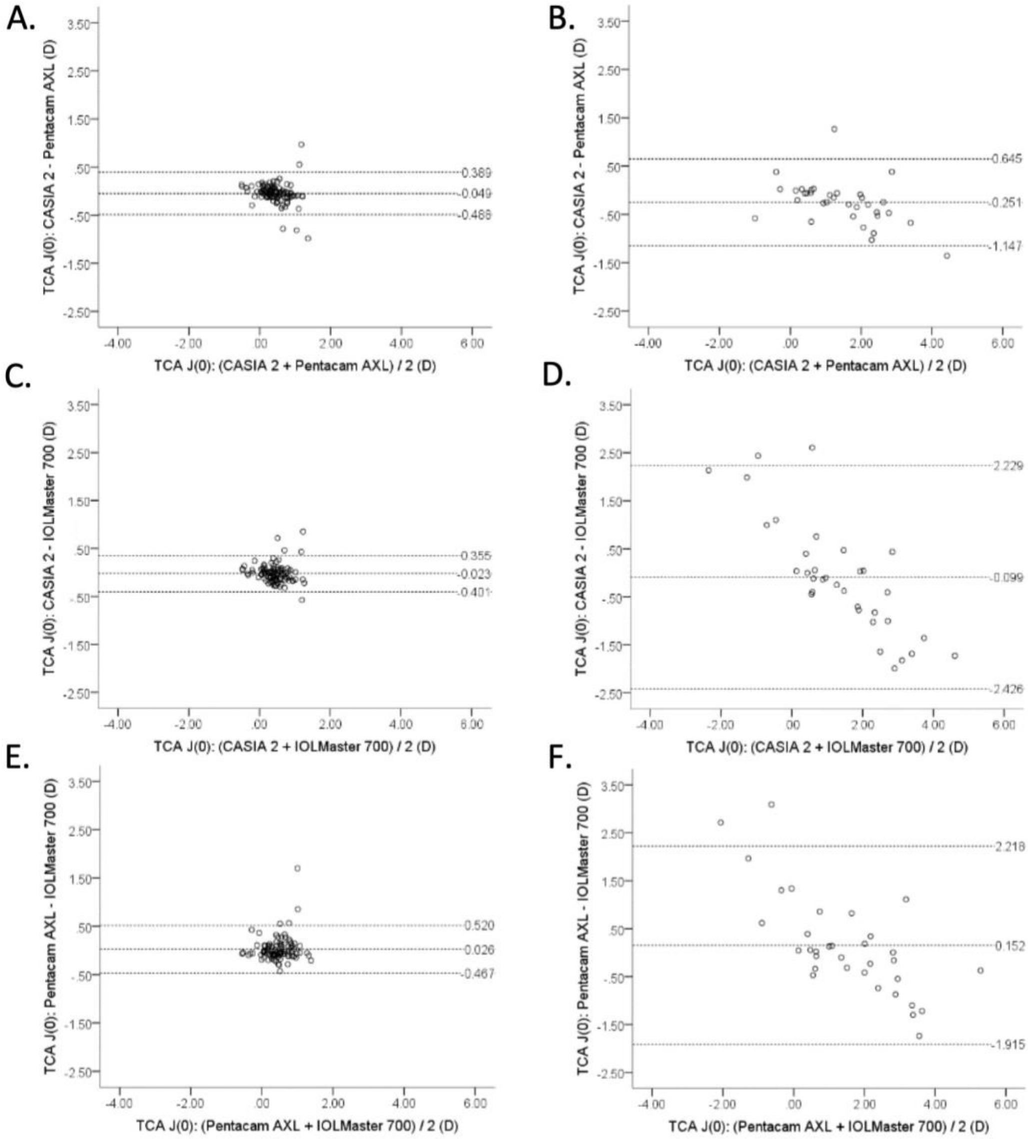

Figure 6. Bland-Altman plot of J0 vector of TCA

showing the agreement of J0 vector of TCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

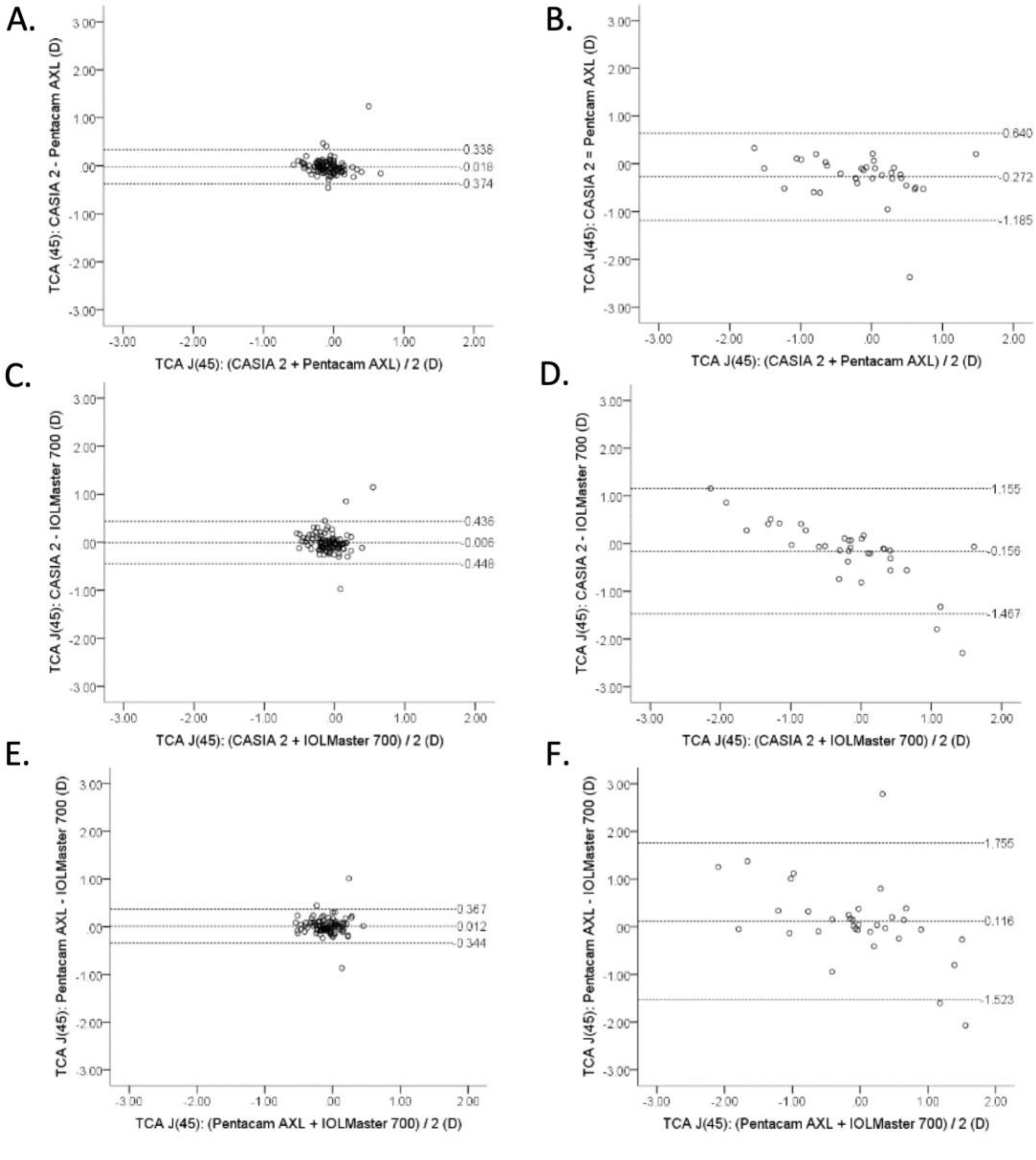

Figure 7. Bland-Altman plot of J45 vector of TCA

showing the agreement of J45 vector of TCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

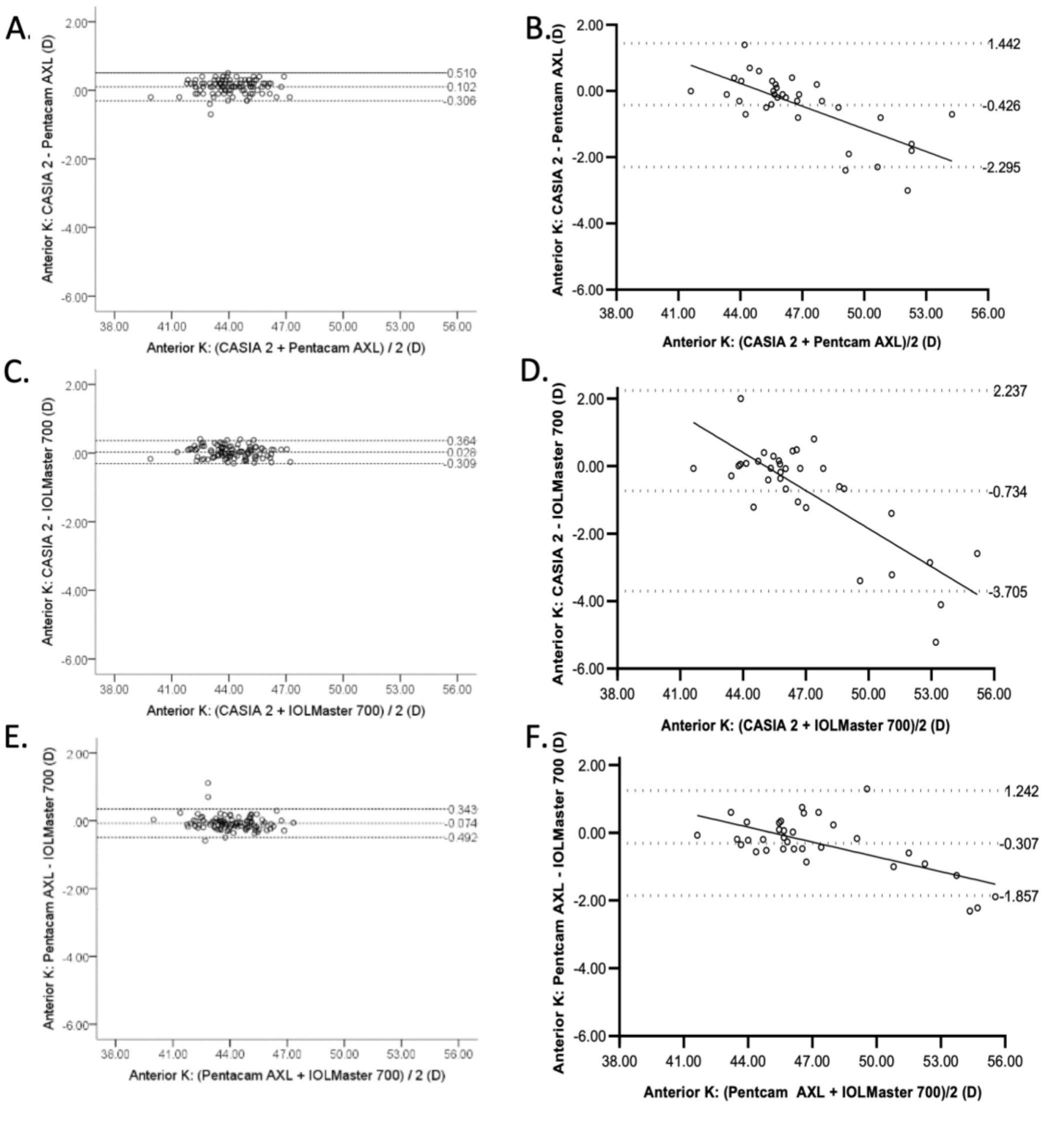

Figure 8. Bland-Altman plot of anterior K

showing the agreement of anterior K between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

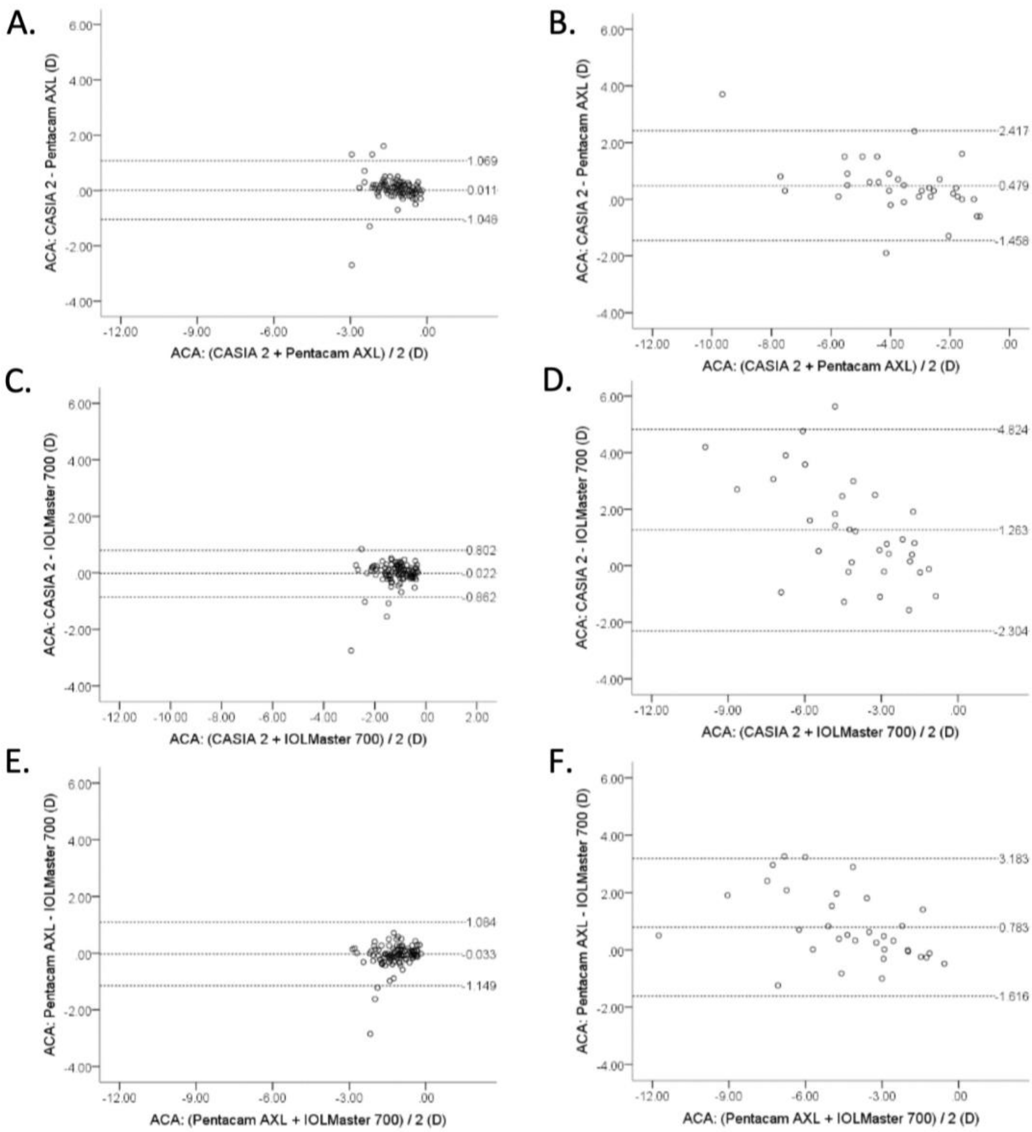

Figure 9. Bland-Altman plot of ACA

showing the agreement of ACA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

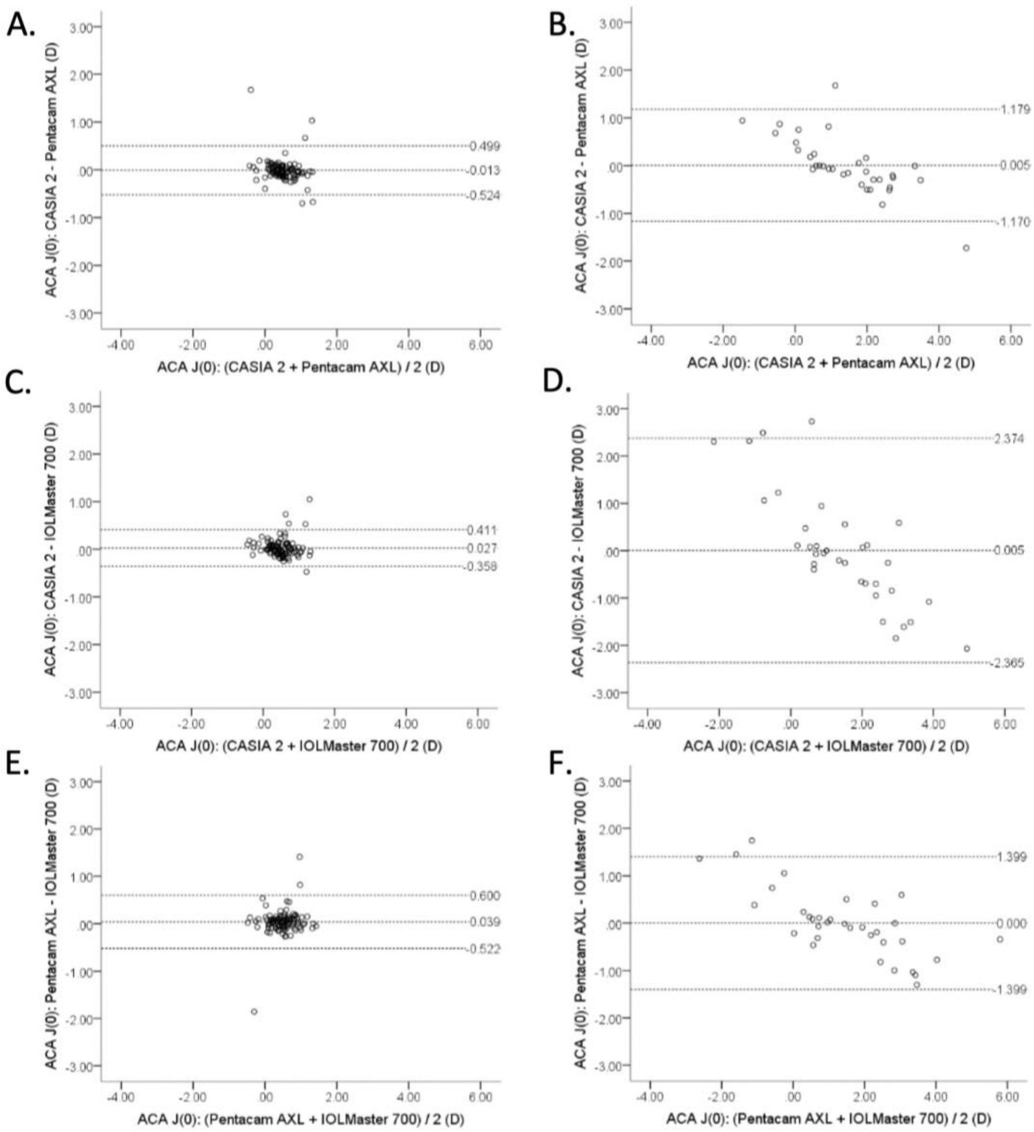

Figure 10. Bland-Altman plot of J0 vector of ACA

showing the agreement of J0 vector of ACA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively

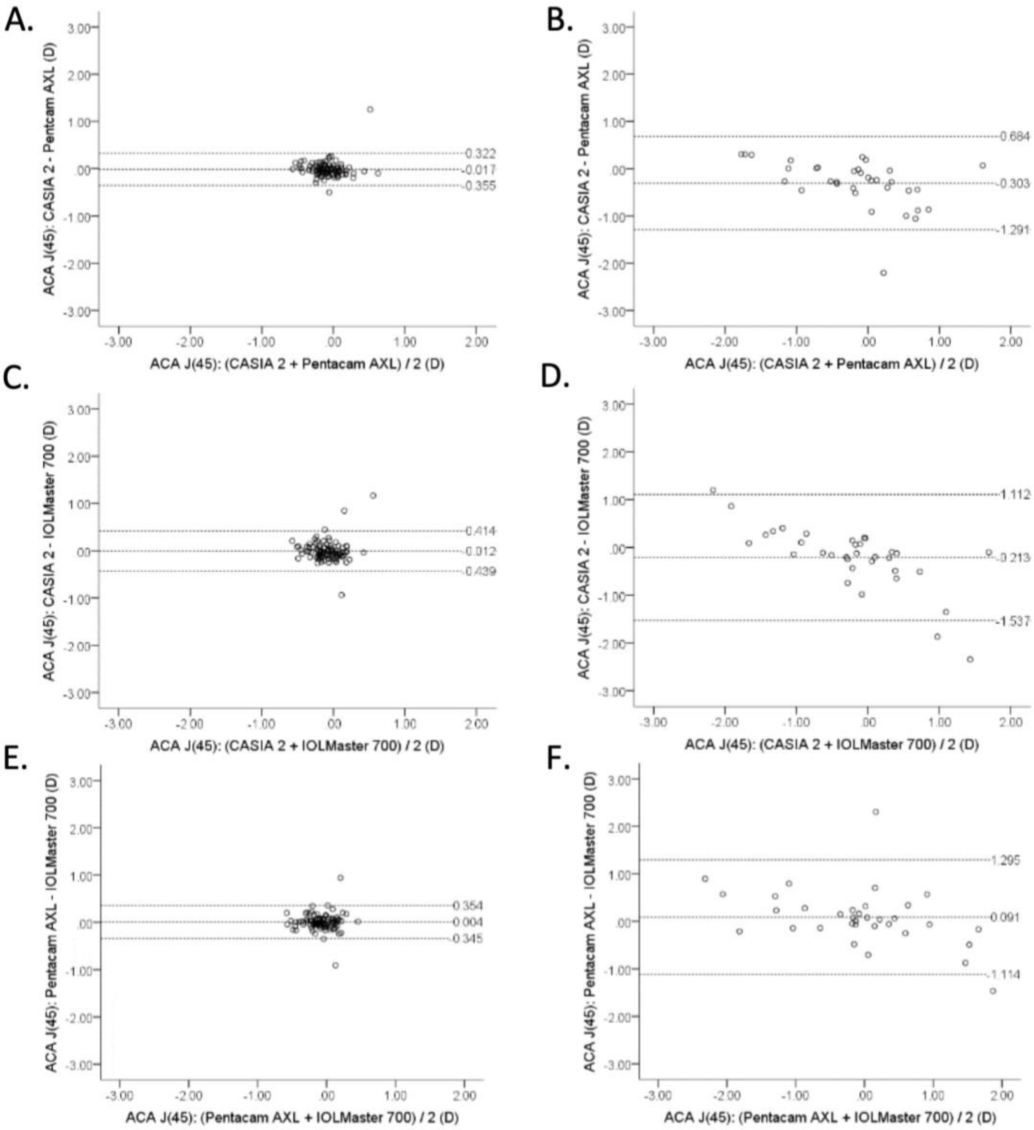

Figure 11. Bland-Altman plot of J45 vector of ACA

showing the agreement of J45 vector of ACA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

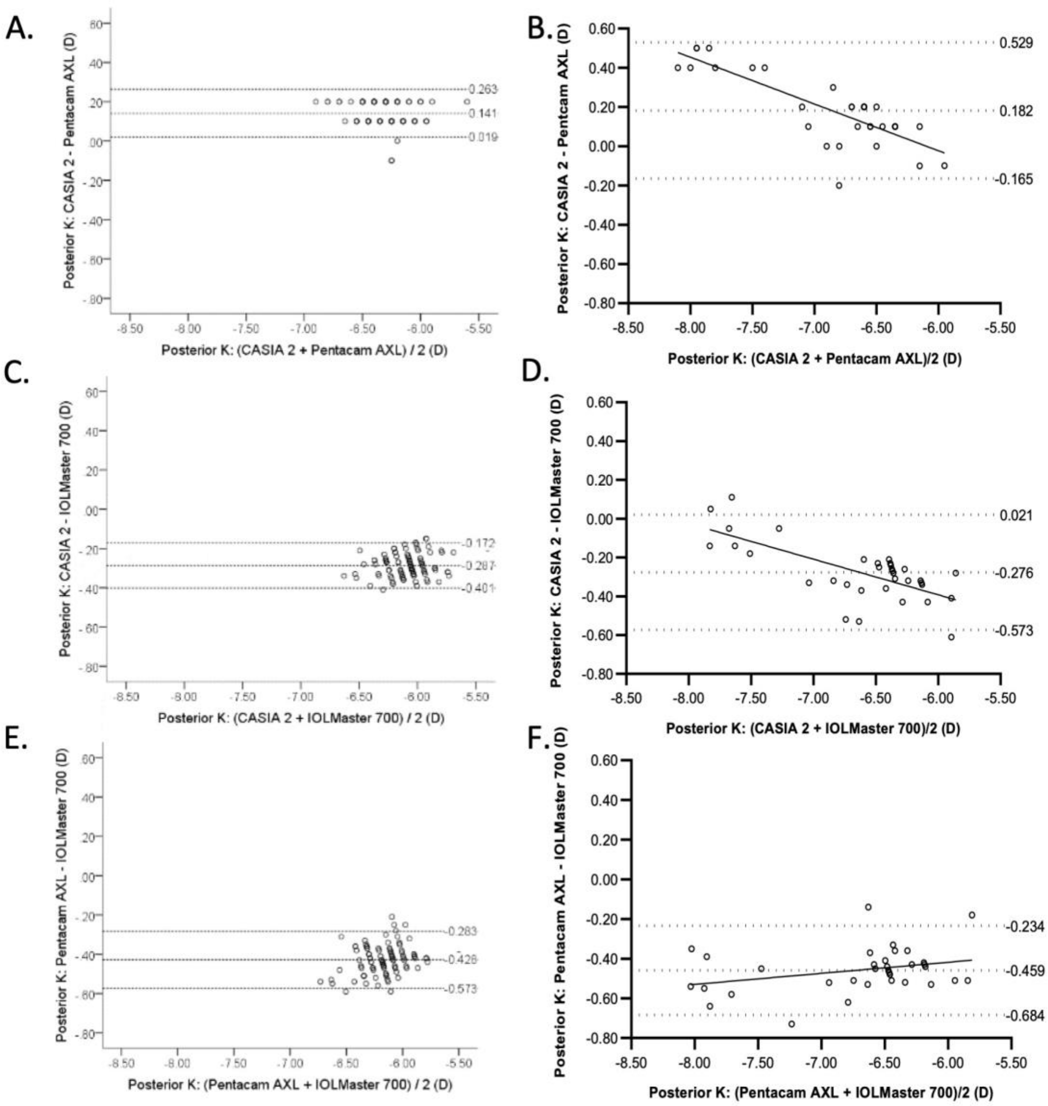

Figure 12. Bland-Altman plot of posterior K

showing the agreement of posterior K between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

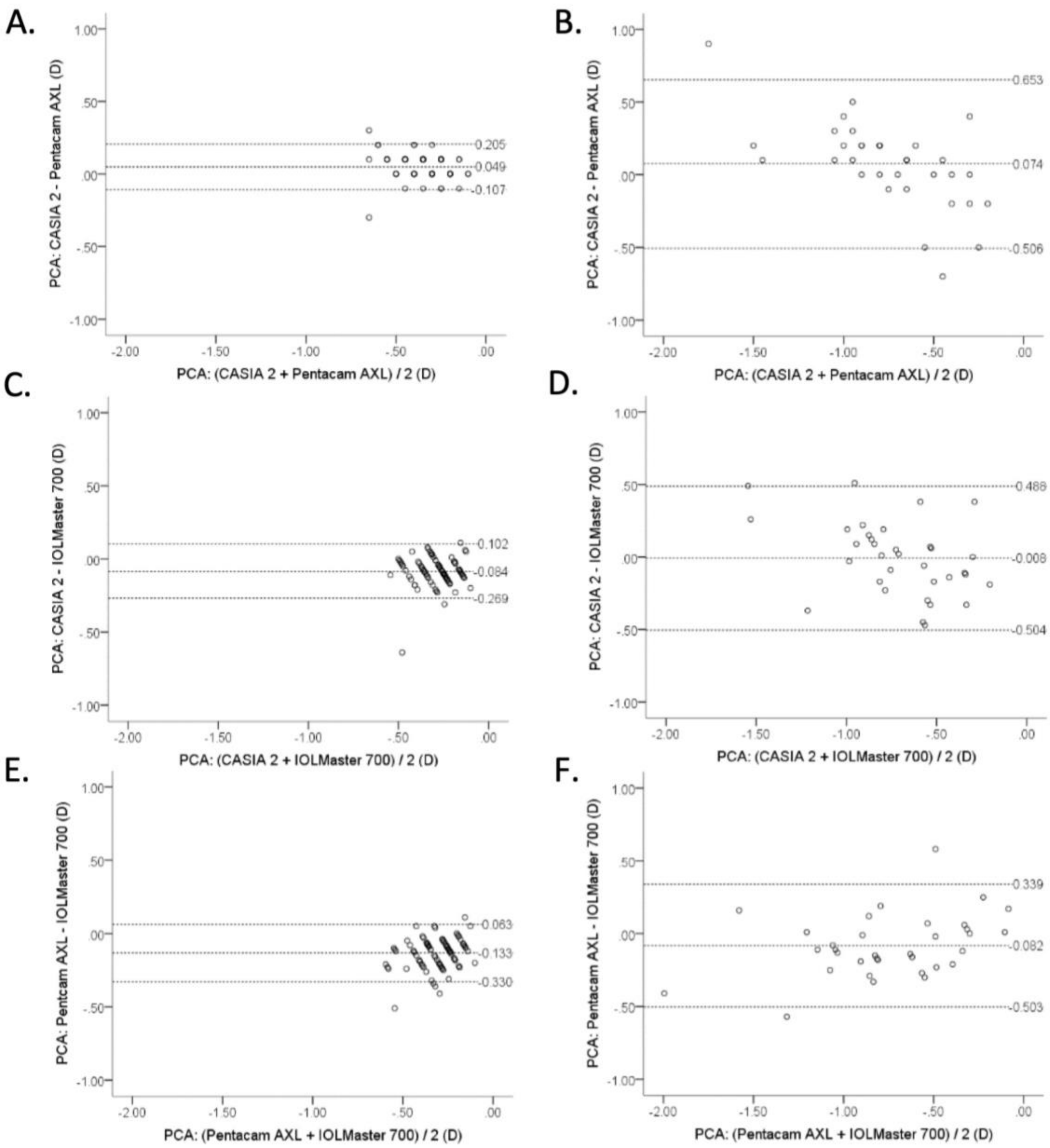

Figure 13. Bland-Altman plot of PCA

showing the agreement of PCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

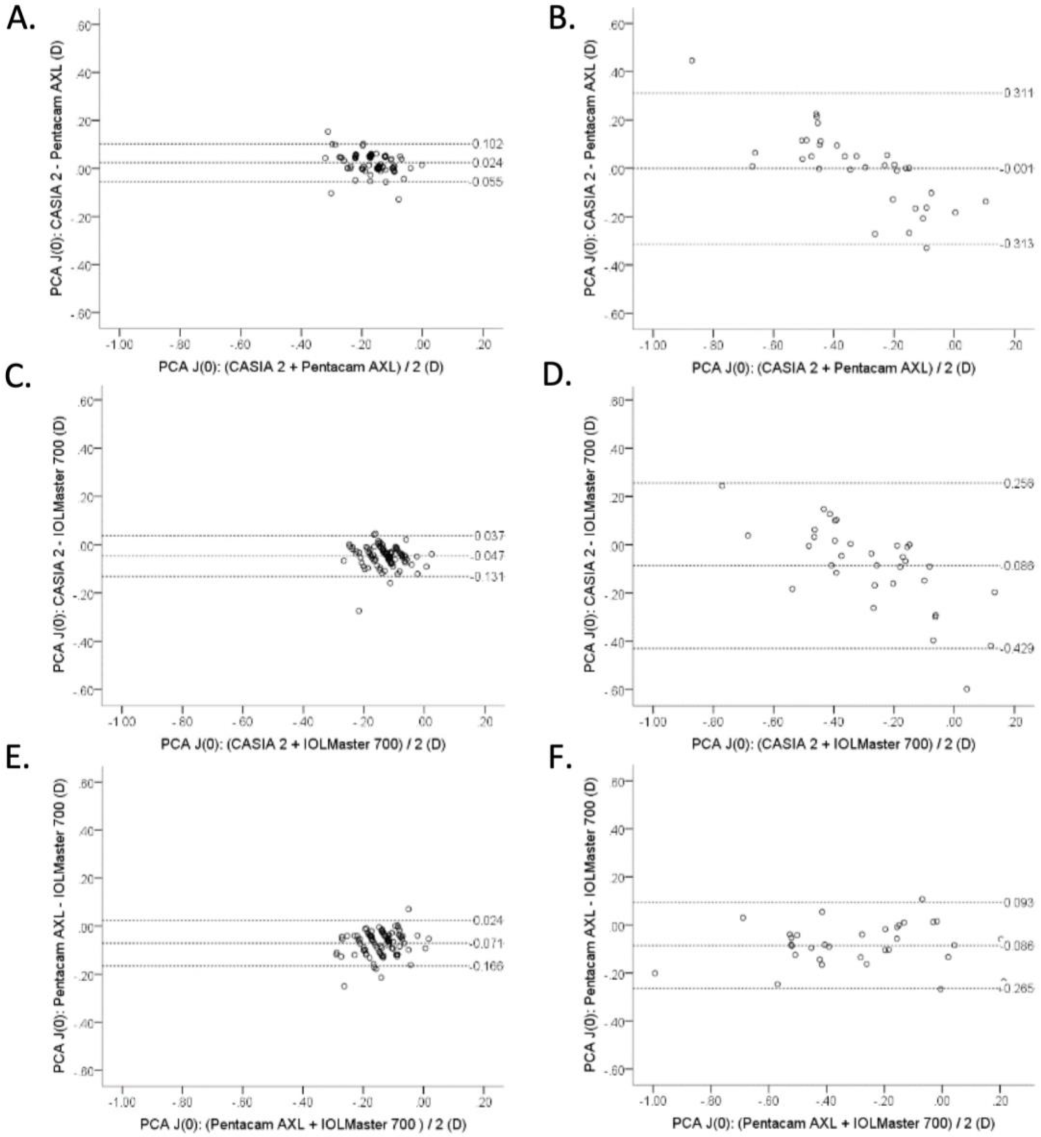

Figure 14. Bland-Altman plot of J0 vector of PCA

showing the agreement of J0 vector of PCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

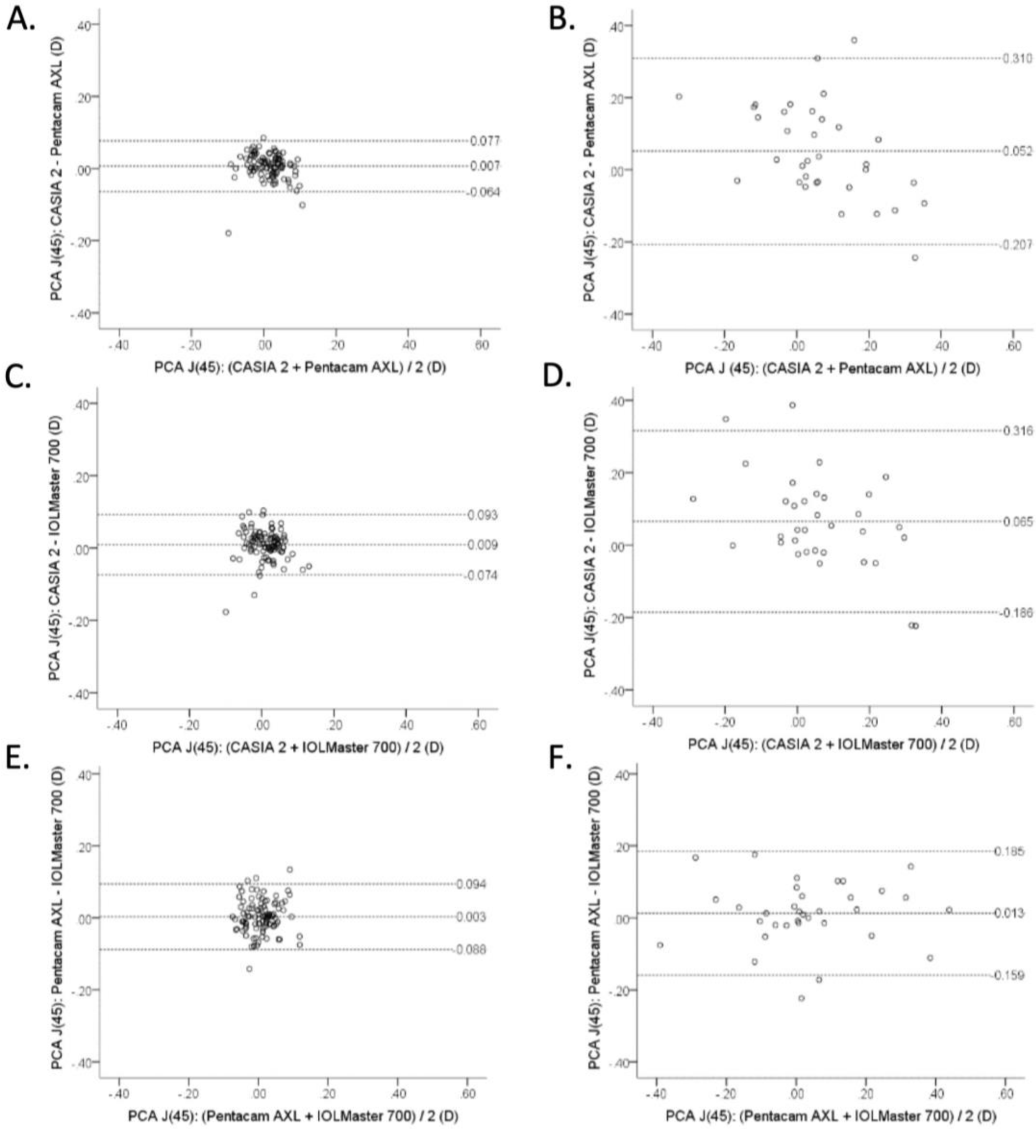

Figure 15. Bland-Altman plot of J45 vector of PCA

showing the agreement of J45 vector of PCA between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

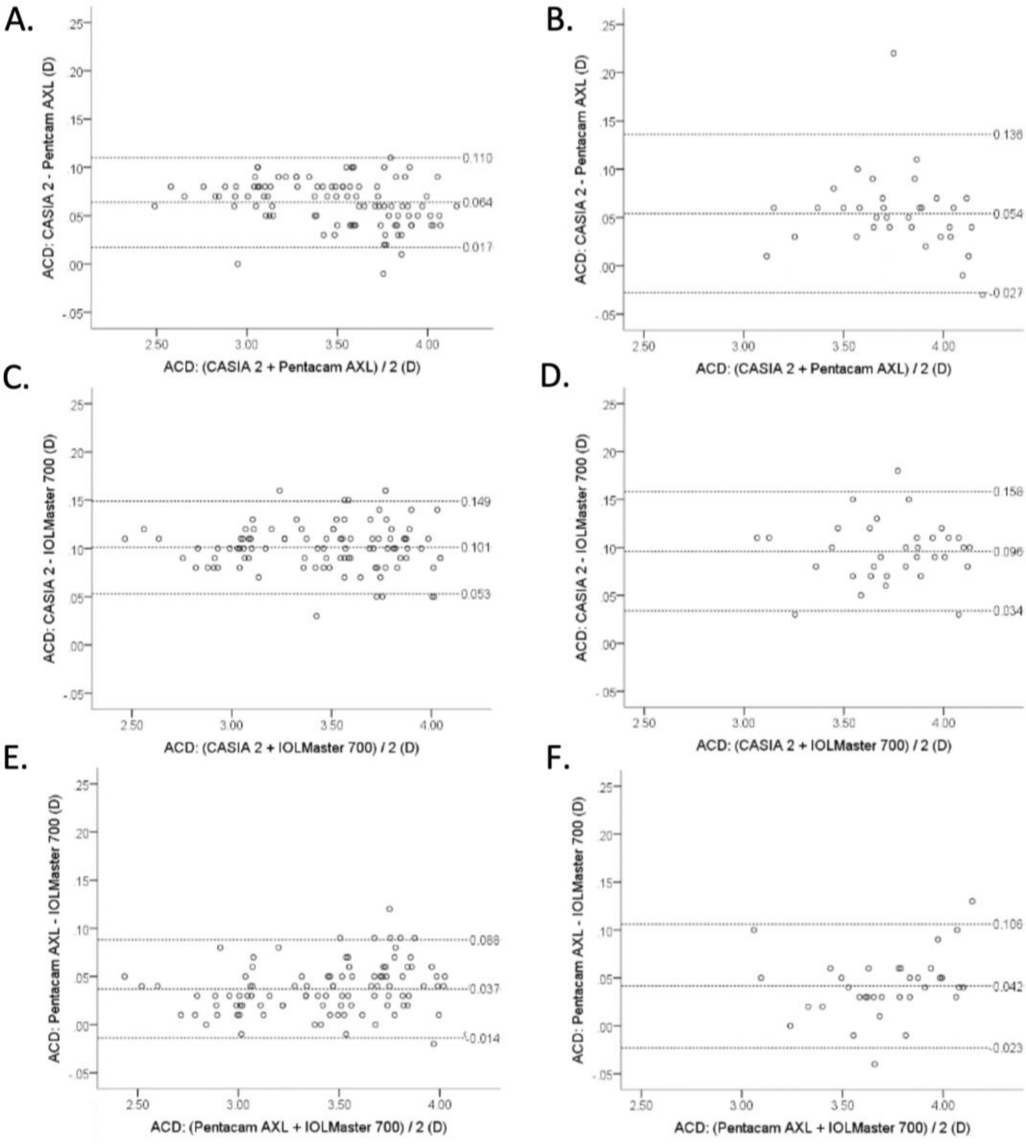

Figure 16. Bland-Altman plot of ACD

showing the agreement of ACD between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively

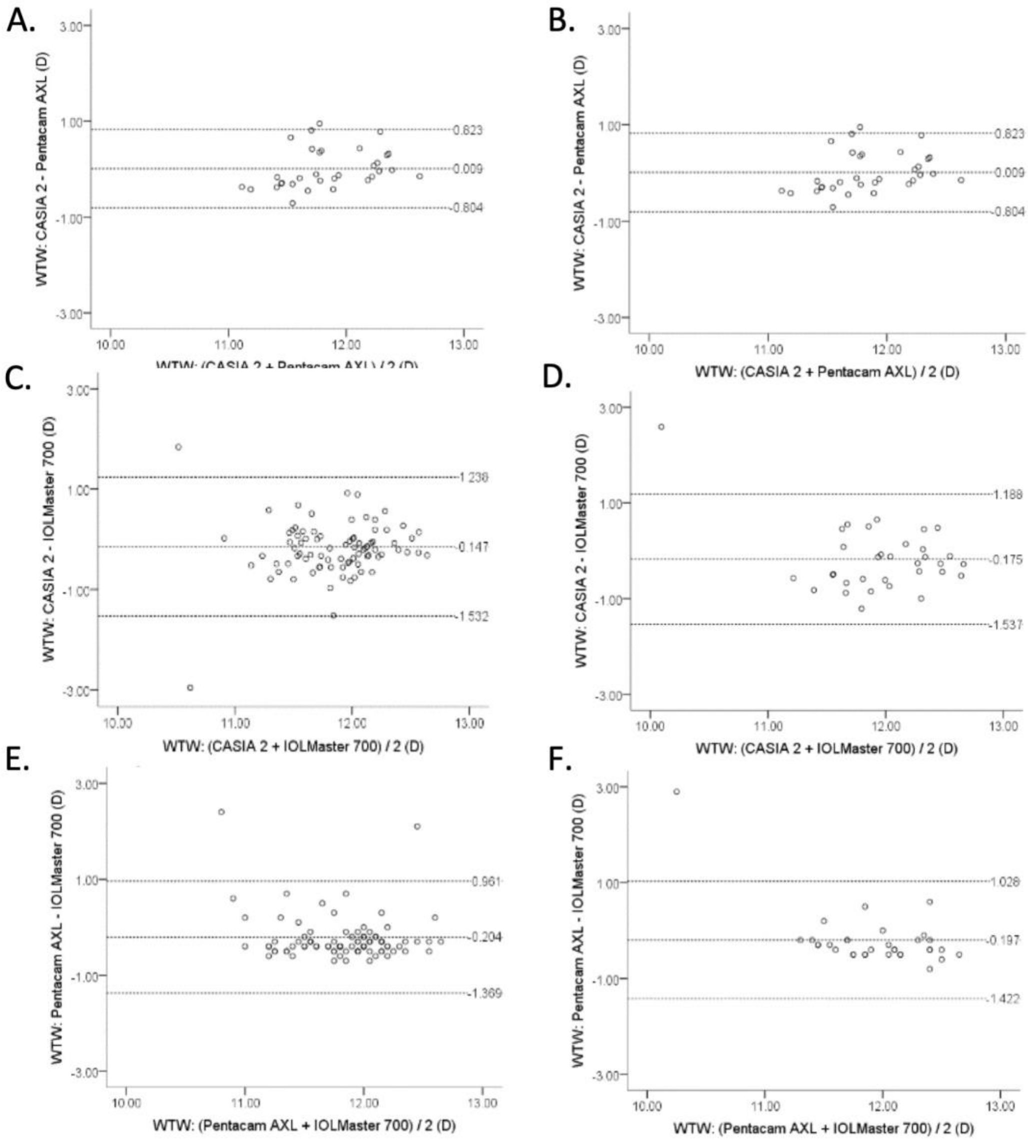

Figure 17. Bland-Altman plot of WTW

showing the agreement of WTW between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

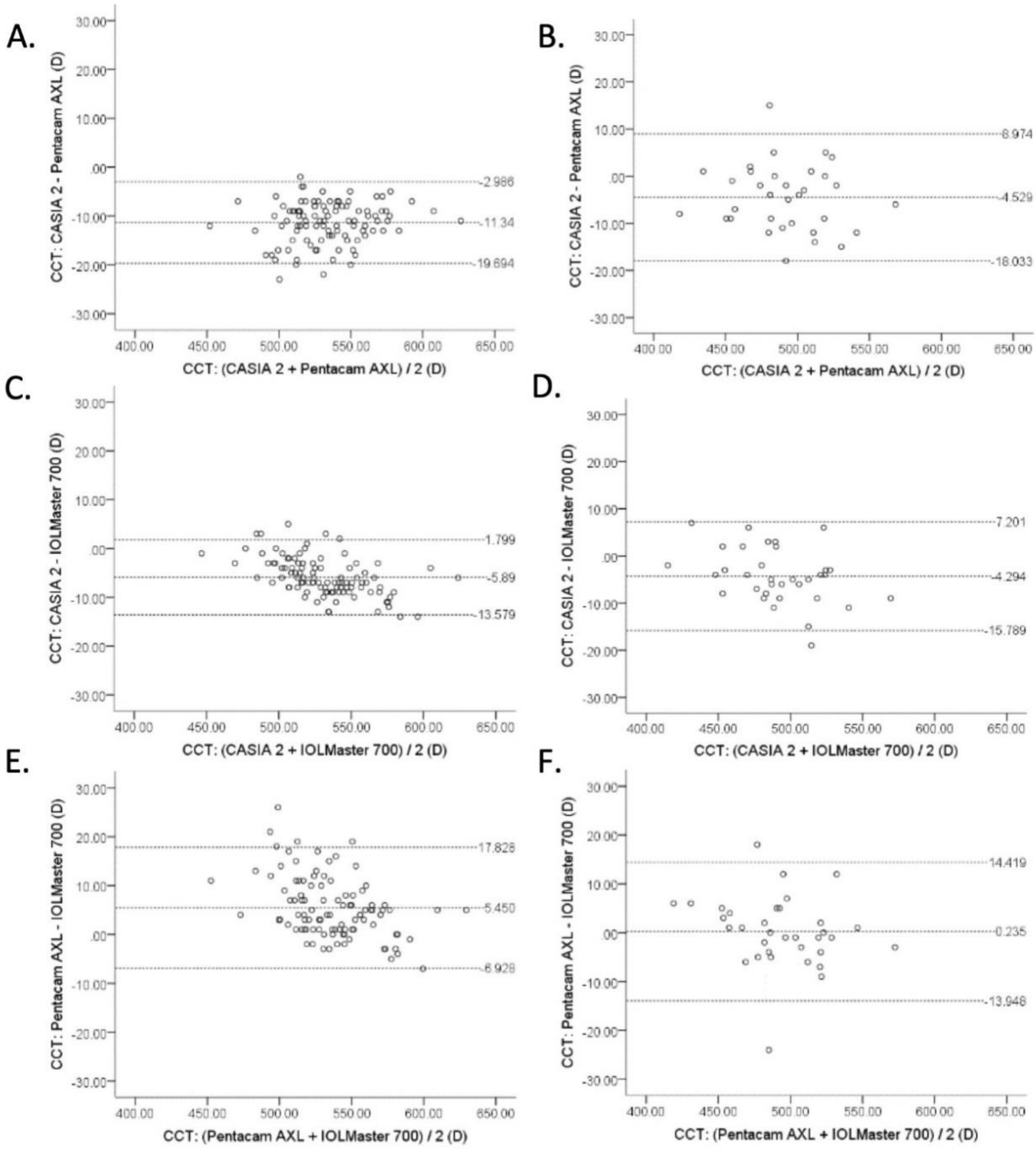

Figure 18. Bland-Altman plot of CCT

showing the agreement of CCT between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

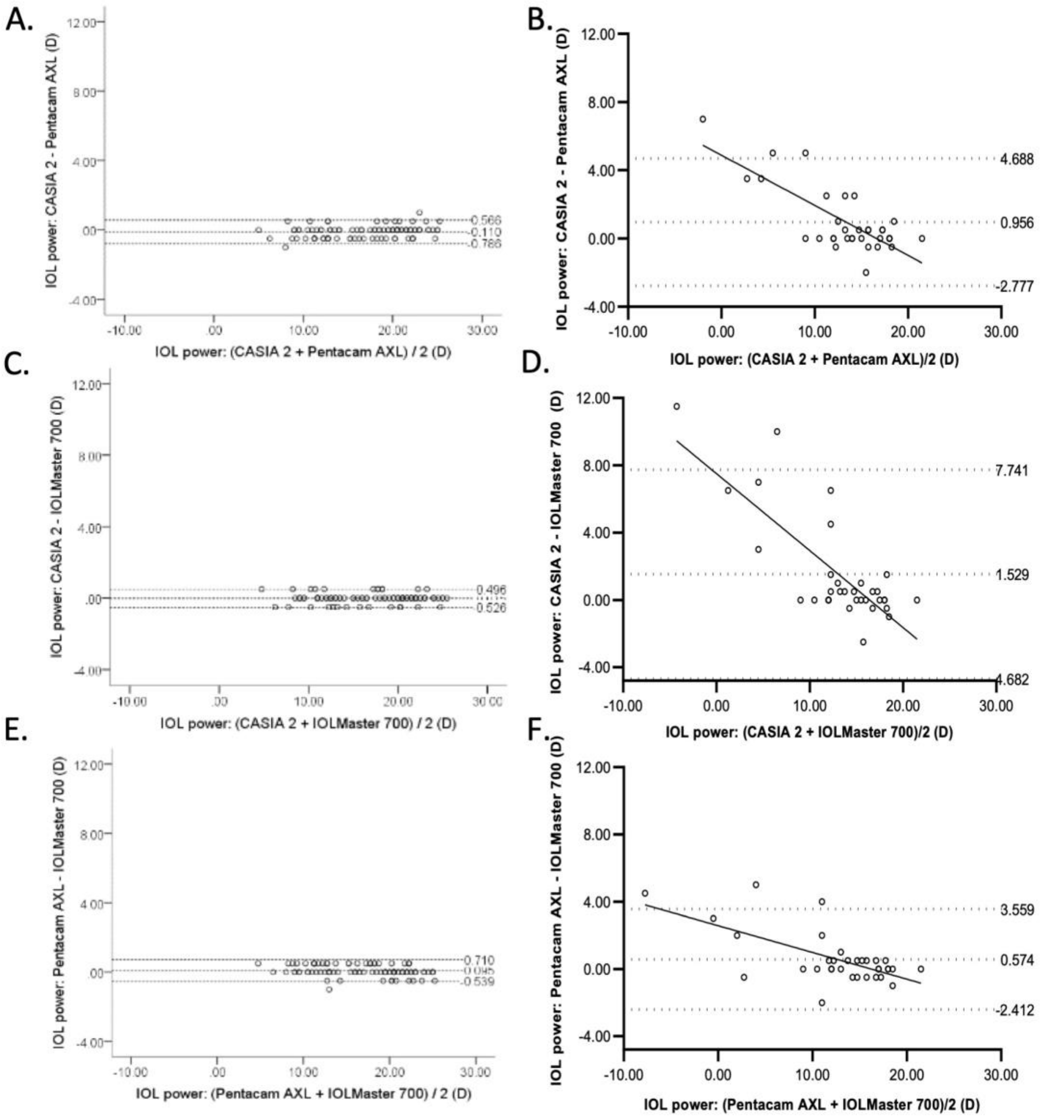

Figure 19. Bland-Altman plot of IOL power by SRK/T

showing the agreement of IOL power by SRK/T between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

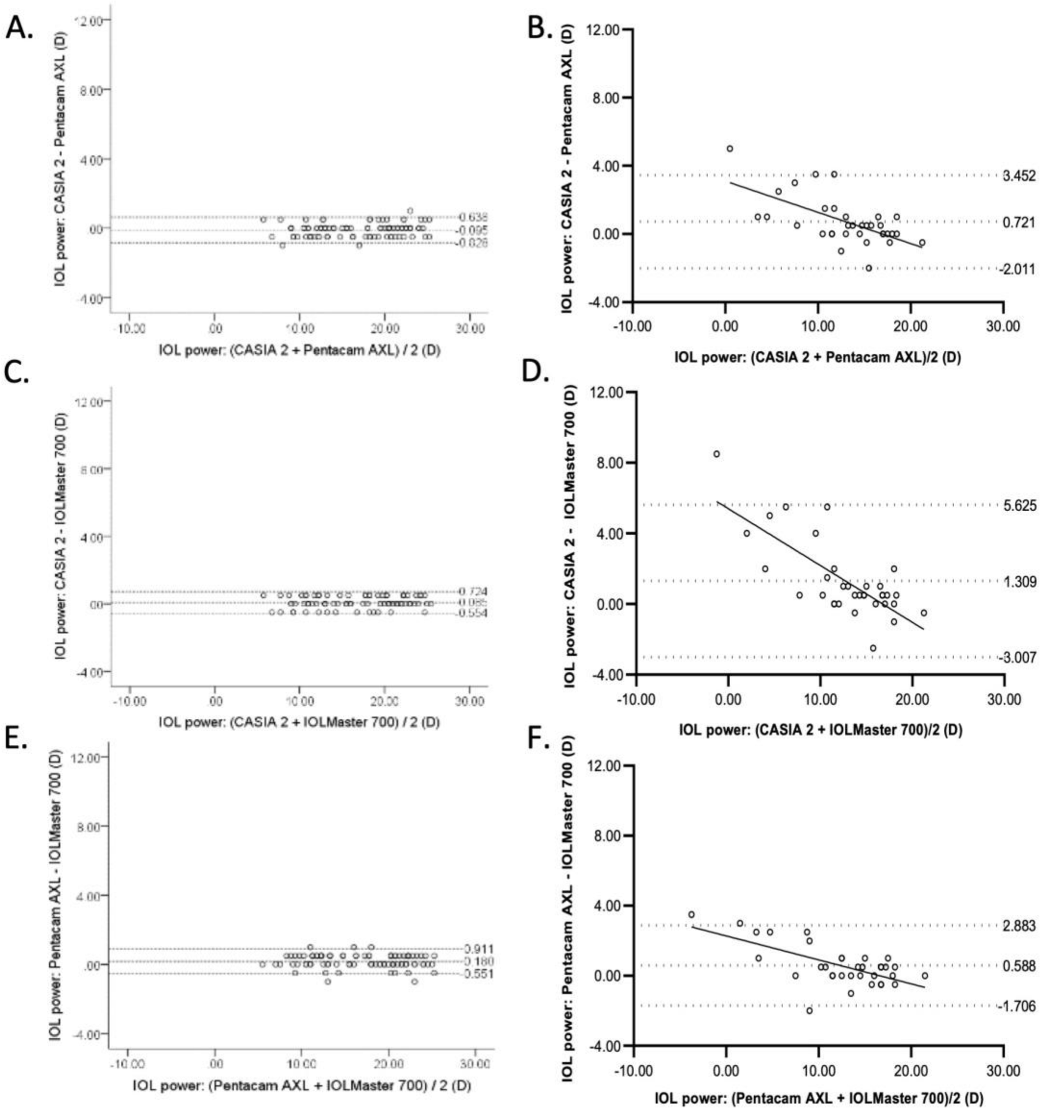

Figure 20. Bland-Altman plot of IOL power by Barrette Universal II

showing the agreement of IOL power by Barrette Universal II between CASIA 2 and Pentacam AXL (A, B), CASIA 2 and IOLMaster 700 (C, D) and Pentacam AXL and IOLMaster 700 (E, F) in normal (A, C, E), and keratoconic (B, D, F) participants. The middle-dashed line shows the mean difference, and the top and bottom dashed lines show the upper and lower 95% limits of agreement, respectively.

Chapter 5: Discussion

This study showed that the repeatability and the reproducibility of TCP measured by CASIA 2, Pentacam AXL, and IOLMaster 700 were high. Among the three devices, CASIA 2 showed the lowest mean differences in both repeatability and reproducibility analyses. The agreement of TCP among the three devices was excellent in both normal and keratoconic eyes. However, the mean differences and 95% LoAs between any two devices were respectively higher and wider in keratoconic eyes compared with normal. Bland-Altman plot in keratoconic eye demonstrated that increase in TCP tended to show higher mean differences in the TCP among the devices.

CASIA 2, Pentacam AXL, and IOLMaster 700 use different technologies to measure TCP and the other ocular biometers. CASIA 2 is an SS-OCT-based device with a wavelength of 1310 nm. CASIA 2 determines TCP which is called real keratometry derived from measuring anterior corneal surface, posterior corneal surface, and pachymetry by using 16 radial B-scans centered on corneal vertex at 2.5 mm and 3.0 mm zones.[46] Pentacam AXL uses a rotating Scheimpflug camera for keratometry, CCT, and ACD measurements. The TCP measured from Pentacam AXL includes total corneal refractive power and true net power. Total corneal refractive power (TCRP) uses a ray-tracing method with snell's law to calculate refractive power at any point of the cornea which is stated by the manufacturer that may represent actual refractive power.[47] Total corneal refractive power (TCRP) at 3 mm zone was used as TCP in this study. IOLMaster 700 is an SS-OCT base device with a wavelength of 1055 nm. Eighteen points of telecentric keratometry in 3 zones (1.5, 2.5, 3.5 mm) are used in anterior corneal surface measurement, while the SS-OCT system is implemented in the posterior corneal surface, CCT, ACD, and axial length measurements. Total keratometry (TK) from IOLMaster 700 determined by calculated anterior corneal surface, posterior corneal surface, pachymetry combined with thick lens formula,[48] was used as TCP in this study.

TCP measured by the three devices had excellent repeatability, reproducibility, and agreement. Our results were similar to previous reports that showed high repeatability of TCP measured by Pentacam AXL[29, 31] and IOLMaster 700.[29, 30] However, the repeatability and reproducibility of TCP measured by CASIA2 have not been mentioned before. Among the three devices, CASIA 2 showed the best repeatability and reproducibility in terms of mean differences in both normal and keratoconic eyes. This might be associated with the different principles of ocular biometric measurements and calculations between the devices. Moreover, CASIA 2 required a shorter time to scan an eye when compared with the other devices. The measurement speed of CASIA 2 is 50,000 A-scan per second requiring 0.34 seconds for each measurement while the scan speed of IOLMaster 700 is 2,000 A-scan per second and the time requiring for each measurement of Pentacam AXL is 1 second.[54] The shorter time required for measurement would contribute to fewer motion artifacts associated with eye movement and patient fatigue.

In this study, we found that TCP obtained from IOLMaster 700 had the highest value, followed by Pentcam AXL and CASIA 2 respectively. When analyzing the agreement of TCP between devices in pair, CASIA 2 and IOLMaster 700 seemed to provide slightly less agreement (ICC = 0.876) with the mean difference of more than 1.0 diopter which may consider clinically significant. Thus, TCP obtained from the different devices should not be used interchangeably. There was proportional bias in keratoconic eyes which increase in TCP tended to show higher discrepancy of TCP among three devices.

Previous reports have been mentioned less repeatability, reproducibility, and errors in keratometric measurements of keratoconic eyes especially in the advanced stage of the disease. The less repeatability, reproducibility, and inaccurate keratometry were considered to be due to the irregularity of corneal curvature and tear film, as well as due to the stromal scars beneath breaks in the Bowman layer.[32, 33, 39, 54] Although, the participants with keratoconus in our study were mainly in the early stage of disease, the mean differences in the TCP and 95% LoA of the repeatability, the reproducibility, and the agreement were respectively higher and wider in keratoconic eyes compared with healthy eyes. Of the three devices, the mean differences in TCP of the repeatability, the reproducibility, and the agreement in keratoconic eyes ranged from 0.038 to 0.059, 0.012 to 0.103, and 0.591 to 1.881 diopters, respectively. Considering the increase in corneal power of more than 1 diopter as a criterion for keratoconus progression[55], the repeatability and the reproducibility of all devices are acceptable, however, the same device should be used for following the progression since the early stage of keratoconus.

This study found that most of the other biometric parameters including TCA, anterior K, ACA, posterior K, PCA, ACD, CCT, and IOL power calculated by SRK/T and Barrette Universal II formula showed good to excellent repeatability and reproducibility in normal eyes and in keratoconic eyes. The astigmatism values with vector analysis including TCA, ACA, and PCA showed good repeatability and reproducibility in healthy participants. Some previous reports that showed slightly less repeatability of TCA and PCA measured by different devices.[27, 31] Furthermore, this study found that most of the other biometric parameters including TCA, anterior K, ACA power, posterior K, ACD, CCT, and IOL power calculated by SRK/T and Barrette Universal II formula showed good to an excellent agreement among the three devices. In contrast, posterior K and both power and meridian of PCA obtained from IOLMaster 700 demonstrated poor to a moderate agreement with the other two devices. According to previous reports, the amount of PCA power in the normal population was -0.26 to -0.76 diopters.[56] Thus, the mean differences in PCA power ranging from 0.049 to 0.133 diopters in this study seem to be clinically significant. Similarly, with previous reports,[27, 29, 30, 32] the agreement in the meridian of TCA, ACA, and PCA between the devices was varied from moderate to excellent. Repeated measurements of the astigmatic meridian should be considered.

WTW was only one parameter that showed moderate repeatability and reproducibility. The error of auto-alignment of the limbus by IOL Master 700 and auto-alignment of the angle by CASIA 2 were observed in some cases. Therefore, the attention of the alignment of marker on devices' screen after measurement is suggested especially if there is any extremely low or high value. WTW also showed poor to moderate agreement among the three devices. This could be due to the different techniques of WTW measurement in each device. Using Pentacam AXL and IOLMaster 700, WTW is measured automatically from the greyscale step to determine limbus in the photograph, therefore any factors include the darkness, device's shadow, and patients' nose or lash may affect the results.[57] CASIA 2 uses anterior chamber angle as a landmark and provides angle-to-angle distance.[58]

Resemble with TCP and previous reports,[27, 32] the other biometric parameters including anterior K, ACA, Posterior K, PCA, ACD, WTW, CCT showed less repeatability and reproducibility in eyes with keratoconus. In addition, keratoconic eyes showed less agreement between the devices and higher mean differences and wider 95% LoA compared with normal eyes.

Despite the optical biometers showed differences between the three devices, the IOL powers were similar in normal eyes. The mean differences in IOP power using SRK/T and Barrette universal II formulas ranged from -0.110 to 0.095 and -0.095 to 0.180 diopters, respectively. Taking the 0.5 diopters is the presently used IOL step, the IOL power derived from each device seems to be interchangeable. This might infer that the IOL constants recommended by the manufacture can be used with no clinically significant difference. In contrast to normal eyes, the mean differences in IOL power in keratoconic eyes were high, which ranged from 0.574 to 1.529 using SRK/T formula and 0.588 to 1.309 using Barrette universal II formula. Furthermore, Barrette universal II formula showed less proportional bias which may provide benefits in IOL power calculation in keratoconic eyes. IOL power calculation in keratoconus is still challenging for many reasons including abnormality in anterior and posterior corneal surface, change in corneal refractive index, inaccurate keratometry, alteration of lens' effective position, and no designed IOL formula available for keratoconic eyes.[40, 42]

Our findings are limited to normal eyes without any eye pathologies or surgeries other than cataract and eyes with early stage of keratoconus. A few participants with advanced keratoconus were included in this study.

This study is a comparative study between the reliability and the accuracy of the ocular biometry measurement and IOL power calculation of three difference devices. The results will show level of agreement of CASIA 2 compared to Pentacam AXL and IOLMaster 700 but cannot conclude that which one is the best device for ocular biometry measurement or IOL power calculation.

In conclusion, according to the findings of this study, CASIA 2, Pentacam AXL, and IOLMaster 700 provided high and comparable reliability devices in terms of good to excellent repeatability and reproducibility in all parameters, except WTW. Most biometric parameters (except posterior K, PCA, astigmatic meridian, and WTW) demonstrated good to excellent agreement among three devices in healthy and keratoconic eyes. The discrepancy among these devices were higher in keratoconic eyes than in normal eyes.

For clinical application of TCP, good to excellent agreement was demonstrated among three devices in normal and keratoconic eyes. IOLMaster 700 provided highest value, followed by Pentacam AXL and CASIA 2 respectively, in both groups. There were clinically significant differences between CASIA 2 and IOLMaster 700 in normal eyes, and between IOLMaster 700 and other two devices in keratoconic eyes. Therefore, TCP from differences devices cannot be used interchangeably.

For anterior K, excellent agreement was demonstrated among devices and there was no clinically significant difference between devices in normal eyes. Anterior K could be used interchangeably between devices in normal eyes. However, in keratoconic eyes, IOLMaster 700 provided higher value than Pentacam AXL and CASIA 2 respectively. The differences of anterior K between devices were higher in keratoconic eyes than in normal eyes.

For IOL power calculation in normal eyes, there was no clinically significant differences among three devices. The IOL power derived from each device seem to be used interchangeably in normal eyes. Contrastly, there was clinically significant differences between devices in keratoconic eyes which CASIA 2 showed highest IOL power followed by Pentacam AXL and IOLMaster 700 respectively. Barrette universal II formula showed better benefits for IOL calculation in this group of patients.

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