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The utility of white-to-white distance in predicting myopia and its practical implications: a review

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THE UTILITY OF WHITE-TO-WHITE DISTANCE IN PREDICTING MYOPIA AND ITS PRACTICAL IMPLICATIONS: A REVIEW

by

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“Live as if you were to die tomorrow. Learn as if you were to live forever.”
– Mahatma Gandhi

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THE UTILITY OF WHITE-TO-WHITE DISTANCE IN PREDICTING MYOPIA AND ITS PRACTICAL IMPLICATIONS: A REVIEW

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ABSTRACT

White-to-white (WTW) distance is one of the anterior segment metrics of the eye that has significant clinical implications and utility. Traditionally used as a diagnostic tool for congenital glaucoma, microcornea, and megalocornea, WTW distance has also been found to play an important role in planning and predicting successful outcomes for refractive cataract and implantable collamer lens (ICL) surgeries. For example, it has become a standard measurement utilized for calculating both the refractive power of intraocular lenses (IOL) for cataract surgeries, and ICL size. The goal of this thesis is to review 1) the various ways in which WTW distance is used in the clinical setting and 2) whether it has any correlation to the degree of myopia.

The current literature on WTW distance, including the various methods of measurement and its utility in clinical procedures is reviewed. Comparative evaluations of the various devices that can measure WTW distance show a generally good repeatability, with no gold standard for accurate measurement. Some argue that a manual measurement using a caliper at the slit lamp is the gold standard, but this method has been found to have high variability.

Additionally, there is ongoing debate on whether WTW distance is sufficient for accurate ICL sizing and successful surgical outcomes. More recent data show alternative metrics such as sulcus-to-sulcus (STS) or angle-to-angle (ATA) diameter to be better predictors of accurate ICL sizes. Despite recent findings of better clinical outcomes using these internal ocular metrics for ICL surgery, whether they are cost effective and clinically significant enough to replace existing methods remains inconclusive.

WTW distance and degree of myopia from the patient database at Boston Vision was also analyzed. A pairwise p-test with Bonferroni correction of WTW distance in 107 eyes with no myopia, low myopia, or high myopia revealed that there was no strong correlation between WTW and degree of myopia ($p > 0.05$). However, the WTW distance was smaller in females than in males (mean difference -0.3245; $p < 0.001$), which confirmed findings from a previous study. Based on these preliminary findings, it doesn’t seem clear that a correlation between WTW distance and degree of myopia exists. While the practical implications of WTW have been widely assessed, additional studies and research using a large dataset should be performed to accurately evaluate the utility of WTW in predicting myopia.

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LIST OF ABBREVIATIONS

AC-OCT	Anterior Chamber-Optical Coherence Tomography
ACD	Anterior Chamber Depth
AI	Artificial Intelligence
AL	Axial Length
ASM	Anterior Segment Metrics
ATA	Angle-to-Angle
CCT	Central Corneal Thickness
CYL	Cylinder
EC	Endothelial Cell
ELP	Effective Lens Position
HVID	Horizontal Visible Iris Diameter
ICL	Implantable Collamer Lens
IOL	Intraocular Lens
IOP	Intraocular Pressure
K	Keratometry
LT	Lens Thickness
OLCR	Optical Low-Coherence Reflectometry
PCLI	Partial Coherence Laser Interferometry
SE	Spherical Equivalent
SIA	Surgically Induced Astigmatism
SPH	Sphere

SS-OCT	Swept-Source Optical Coherence Tomography
STS	Sulcus-to-Sulcus
UBM	Ultrasound Biomicroscopy
VHF	Very High Frequency
WTW	White-to-White

GLOSSARY

Ametropia – state of the eye in which refractive error is present; categorized into myopia, hyperopia, or astigmatism

Angle – term that refers to the angle that forms between the iris and cornea

Angle-to-Angle – distance between the angles within the anterior chamber

Applanation – flattening of the cornea by pressure

Astigmatism – a form of ametropia where either the cornea or the lens has imperfect curvatures that causes blurred distance or near vision

Axial Length – distance from the corneal surface to the retina of the eye

Ciliary Sulcus – space between the anterior side of the ciliary body and posterior side of the base of the iris

Cylinder – the amount of lens power required to correct astigmatism

Haptics – the side structures of an intraocular lens that rest in the internal structures of the eye and hold it in place

Hyperopia – far-sightedness; a form of ametropia where the eye is too short and the focal point falls behind the retina

Manifest Refraction – measurement of the degree of ametropia in one’s eye

Myopia – near-sightedness; a form of ametropia where the eye is too long and the focal point falls in front of the retina

Pachymetry – measurement of corneal thickness

Phakic – a state in which a lens is implanted without the extraction of the eye’s natural lens

Placido Rings – concentric rings on a device used for corneal imaging

Pseudophakic – a state in which the eye’s natural lens is removed before inserting a lens implant

Sphere – the amount of lens power required to correct ametropia

Spherical Equivalent – the amount of lens power required to correct ametropia and astigmatism, combined using a formula that converts sphere and cylinder

Vault – the distance between an implantable collamer lens (ICL) and the anterior surface of the eye’s natural lens

INTRODUCTION

The white-to-white (WTW) measurement refers to the horizontal corneal diameter on the surface of the eye. It measures the distance between the corneal limbus borders, which are at the junction of the cornea and sclera (Van Buskirk, 1989). WTW values have traditionally been used as a diagnostic tool for various ocular disorders such as congenital glaucoma, microcornea, and megalocornea, which share a phenotypical deviation from normal corneal diameters (Abu-Amero & Edward, 1993; Moshirfar et al., 2022). More recently, WTW measurements have been found to be important for calculating the power of intraocular lens (IOL) implants for cataract surgery. It has also been found to be associated with postoperative astigmatism after cataract surgery (Theodoulidou et al., 2016). Furthermore, WTW distance has been found to be important for refractive cataract surgeries (Han & Kim, 2019), as well as implantable contact lens (ICL) sizing. For these reasons, the WTW distance is increasingly taken into consideration when planning for both cataract and refractive surgeries.

In the first section of this thesis, background information on the anatomy of the eye, focusing on the relevant structures in the anterior segment, will be provided. Next, the various methods currently used to measure WTW distance will be reviewed, comparing the accuracy and reliability of such methods. Investigation of the important implications of WTW distance in predicting myopia, IOL power calculation, and ICL sizing will follow. In addition, an analysis of the correlation between WTW distance and myopia from the patient database at

Boston Vision will be included. Finally, the paper will explore the current literature's discussion about the accuracy of various WTW measurement methods and the adequacy of using WTW distance for surgical planning instead of other anterior segment metrics (ASM).

Anatomy of the Eye

The human eye can be divided into two compartments – the anterior and posterior segments. For the purpose of this paper, we will focus on the anterior segment of the eye, which includes the anterior and posterior chambers, iris, ciliary body, cornea, sclera, and crystalline lens (**Figure 1**). Our metric of interest, the WTW distance, is also a measurement of the anterior segment, between the borders of the corneal limbus (Wei et al., 2021).

The anterior segment is filled with aqueous humor composed of filtered plasma which supplies necessary metabolites to the avascular cornea and lens while removing metabolic waste. The corneal limbus (**Figure 2**), which lies at the border between the opaque sclera and transparent cornea, contains the trabecular meshwork, Schlemm's canal, and aqueous collector channels which are sites of aqueous humor outflow (Van Buskirk, 1989). The balance of production and drainage of aqueous humor in the anterior segment is crucial to maintaining a healthy intraocular pressure (IOP).

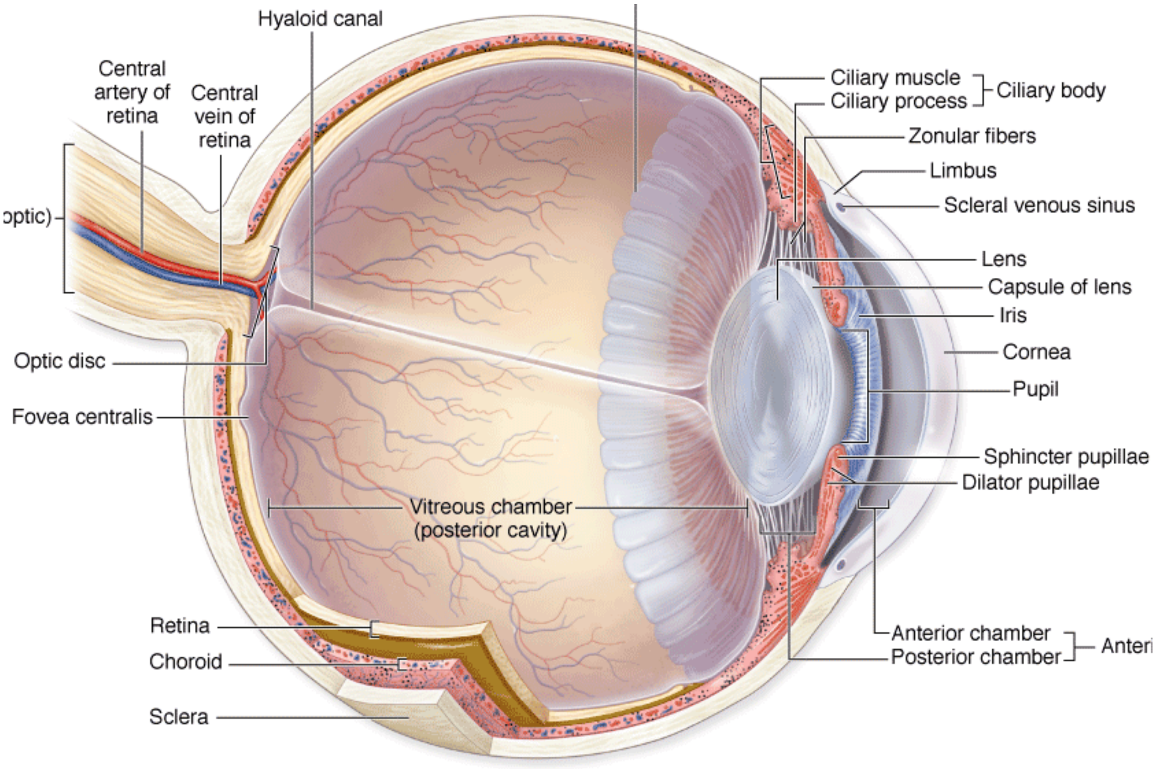

Figure 1. Anterior and Posterior Segments of the Eye. This figure identifies the major ocular structures in the anterior and posterior segments of the human eye. The anterior segment includes the anterior and posterior chambers, cornea, iris, and lens. The vitreous chamber, retina, and optic nerve lie in the posterior segment. The anterior segment is filled with aqueous humor while the posterior segment is filled with a vitreous, jelly-like humor. Adapted from Mescher, 2018. **Figure downloaded from:** http://www.accessmedicine.com

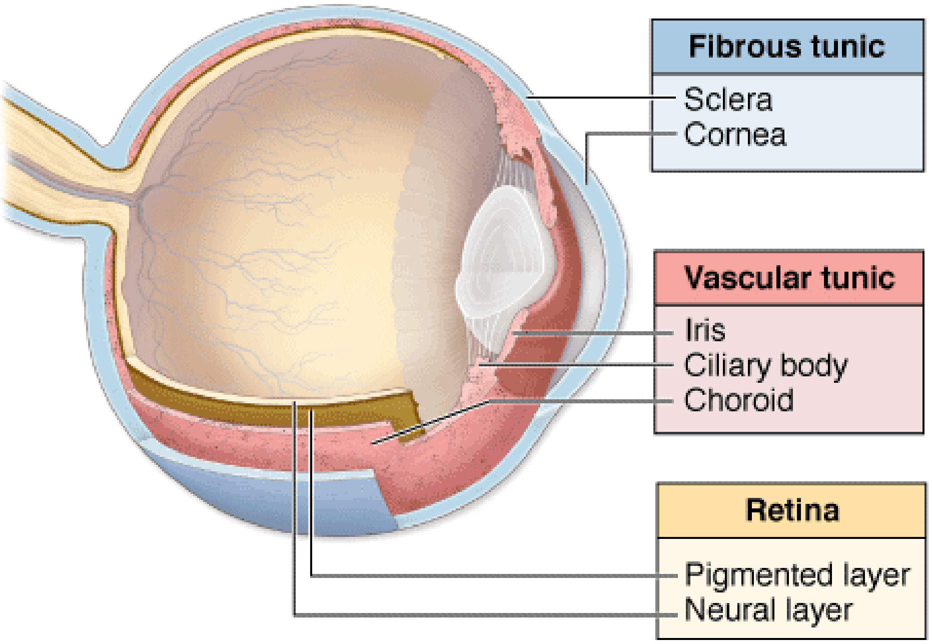

Figure 2. The Three Layers of the Eye. This figure demonstrates the three layers of the eye: Fibrous tunic, vascular tunic, and retina. The corneal limbus is part of the fibrous tunic layer, demarcating the border between the transparent cornea and opaque sclera. Adapted from Mescher, 2018
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Methods of WTW Measurement

There are various methods to obtain WTW distance through either digitalized imaging or manual measurement. Digital image processing can be performed by the IOL master, Lenstar, Orbscan II, Galilei, Pentacam, or EyeSys systems (Baumeister et al., 2004; Salouti et al., 2009). Digital imaging systems are often paired with a software that analyzes the maximum horizontal distance between the corneal limbus borders to obtain WTW distance (**Figure 3**; Consejo et al., 2017). The WTW distance can also be measured manually using the Vernier or Castroviejo caliper (**Figure 4**; Taneja et al., 2012).

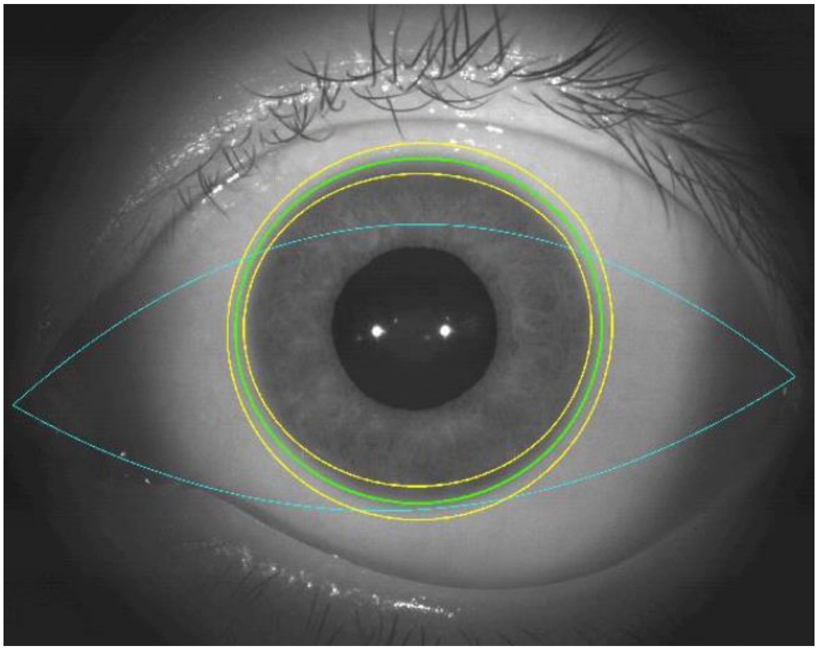

Figure 3. Mean shape of the human limbus. This figure shows a model of the mean shape of the corneal limbus (green line). The range of variability can be calculated as one standard deviation from the mean (yellow lines). This area includes the “blue-grey zone” that allows room for subjective errors and interrater variability. Usually, the average eyelids cover the superior and inferior sides of the limbus (cyan lines). Adapted from Consejo et al., 2017.

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Invest. Ophthalmol. Vis. Sci.. 2012;53(14):4908.

Figure 4. Vernier and Castroviejo Calipers. Pictured in this figure is the digital Vernier caliper and compass-like Castroviejo caliper commonly used in ophthalmology today. The Vernier caliper measures from 0 to 150 mm in 0.01-mm increments while the Castroviejo caliper measures from 0 to 20 mm in 1-mm increments (with allowed estimates in 0.5 mm increments). Adapted from Taneja et al., 2012.

The difficulty of accurately measuring WTW distance lies in the subjectivity of determining the corneal limbus borders. The “blue-grey zone” of the limbus is a transitional area spanning a width of about 1.2 mm between the opaque sclera and transparent cornea (Van Buskirk, 1989). The blue-grey zone gets its name from the blue-grey appearance of this transitional area when viewed externally. Depending on where in the blue-grey zone (the center or edge) the measurement is taken from, there could be significant differences in WTW distance. The subjectivity of determining the edges of the corneal limbus may be more apparent when using a manual caliper. However, in the current literature, there is no consensus as to which method is the most accurate. In this section, the different methods of WTW measurement will be introduced and the previous studies that discuss their validity and reliability will be explored.

1. Ophthalmic Calipers

A caliper is a measuring device used to obtain the distance between two points on a plane as well as other dimensions of an object. French scientist Pierre Vernier invented the first graduated caliper, the Vernier caliper, which measures from 0 to 150 mm in 0.01-mm increments (Taneja et al., 2012). In ophthalmology today, the Castroviejo caliper and the Jameson caliper are more commonly used (Mohamed et al., 2013). The Castroviejo caliper, invented in the 1950s, measures from 0 to 20 mm in 1 mm increments (Jose & Roy, 2004). There is also a caliper invented by Kohnen in 1997 specifically for determining incision size for cataract surgery and measures from 1 to 6 mm in 0.1 mm increments (Kohnen, 1997). In a study comparing the measurements of various metrics including horizontal corneal diameter, Mohamed et al. found no significant differences between the types of calipers and found that their precision is limited to approximately 0.1 mm (Mohamed et al., 2013). Furthermore, another study by Taneja et al. confirmed that there was no significant difference in the variability between the Vernier and Castroviejo calipers (Taneja et al., 2012).

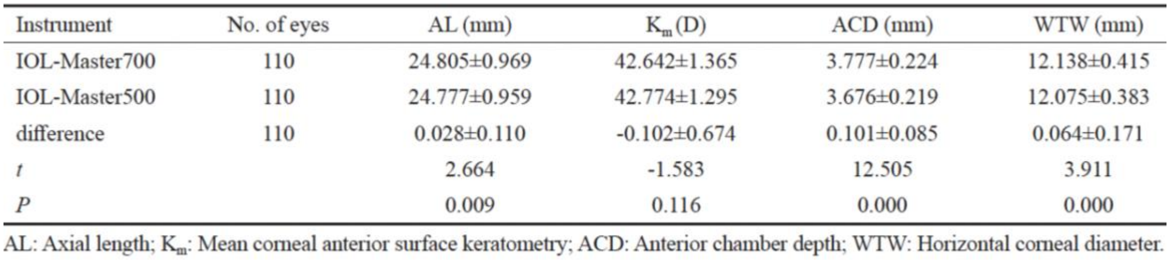
The Castroviejo caliper appears to be the most commonly used caliper in ophthalmology today, due to its portability, ease of use, and accuracy (Al-Essa & Alkharashi, 2021). With manual measuring devices, inter-rater variability and damage to the instrument with prolonged use may affect their precision. Calibration of such devices is important to ensure accurate measurements and to avoid various complications in ophthalmic procedures, including poorly fitted anterior chamber intraocular lenses and improper sizing of ICLs (Al-Essa & Alkharashi, 2021). In one study, 41 calipers were evaluated for discrepancies (>0.5 mm) in their measurements compared to a standard ruler and almost 40% of them had at least one point of discrepancy on the caliper reading scale (Al-Essa & Alkharashi, 2021). Another study in France previously confirmed these findings by assessing 71 calipers and showed that 42% of them had an error of >0.5 mm when calibrated against their standard ruler measurement points (Dahrab & LaRoche, 2011). As these studies have shown, the Castroviejo calipers are prone to variability and bias and therefore, periodic calibration is necessary to detect any errors when using them.

2. IOLMaster

The IOLMaster is an instrument traditionally used to measure axial length (AL), which is an important value for accurate power calculation of intraocular lens (IOL) in cataract surgery (Sheng et al., 2004). It utilizes partial coherence laser interferometry (PCLI) with a wavelength of 780 nm to measure AL in a noninvasive and time efficient way. This method has replaced the conventional ultrasound biometry which requires applanation and therefore, local anesthesia or pupil dilation, offering a more comfortable experience for patients. It has also been found that the IOLMaster is more repeatable than the previously used ultrasound method (Sheng et al., 2004). Furthermore, studies have shown PCLI to yield higher accuracy and precision which led to improved refractive outcomes in patients who had cataract surgeries (Drexler et al., 1998; Findl et al., 2001; Rajan et al., 2002).

Besides its utility for predicting refractive outcomes for cataract surgery, the IOLMaster can also measure WTW distance, along with other ocular measurements such as anterior chamber depth (ACD), corneal anterior surface keratometry (K), and central corneal thickness (CCT) (Nemeth et al., 2010). With developing technology, there are now two models – IOLMaster 500 and 700. The IOLMaster 700 uses a novel swept-source optical coherence tomography (SS-

OCT) technology that offers three-dimensional anterior segment data with high lateral and axial resolution (An et al., 2019; Bullimore et al., 2019). In a study comparing the two models, some statistical differences in AL, ACD, and WTW distances were found but these differences were not considered clinically significant (**Table 1**; Shi et al., 2021). In fact, both models have been found to provide measurements that agree with each other.



Instrument	No. of eyes	AL (mm)	K_m (D)	ACD (mm)	WTW (mm)
IOL-Master700	110	24.805±0.969	42.642±1.365	3.777±0.224	12.138±0.415
IOL-Master500	110	24.777±0.959	42.774±1.295	3.676±0.219	12.075±0.383
difference	110	0.028±0.110	-0.102±0.674	0.101±0.085	0.064±0.171
t		2.664	-1.583	12.505	3.911
P		0.009	0.116	0.000	0.000

AL: Axial length; K_m: Mean corneal anterior surface keratometry; ACD: Anterior chamber depth; WTW: Horizontal corneal diameter.

Table 1. Comparison of measurements by two biometric instruments. (mean ± SD) The table shows a paired t-test analysis of 110 eyes and different biometric parameters measured by the IOLMasters 500 and 700. The mean values and difference of measurements were compared. Results indicate no significant difference between the two models for K values. However, significant differences for AL, ACD, and WTW measurements were found ($p < 0.01$). Adapted from Shi et al., 2021.

3. Lenstar

The Lenstar is another noncontact biometer that allows simultaneous measurement of various ocular metrics including AL, ACD, K, and WTW values (Buckhurst et al., 2009). It utilizes optical low-coherence reflectometry (OLCR) technology and studies have shown its measurements to be highly repeatable and reliable compared to those obtained with the IOLMaster (Holzer et al., 2009; Rohrer et al., 2009). In a study measuring 160 cataract eyes, 122 of which were successfully measured by both the IOLMaster and Lenstar, a strong correlation between the measurements were found (**Figure 5**; Hui & Yi, 2014). Furthermore, the Lenstar offered accurate power calculations for the IOLs utilized in refractive cataract surgeries. Gathering the results from multiple studies in the current literature, we can conclude that the new Lenstar device is another useful tool for not only efficient measurement of various ocular biometry but also accurate IOL power calculation in cataract patients.

In a later section, an analysis of whether there is a correlation between the degree of myopia and WTW distance has been included. The WTW values for this analysis were obtained from a Lenstar device.

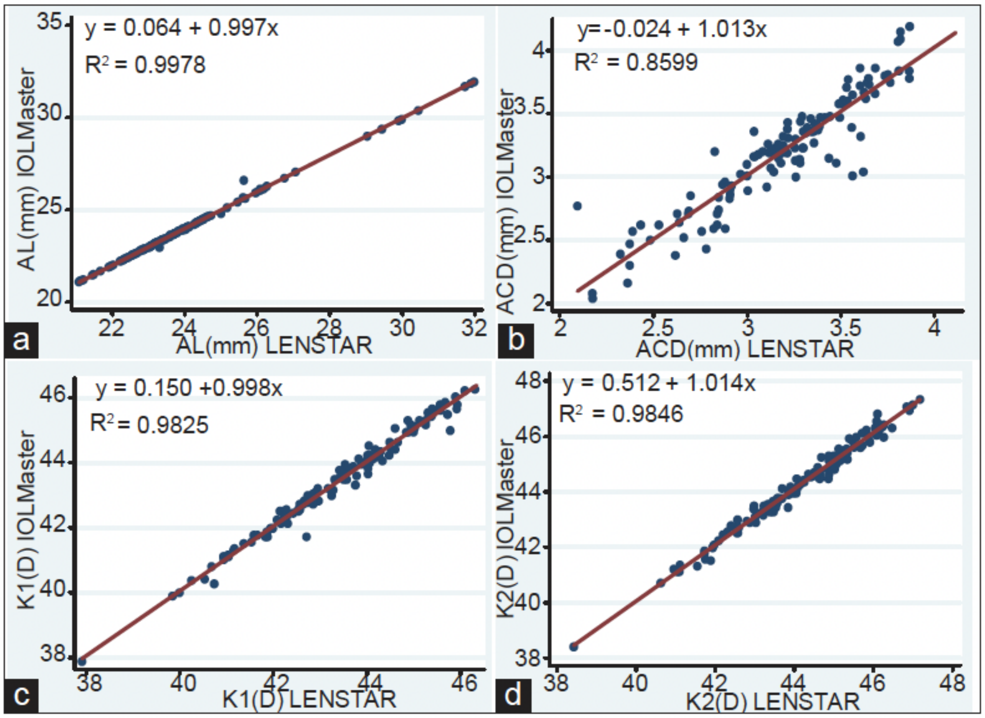


Figure 5. Correlation between Lenstar and IOLMaster measurements. AL = axial length; ACD = anterior chamber depth; K1 & K2 = corneal refractive power. *n* = 122 eyes. This figure illustrates the correlation between measurements obtained by a Lenstar and IOLMaster. Of the 4 different parameters obtained, the correlation for AL is the strongest (R^2 = 0.9978) while the correlation for ACD is the weakest (R^2 = 0.8599). Linear regression showed high degree of correlation with Pearson r values of 0.999, 0.991, 0.992, and 0.927 for AL, K1, K2, and ACD, respectively. **Adapted from Hui & Yi, 2014.**

4. Scheimpflug Camera

Another technology that allows digital imaging of WTW distance is the Scheimpflug camera (Sung et al., 2016). There are multiple instruments that utilize the rotational Scheimpflug camera, including the Pentacam and Galilei (Baradaran-Rafii et al., 2017). The Pentacam was introduced as a new topographer than can also measure WTW distance (Barkana et al., 2005). Initial studies have found the Pentacam to accurately measure central corneal thickness (CCT) with high repeatability, comparable to that measured by traditional pachymetry (O’Donnell & Maldonado-Codina, 2005; Sedaghat et al., 2010; Shankar et al., 2008). It has become a useful tool for planning and evaluating the results of laser refractive surgery (Ambrósio et al., 2013), leading to continuous advancement and utilization of the Scheimpflug camera technology.

The Galilei dual-Scheimpflug analyzer uses dual Scheimpflug cameras and a Placido disk which serve to improve the accuracy of corneal measurements (Wang et al., 2010). A study performed in Spain investigated the precision and agreement of single versus dual Scheimpflug camera for anterior segment evaluation. While they found excellent repeatability and reproducibility for all the anterior segment parameters that they tested, the single-Scheimpflug camera was more precise for curvature and astigmatism, while the dual-Scheimpflug camera was more precise for corneal thickness measurements (Aramberri et al., 2012). However, there is still no gold standard for corneal topography and studies continue to show a strong correlation between the measurements obtained by the Pentacam (single-camera) and Galilei (dual-camera) in most anterior segment parameters (Baradaran-Rafii et al., 2017).

Since its utility as a tool for measuring anterior segment metrics has been proven, Scheimpflug camera devices have also been used for WTW corneal measurement. In one study, there was no statistical difference between WTW distance measured by the Pentacam versus Galilei but poor agreement, concluding that the two instruments cannot be used interchangeably (**Figure 6**; Domínguez-Vicent et al., 2014).

5. Placido disc-based system

The EyeSys topographer is another digital imaging instrument that can be used to measure WTW distance. It uses a Placido disc-based data acquisition system that analyzes placido rings reflected off the cornea (Koch et al., 1992). The instrument's claimed advantage is that it allows for rapid data analysis and display of the topography of the anterior segment, along with its ease of use and compact design (Salouti et al., 2009). In a study comparing WTW distance in 74 eyes, those obtained by the EyeSys topographer did not statistically differ from those obtained by the Galilei (Salouti et al., 2009). The Galilei utilizes both the Placido disc-based system and Scheimpflug camera.

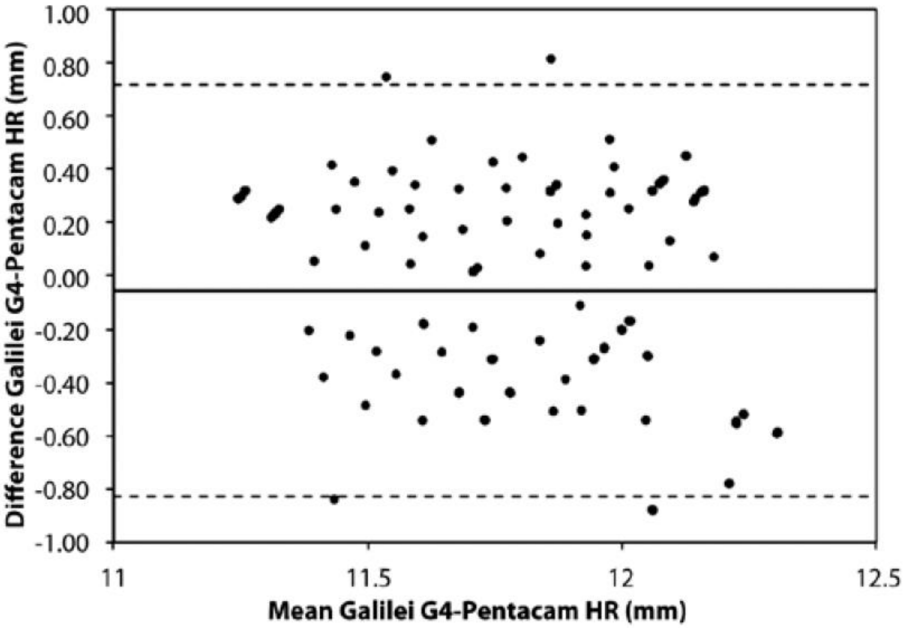


Figure 6. Bland-Altman plot comparing WTW distance measured by Pentacam vs. Galilei. In comparing WTW distances measured by the two instruments, the mean difference (-0.05 ± 0.39 mm) was found to be not statistically significant ($p > 0.05$). However, the Bland-Altman plot shows a wide 95% limits of agreement, revealing poor agreement between them. Adapted from Domínguez-Vicent et al., 2014.

6. Orbscan II

The Orbscan II, though outdated today, used to be one of the most common digital imaging methods used for measuring WTW (Salouti et al., 2009). It is a scanning-slit topography that utilizes a horizontally-moving, vertically-oriented slit beam to produce 140 slit images that are digitally processed to reconstruct a grey-scale image of the anterior segment (Gharaee et al., 2014; Salouti et al., 2009). For WTW measurement, the software calculates the horizontal corneal diameter by detecting the corneal limbus borders in a step-wise fashion (Wang & Auffarth, 2002). In a study that measured WTW distance in 74 eyes, Salouti et al. reported measurements with the Orbscan II were smaller than that with the Galilei and EyeSys (Salouti et al., 2009). In a later study comparing WTW measurements in 101 eyes obtained by the Pentacam and Orbscan II, the differences were not considered clinically significant and the two instruments were found to be interchangeable in clinical practice (Salouti et al., 2013).

Comparison of current methods

In the current literature, there is no gold standard for measuring WTW distance. Domínguez-vincent et al. has performed a thorough review of the commonly used devices for anterior segment measurement, including Orbscan II, Pentacam, Galilei, IOLMaster, and Lenstar. After reviewing many comparative studies, they concluded that all devices generally showed good agreement with one another for WTW distance values (Domínguez-Vicent et al., 2016). Some of the results from the review have been summarized in Table 2, adapted to include only the machines that have been introduced in this paper. In this section, the results from the comparative studies on these devices, specifically for repeatability and agreement of WTW distance measurement will be further explored.

In 2004, Baumeister et al. evaluated the WTW distance measured by a manual caliper, IOLMaster, and Orbscan II in 100 eyes. The study revealed that the mean WTW distance measured by Orbscan II were shorter by 0.24 mm compared to that of the IOLMaster (Baumeister et al., 2004). They also found a significant difference in results obtained by 2 different examiners with the manual caliper ($p < 0.001$), but this was not the case with the 2 digital imaging devices. These findings provide reason to be cautious of interrater variability when using a manual caliper to measure WTW diameter. In 2009, Salouti et al. compared WTW distance measured by the Galilei, EyeSys, and Orbscan II for 74 eyes and found that WTW distance measured by Orbscan II was smaller than that obtained by the Galilei and EyeSys systems (Salouti et al., 2009). These results, along with those from Bausmeister et al. reveal a trend in which Orbscan II measures smaller than other automated devices. Furthermore, they found that out of the 3 machines, the Galilei and Orbscan II showed the best agreement but still concluded that it would be inadvisable to use them interchangeably.

A study by Venkataraman et al. revealed a statistically significant difference between WTW distance measured manually versus automatically (Venkataraman et al., 2010), corroborating the presence of variability among currently used methods of WTW measurement. In 2013, Salouti et al. evaluated WTW measurements by the Pentacam and Orbscan II in 101 eyes. As a result, they found that the measurements were highly correlated (Pearson correlation coefficient = 0.948; $p < 0.001$) and concluded that the Pentacam and Orbscan II may be used interchangeably (Salouti et al., 2013).

With the advancement of technology, comparative studies in the current literature continue to evolve to include new devices. In 2018, Passi et al. compared the agreement and efficiency of 2 machines, the IOLMaster and Lenstar, in 64 eyes undergoing cataract evaluation. They found a high degree of agreement between the anterior segment biometrics measured by both devices (Passi et al., 2018). However, they also found that the IOLMaster took about 73% less time on average to obtain the values compared to the Lenstar. The study provides results that may be valuable when considering the importance of reducing time to improve efficiency in a high-volume clinical setting.

While there is not yet an established gold standard for WTW measurement, many comparative studies have made it clear that various factors such as inter-rater variability and repeatability should be taken into consideration when choosing one device over another.

Instrument	Orbscan II	Pentacam	Galilei	IOLMaster	Lenstar	EyeSys
Orbscan II		-	0.38±0.56	0.32±0.11	-	0.42±0.78
Pentacam	-		-	-	-	-
Galilei	0.38±0.56	-		-	-	0.05±0.75
IOLMaster	0.32±0.11	-	-		0.06	-
Lenstar	-	-	-	0.06		-
EyeSys	0.42±0.78	-	0.05±0.75	-	-	

Table 2. Mean difference between pairs of devices for WTW distance (mm). This table summarizes the difference in mean between each pair of devices used to measure WTW distance (mean WTW distance±standard deviation in mm). The values have been taken from different comparative studies which evaluated the WTW values obtained by the different digital imaging instruments introduced in this paper. Adapted from Domínguez-Vicent et al., 2014.

THE UTILITY OF WTW DISTANCE

IOL Power Calculation

In the history of cataract surgery, there has been a constant evolution of formulas used to calculate the refractive power of IOLs. Especially for modern-day cataract surgeries, success has become increasingly defined by the refractive outcomes. Older generation formulas such as Sanders-Retzlaff-Kraff formulas (SRK I/SRK II) utilize a regression-based, statistical approach (Olsen, 2007) that has been outdated and proven to be less accurate than new generation formulas such as Barrett Universal II and Holladay that incorporate ocular biometry factors like AL, ACD, lens thickness (LT), keratometry, preoperative refraction, and WTW distance (Amro et al., 2018; Nemeth & Modis, 2021; Xia et al., 2020). Each new modification to the formulas serves to improve the prediction of postoperative lens position, also known as the effective lens position (ELP). Utilizing anterior segment metrics like WTW distance in the formulas is thought to offer a better predictive tool for final ELP and consequent refractive success.

In a retrospective case study of 13,301 cataract surgeries, Melles et al. found that 50% of refractive predictions based on the Barrett Universal II formula were within 0.25D from the true refraction (Melles et al., 2018). This study demonstrated that even among the new generation formulas including Haigis, Holladay, and SRK/T, the Barrett formula had the lowest prediction error. The fact that WTW distance is incorporated into the Barrett formula indicates the value of utilizing this biometry for better refractive outcome of cataract surgeries.

Furthermore, incorporating WTW distance in IOL power calculation has been found to be especially important for better outcomes in highly myopic cases with very long eyes (AL > 30 mm), where calculation accuracy is relatively more difficult to obtain (Wei et al., 2021). Therefore, in the case of cataract surgeries, accurate WTW measurement is important for accurate lens power calculation to ensure satisfactory refractive outcomes. Additionally, Theodoulidou et al. found that WTW distance is a factor that influences surgically induced astigmatism (SIA) after cataract surgery (Theodoulidou et al., 2016). In a study of 330 eyes with corneal astigmatism that underwent cataract surgery, greater degree of SIA was found in eyes with WTW distance ≤ 11.6 mm and 11.7 to 11.9 mm ($p < 0.05$). This is presumably due to the position of the incision being closer to the optical center in small corneas and therefore having a greater effect on the central corneal curvature and consequently larger SIA. Their findings led to the conclusion that measuring WTW distance preoperatively during cataract surgery planning is important, especially for cases of small corneas.

While correct WTW measurement is important for preoperative planning, the main consequence of inaccurate measurement for cataract surgeries is a poor refractive outcome. This is due to the fact that IOL implantation in cataract surgeries is pseudophakic, meaning that the eye’s natural crystalline lens is removed before inserting the new lens. Therefore, the physical size of the IOL in the anterior or posterior chamber is not as critical for determining successful outcome for cataract surgeries. However, this is not the case for implantable collamer lens (ICL) surgeries, which will be discussed in the next section.

ICL Sizing

ICL surgery is a type of refractive surgery that is widely accepted as an alternative treatment to the traditional excimer laser correction (LASIK or PRK) for ametropic eyes (Lovisolo & Reinstein, 2005). It is often recommended for individuals who have high myopia and therefore laser ablation for treatment is less attractive (Goldsmith et al., 2005). Also known as an implantable contact lens procedure, it involves a phakic intraocular lens implantation, meaning the lens is placed in front of the eye’s natural crystalline lens. The phakic intraocular lens (pIOL) is designed to sit in either the anterior or posterior chamber of the eye. The currently approved types are anterior chamber pIOLs (iris-fixated), posterior chamber pIOLs, and angle-supported pIOLs (“Phakic Intraocular Lenses for the Treatment of Refractive Errors,” 2009). The Visian® ICL™ by STAAR® Surgical is the most commonly used FDA-approved lens for ICL surgery. It is a posterior chamber pIOL, implanted posteriorly to the iris and anteriorly to the natural lens, resting its haptics on the ciliary sulcus complex (Cerpa Manito et al., 2021). Haptics are the side structures of a lens that support its position by holding it in place within the internal structures of the eye (Bellucci, 2013). Due to the anatomical position of the implant, it is crucial that the lens is compatible with the internal ocular structures.

For a good surgical outcome, the ICL should not interfere with the natural structures of the eye on its anterior and posterior sides (Reinstein et al., 2013). The vault refers to the distance between the ICL and anterior surface of the crystalline lens and it is important that it falls between 250 to 1000 µm to predict the implant's safety (**Figure 7**; Nakamura et al., 2020; Tinwala & Titiyal, 2013). Cerpa Manito et al. conducted a study to determine factors that may cause a sub-optimal vault – either low (< 250 µm) or high (> 1000 µm) vault. In a retrospective case series of 360 eyes implanted with myopic spherical or toric ICLs, they found that eyes with a more protruded crystalline lens and low myopic ICL power were correlated with risk of low vaulting, while excessive compression by a large ICL (13.7 mm), high myopic ICL power, and younger age were correlated with risk of high vaulting (Cerpa Manito et al., 2021).

Another factor to consider in predicting successful postoperative outcomes is how the vault changes after ICL implantation. Alfonso et al. evaluated 133 eyes that underwent ICL implantation by continuously measuring the vaulting with optical coherence tomography (OCT) over 1 week, 1, 3, and 6 months, and yearly postoperatively. During the post-operative time range of 6 to 73 months, they found that the mean vaulting significantly decreased by 71 ± 58 µm ($p = 0.028$) within the first 6 months (Alfonso et al., 2012). After this initial phase of rapid decrease, they found a trend of lower reduction, with a mean decrease of <

2 µm per month. They also found that eyes with the greatest decrease in vaulting (> 100 µm) had a greater mean initial vault than eyes that showed little change or increase in vaulting over time (Alfonso et al., 2012). Using a more advanced ultrasound biomicroscopy (UBM) technology, Zhang et al. were able to follow and image postoperative positions of the ICL and their relationship with vault. With Compact Touch STS UBM, they obtained direct images of the ICL post-implantation in 134 eyes within a postoperative time frame of 1 week to 7 years. They found various positions of the ICL in the posterior chamber, as well as haptics that were inserted in varying positions: out of the 134 eyes, about 64.9% obtained ideal vault, 21.6% had low vaulting, and 13.4% had high vaulting (Zhang et al., 2018). In general, the varying positions of the haptics (**Table 3**) did not affect the vault from deviating from the ideal range, with a few exceptions. Three eyes in the study had haptics that were positioned on top of the ciliary sulcus, causing excessive vaulting and one eye had uneven positioning of the haptics, with one side pushing into the iris (**Figure 8**; Zhang et al., 2018). They also confirmed previous studies' findings that vault decreases over time postoperatively.

Additionally, Zhu et al. performed an assessment on 83 eyes that underwent ICL implantation to determine whether certain preoperative biometric factors played a role in postoperative changes in vault. In their evaluation of the trend in vault changes, they found results that agreed with Alfonso et al. – there was a significant decrease in vaulting over time postoperatively. Furthermore, they found that ICL size, sulcus-to-sulcus (STS) distance, and crystalline lens thickness (LT) are significant predictors of postoperative vaulting, especially at 1 month post-surgery (Zhu et al., 2021). These findings serve to add more weight on the significance of obtaining accurate preoperative biometrics for surgeons when planning and choosing the appropriate ICL size.

Furthermore, the literature provides evidence that incorrect sizing of the lens can lead to a variety of complications. If the ICL is undersized, this could lead to its mobility, rotation, and dislocation which can cause damage to the eye's internal structures, increasing the risk of cataract formation. If the ICL is oversized, this could lead to elevated intraocular pressure (IOP), angle closure resulting in glaucoma, and peripheral anterior synechiae (PAS), in which the iris adheres to the angle (Eissa et al., 2016; Goldsmith et al., 2005; Reinstein et al., 2009).

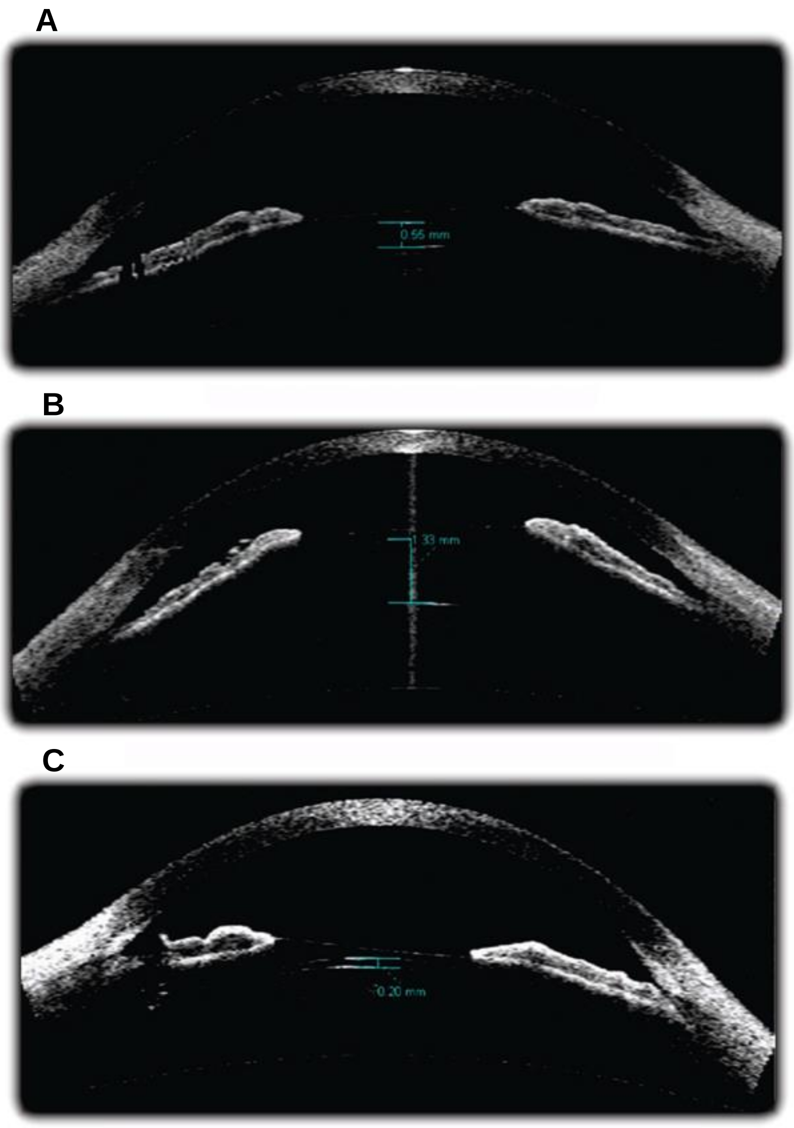


Figure 7. AS-OCT imaging of normal, high, and low vaulting. These images of the anterior segment of an eye post implantation of a phakic IOL were obtained via anterior segment optical coherence tomography (AS-OCT). **A)** Normal vaulting (550 µm) within the range of 250 to 1000 µm. **B)** High vaulting (1330 µm). Eyes with abnormally high vaulting are susceptible to greater endothelial cell loss. **C)** Low vaulting (200 µm). Eyes with low vaulting have a higher risk of cataract formation. Adapted from Tinwala & Titiyal, 2013.

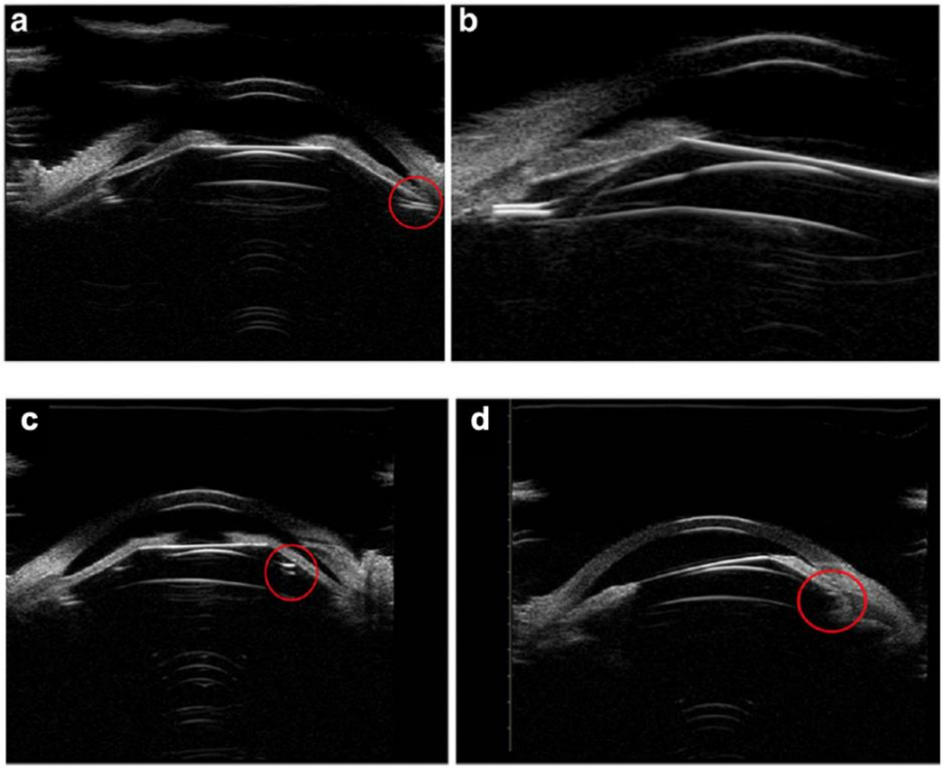
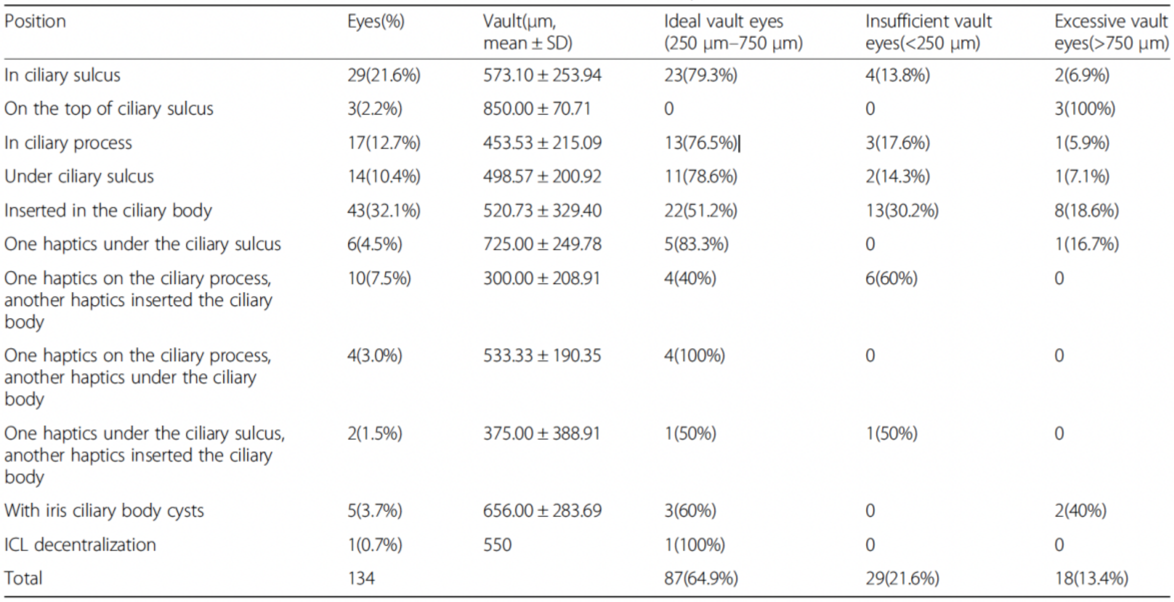


Figure 8. UBM scans of abnormal haptics positions. This figure shows direct scanning of abnormal haptics positions post-ICL implantation**. a)** One haptic was inserted into the ciliary body, which led to excessive vaulting. **b)** Close up of the haptic position inserted into the ciliary body. **c)** One side of the ICL lies on top of the ciliary sulcus, causing a vault greater than 750 um. **d)** The position of one haptic on top of ciliary sulcus resulted in loss of normal arc of the iris due to physical compression by the ICL. Red circles indicate the haptic positions. Adapted from Zhang et al., 2018.



Position	Eyes(%)	Vault(μm, mean ± SD)	Ideal vault eyes (250 μm–750 μm)	Insufficient vault eyes(<250 μm)	Excessive vault eyes(>750 μm)
In ciliary sulcus	29(21.6%)	573.10 ± 253.94	23(79.3%)	4(13.8%)	2(6.9%)
On the top of ciliary sulcus	3(2.2%)	850.00 ± 70.71	0	0	3(100%)
In ciliary process	17(12.7%)	453.53 ± 215.09	13(76.5%)	3(17.6%)	1(5.9%)
Under ciliary sulcus	14(10.4%)	498.57 ± 200.92	11(78.6%)	2(14.3%)	1(7.1%)
Inserted in the ciliary body	43(32.1%)	520.73 ± 329.40	22(51.2%)	13(30.2%)	8(18.6%)
One haptics under the ciliary sulcus	6(4.5%)	725.00 ± 249.78	5(83.3%)	0	1(16.7%)
One haptics on the ciliary process, another haptics inserted the ciliary body	10(7.5%)	300.00 ± 208.91	4(40%)	6(60%)	0
One haptics on the ciliary process, another haptics under the ciliary body	4(3.0%)	533.33 ± 190.35	4(100%)	0	0
One haptics under the ciliary sulcus, another haptics inserted the ciliary body	2(1.5%)	375.00 ± 388.91	1(50%)	1(50%)	0
With iris ciliary body cysts	5(3.7%)	656.00 ± 283.69	3(60%)	0	2(40%)
ICL decentralization	1(0.7%)	550	1(100%)	0	0
Total	134		87(64.9%)	29(21.6%)	18(13.4%)

Table 3. Varying ICL haptics positions and consequent vault in 134 eyes. This table from Zhang et al. (2018) lists the different positions of ICL haptics post-implantation, found by UBM imaging. Other than in the case where the haptics were placed on top of the ciliary sulcus, ideal vault was still attainable in most cases of abnormal haptic positioning.

Additionally, the most common postoperative complications that have been found are cataract formation and endothelial cell (EC) loss (Fernandes et al., 2011; Sanders, 2008). Underestimation of ICL diameter leads to low vaulting and therefore increases the risk of cataract formation. This occurs as the proximity of the ICL to the eye's natural lens increases the likelihood of physical contact between the ICL and the anterior lens capsule (Fernandes et al., 2011). Overestimation of ICL diameter leads to high vaulting and increases risk of elevated IOP and glaucoma due to angle closure. Furthermore, an oversized ICL can theoretically lead to postoperative EC loss. The EC layer is the most posterior side of the cornea and faces the anterior chamber (**Figure 9**;

Navaratnam et al., 2015). ECs are crucial for maintaining corneal hydration and corneal transparency, which are both essential for vision (Navaratnam et al., 2015). With a high vault, the likelihood of the disruption of the corneal endothelium increases as the ICL pushes up into the anterior chamber, decreasing the distance between the endothelial layer and the ICL (Tinwala & Titiyal, 2013; Yang et al., 2017). Having reviewed the literature on various postoperative complications, it is evident that accurate lens sizing is especially important for improving clinical outcomes of ICL surgeries.

In many clinical practices today, WTW distance is the standard measurement used when calculating ICL size. The lens size is determined by adding 0.50 to 1.00 mm to WTW distance, or the horizontal corneal diameter (Lovisolo & Reinstein, 2005). STAAR Surgical also provides recommended ICL diameters based on WTW and ACD measurements, based on the data acquired from their initial clinical trials (**Table 4**; AG, 2005). Therefore, accurate WTW values are required to prevent complications that arise due to poor lens sizing. Given that there are multiple instruments commonly used to measure WTW distance, it is important to recognize the potential discrepancies that might occur. In a study evaluating 55 eyes with the SS-OCT, AC-OCT, and Scheimpflug camera technologies, Oleszko et al. found that there was a significant difference in WTW distance and therefore concluded that the machines should not be used interchangeably. Additionally, they suggested that it may be beneficial to consider angle-to-angle (ATA) distance to support ICL sizing and help verify the variable WTW values (Oleszko et al., 2021).

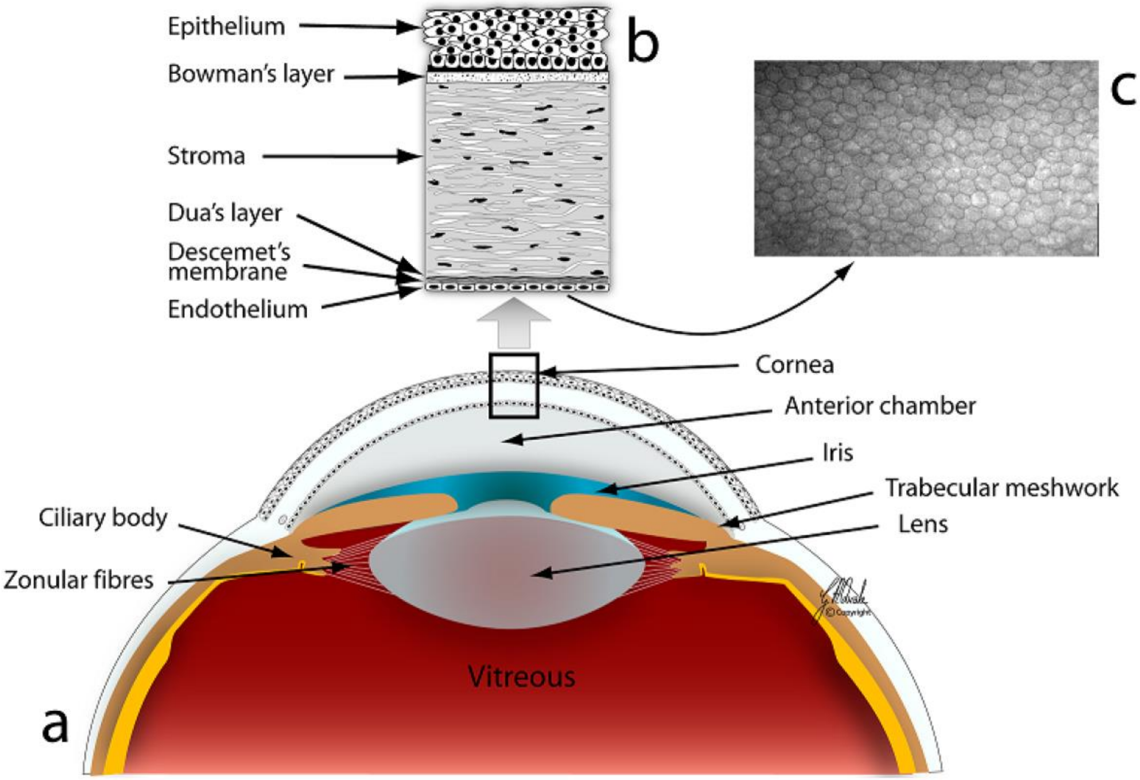


Figure 9. Anatomy of the corneal layers. This figure illustrates the layers of the transparent cornea of the human eye. A) Sagittal section of the anterior section of the eye. B) 6 layers of the cornea, demonstrating the location of the endothelial layer which is exposed to the anterior chamber. C) Confocal microscopy image of the endothelial cells. Adapted from Navaratnam et al., 2015.

White-to-White (mm)	ACD (mm) All	≤ 3.5	> 3.5
< 10.50	Not Recommended	—	—
10.50 – 10.60	—	Not Recommended	12.1
10.70 – 11.00	12.1	—	—
11.10	—	12.1	12.6
11.20 – 11.40	12.6	—	—
11.50 – 11.60	—	12.6	13.2
11.70 – 12.10	13.2	—	—
12.20	—	13.2	13.7
12.30 – 12.90	13.7	—	—
≥ 13.00	Not Recommended	—	—

Table 4. Recommended Visian® ICL Overall Diameter (for myopia) based on WTW and ACD values. Sizing of the Visian® ICL myopic lenses was determined with the data gathered from the original clinical trials by STAAR® Surgical. For eyes with ACD ≤ 3.5 mm, 1.1 mm was added to the WTW distance to calculate lens size. For eyes with ACD > 3.5 mm, up to 1.6 mm was added to the WTW distance, up to a maximum of 13.7 mm lens diameter. Adapted from AG, 2005 (STAAR Surgical).

Debates in the Literature

There is no doubt that correct ICL sizing is crucial for satisfactory postoperative outcomes without detrimental complications. On the contrary, an increasing number of studies are revealing findings that question the adequacy of using just WTW distance for accurate ICL sizing. The WTW is a measurement of the external corneal diameter and studies have found that there is a poor correlation between WTW and sulcus diameter, which spans the area between where the haptics of the ICL actually sit (Bergmanson & Martinez, 2017). The ongoing debate regarding the adequacy of WTW and validity of other metrics that the current literature suggests will be further discussed in this section.

One of the unsettled topics is the definition of the corneo-limbal diameter and how it is measured. When measuring WTW distance using a manual caliper, it is likely that the examiner is actually measuring the horizontal visible iris diameter (HVID) which measures the horizontal distance between the white part of one side of the eye and that of the other side. This measurement does not take into consideration the limbal width, or the “blue-grey zone” mentioned earlier, and therefore the HVID most likely underestimates the true corneo-limbal diameter (Bergmanson & Martinez, 2017). Furthermore, Pop et al. evaluated 43 eyes using ultrasound biomicroscopy (UBM) to measure ACD, sulcus size, and CCT and compared these measurements to limbus size measured with a caliper. As a result, they found that manual limbal measurement is inadequate for accurately estimating sulcus size (Pop et al., 2001). Considering the fact that the haptics of the ICL lens sits in the ciliary sulcus complex, a more accurate measurement of the internal dimensions of the posterior chamber may be necessary for improved postoperative outcomes.

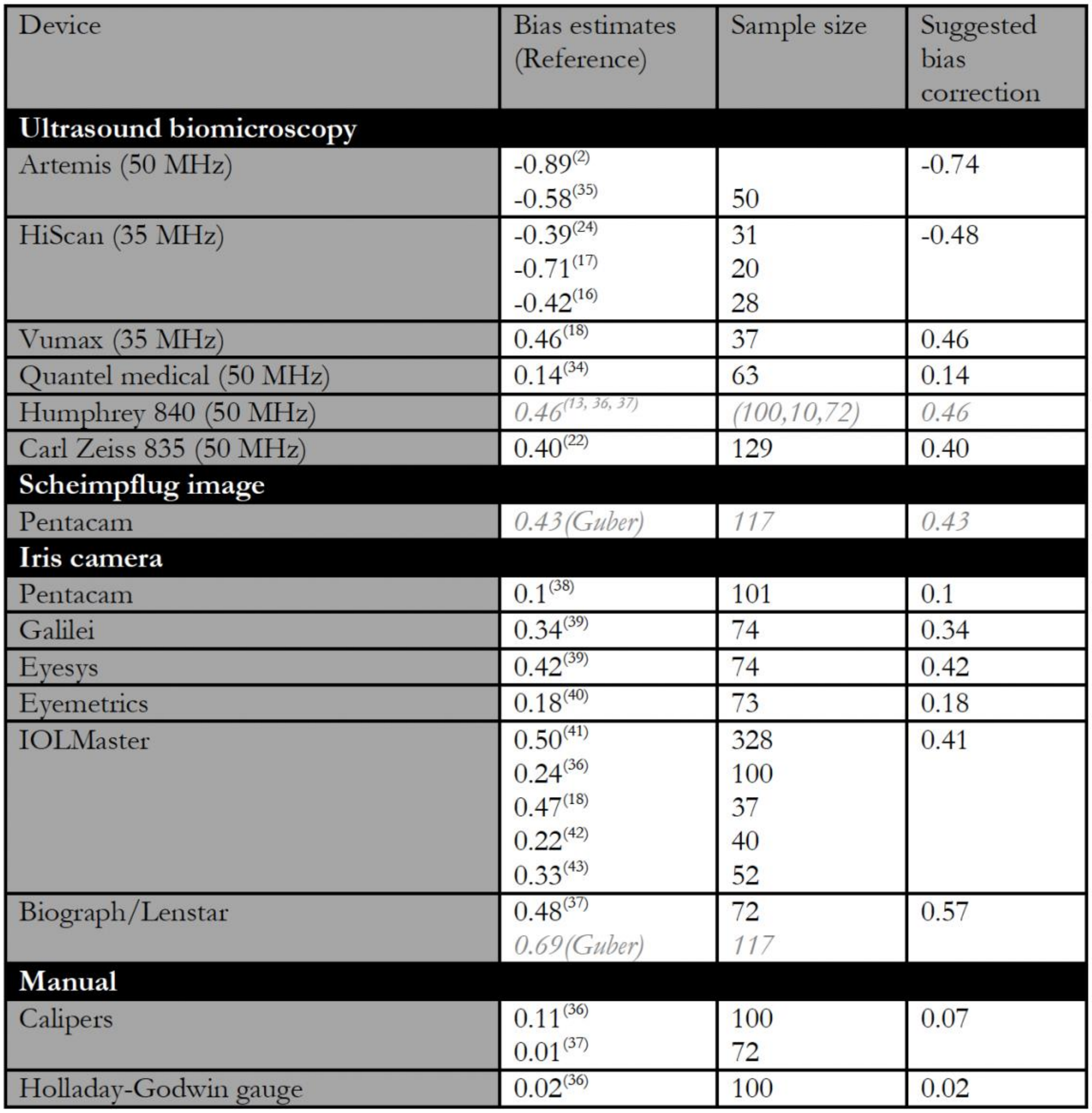
A novel 35 MHz UBM technology allows for measurement of the horizontal ciliary sulcus diameter, or sulcus-to-sulcus (STS) distance. In a prospective trial evaluating various ocular measurements via a 35 MHz UBM unit in 20 eyes, Kim et al. found that STS distance did not correlate with WTW distance but did significantly correlate with mean corneal curvature ($p < 0.001$) (Kim et al., 2008).

They concluded that mean corneal curvature measurements can be used to predict STS diameter which could improve the accuracy of ICL sizing. In 2011, Biermann et al. also measured STS diameter using UBM in myopic eyes and compared the measurements to WTW values obtained by the Orbscan and IOLMaster. The mean STS diameter was 12.19 ± 0.47 mm ($p < 0.01$) and the mean WTW diameters measured by the IOLMaster and Orbscan were 12.20 ± 0.42 mm and 11.73 ± 0.37 mm, respectively. Using the Pearson correlation to assess the agreement between STS and WTW diameters, they found that the correlation was weak in myopic eyes ($r^2 = 0.36$ and $r^2 = 0.40$) (Biermann et al., 2011). They also found that the STS diameter was most precisely measured using UBM and concluded that WTW diameter may not be adequate for accurate calculation of myopic ICL lenses.

The Artemis arc-scanner is another imaging technology that uses very high frequency (VHF) digital ultrasound that can measure the internal structure metrics such as angle and sulcus diameters (Reinstein et al., 2000). In 2009, Reinstein et al. used the arc-scanner on 40 highly myopic eyes to determine whether ATA and STS distance can be accurately estimated by measuring the external WTW distance. As a result, they found a statistically significant but weak correlation between WTW and ATA distance ($r^2 = 0.59$), and between WTW and STS ($r^2 = 0.32$) (Reinstein et al., 2009). Furthermore, they found that there would be a 38% chance of making an error greater than 0.5 mm in lens sizing if WTW distance was used to estimate sulcus diameter. Reinstein et al. claim that the arc-scanner can be used to directly and accurately measure sulcus and angle diameters so the conventional method of estimating these values from WTW measurements should eventually be replaced. However, the debate on whether the direct measurement of internal ocular metrics is absolutely necessary for successful postoperative outcome remains unsettled.

In 2013, Reinstein et al. performed a study on 50 myopic eyes that underwent ICL implantation based on STS diameter-derived lens size. WTW-based size calculation was simultaneously performed to compare how well each measurement would predict post-implantation vault height. After implantation, the actual postoperative vault height was measured by the Artemis arc-scanner. WTW distance was incorporated into a formula that calculated the theoretical vault height had the lens size been based on the WTW-based formula. In comparing the outcomes, they found that 2% of eyes with STS distance-based lens calculation had mean vault < 0.09 mm which indicates low vaulting that increases risk of cataract formation (Reinstein et al., 2013). On the other hand, according to the vault height prediction for WTW distance-based calculation, 26% of eyes would have had mean vault < 0.09 mm. They also found that if the lens sizing had been calculated using WTW distance, 60% of eyes would have received the same lens size while 34% would have received a smaller lens and 6% would have received a larger lens. From these findings, Reinstein et al. concluded that a sulcus diameter-based formula had stronger predicting power of postoperative vault height compared to a traditional WTW-based calculation.

In 2016, Guber et al. assessed interdevice variability between WTW and STS diameter measurements in 107 eyes that were assessed for ICL implantation. While they found that WTW values were significantly wider than STS values ($p < 0.01$), they found a generally good agreement between them. However, they do seem to agree with the rest of the studies in the literature by concluding that surgeons should account for inconsistencies between these measurements and the devices used to measure them (Guber et al., 2016). After evaluating the results of their study in addition to those available in the literature, Guber et al. created a device conversion table that can be used with the recommendations provided by STAAR® given in Table 3 (**Table 5**). The estimated bias correction given in the table accounts for the variability between the Orbscan and other devices used to measure WTW distance.



Device	Bias estimates (Reference)	Sample size	Suggested bias correction
Ultrasound biomicroscopy			
Artemis (50 MHz)	-0.89(2) -0.58(35)	 50	-0.74
HiScan (35 MHz)	-0.39(24) -0.71(17) -0.42(16)	31 20 28	-0.48
Vumax (35 MHz)	0.46(18)	37	0.46
Quantel medical (50 MHz)	0.14(34)	63	0.14
Humphrey 840 (50 MHz)	*0.46(13, 36, 37)*	*(100,10,72)*	*0.46*
Carl Zeiss 835 (50 MHz)	0.40(22)	129	0.40
Scheimpflug image			
Pentacam	*0.43(Guber)*	*117*	*0.43*
Iris camera			
Pentacam	0.1(38)	101	0.1
Galilei	0.34(39)	74	0.34
Eyesys	0.42(39)	74	0.42
Eyemetrics	0.18(40)	73	0.18
IOLMaster	0.50(41) 0.24(36) 0.47(18) 0.22(42) 0.33(43)	328 100 37 40 52	0.41
Biograph/Lenstar	0.48(37) *0.69(Guber)*	72 *117*	0.57
Manual			
Calipers	0.11(36) 0.01(37)	100 72	0.07
Holladay-Godwin gauge	0.02(36)	100	0.02

Table 5. Inter-device conversion of WTW distance. This table provides a suggested bias correction for WTW distance measured by various clinical devices, based on the original nomogram (**Table 3**) that is developed on Orbscan measures. For example, if one acquires a WTW distance of 12.00 mm with the IOLMaster, the value can be corrected by subtracting 0.41 mm, resulting in 11.59 mm as the value to be used to calculate lens size. They claim that this correction accounts for inter-device bias and therefore results in better agreement with the recommended sizes provided by STAAR® Surgical. (Numbers in parentheses in the second column indicate the references to the original studies. See Guber et al., 2016 for those references.)

While the ongoing debate about whether the WTW distance is sufficient to accurately calculate ICL size has yet to be settled, studies attempting to determine the best predictor of postoperative success continue to arise. In 2019, Igarashi et al. conducted a study on 44 eyes that underwent ICL implantation to determine whether angle-to-angle (ATA) and WTW measurements can predict postoperative vaulting. They found that there was a significant correlation between postoperative vault and ATA distance but the same did not apply for WTW distance (Igarashi et al., 2019). Therefore, they concluded that ATA distance was a better predictor of postoperative vault.

There are a few unsettled matters related to WTW distance in the literature. First, while technology is constantly evolving and instruments that measure WTW distance are improving in accuracy, there is not yet a gold standard for WTW measurement. Some studies found a significant discrepancy in repeatability among devices, while some have found that these differences are not considered significant in a clinical setting. Second, it is uncertain whether claims that dismiss WTW distance as an inadequate tool for accurate pIOL sizing are significant enough to replace it with internal ocular biometry such as STS or ATA. Measuring STS or ATA with UBM technology requires manual input of where to measure the diameter and therefore is subject to interrater variability. While proponents of the ArcScan claim that its more automated method can increase interrater reliability, it may be difficult to convince surgeons to purchase this expensive equipment when clinically significant vault outliers are rare in reality. Finally, the utility of WTW distance as a predictor of myopia has yet to be discovered with any conclusive data and should be further investigated. More studies and data must be gathered for these debates to be settled in the future.

Correlation with Degree of Myopia

It is evident that WTW distance is highly utilized as an integral part of IOL power calculation and ICL sizing. However, the utility of WTW distance in predicting myopia is still inconclusive and there is not enough data in the current literature to draw any conclusions. This brings into question whether there is a correlation between WTW distance and degree of myopia. If there were a strong correlation between the two, perhaps WTW distance can be used as a metric that has the power to predict myopia. After investigating the distribution of WTW distance in 39,986 Chinese cataractous eyes, Wei et al. reported that the largest WTW values were found in moderately myopic (24.5 mm < AL < 26 mm) eyes, while not among highly (26 mm < AL < 28 mm) or extremely myopic (AL > 28 mm) eyes (Wei et al., 2021).

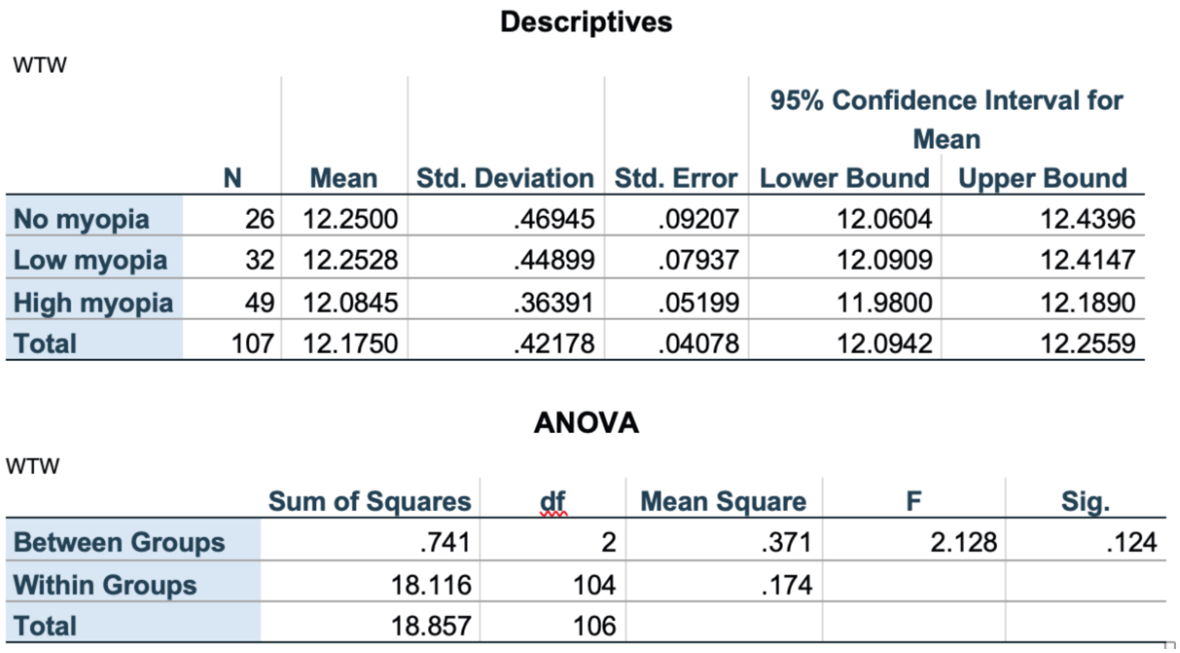
In light of these findings, a preliminary data analysis of WTW distance measurements to investigate whether there is a correlation between WTW distance and degree of myopia was performed. Using the large database of patients at Boston Vision, WTW distance values from the Lenstar were obtained. Most of the measurements were acquired from patients who were evaluated for ICL surgery at the clinic. Through random selection, patients were sorted into 3 age-matched groups – no myopia (-1.00 < SE < +1.00), low myopia (-6.00 < SE < -1.00), and high myopia (SE < -6.00), where SE stands for spherical equivalent.

The spherical equivalent (SE) values were calculated from the patients' manifest refraction using the following formula:

$$SE = Sph + (Cyl * 0.5),$$

where Sph and Cyl stand for the spherical and cylindrical powers of the patients' prescription, respectively. The aim was to collect a sample size of 30 eyes per group and the result of sample collection was the following: no myopia (N = 26), low myopia (N = 32), and high myopia (N = 49). After gathering the SE data, WTW measurements were acquired from the Lenstar database and an analysis of variance (one-way ANOVA) with Bonferroni correction of the 3 groups was performed.

The ANOVA results indicated that there was no significant difference (p > 0.05) in the mean WTW distance among the 3 groups (**Table 6**). Furthermore, the pairwise p-test with Bonferroni correction confirmed that there was no significant difference in mean WTW distance between any combination of 2 out of the 3 groups (**Table 7**). As a preliminary finding, it can be concluded that there is no strong correlation between WTW distance and degree of myopia. For more significant results, the study should be repeated with increased sample size and improved randomization of subjects. It may also be interesting to evaluate this correlation among Asian eyes since it has been found that there is a greater prevalence of high myopia but small anterior segment in East Asian eyes (Morgan et al., 2012). This anatomical disparity is a source of complications such as opaque bubble layer (OBL) and inaccurate vault sizing in LASIK and ICL, respectively. If the relationship between WTW distance and degree of myopia in Asian eyes can be established, it can potentially serve as a valuable predictive tool that can be utilized to prevent these complications.



Descriptives

WTW

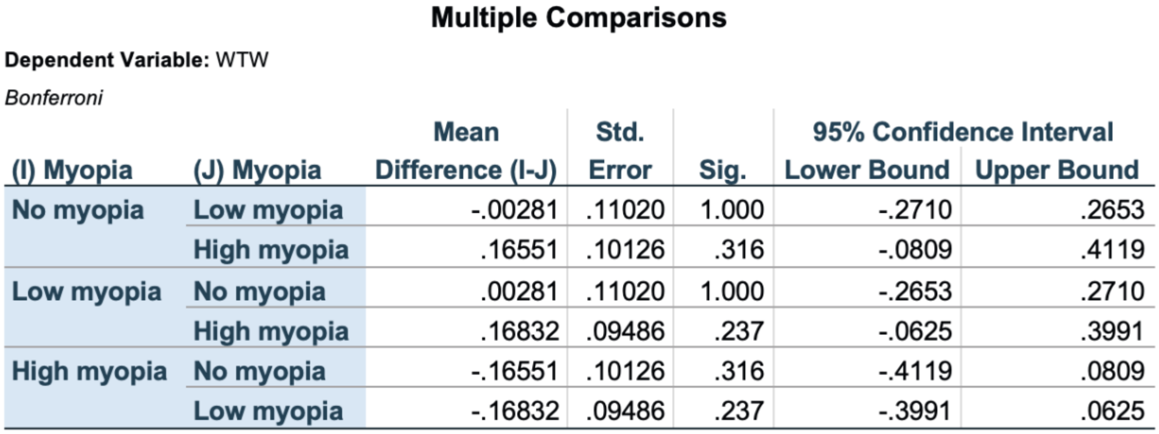
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
No myopia	26	12.2500	.46945	.09207	12.0604	12.4396
Low myopia	32	12.2528	.44899	.07937	12.0909	12.4147
High myopia	49	12.0845	.36391	.05199	11.9800	12.1890
Total	107	12.1750	.42178	.04078	12.0942	12.2559

ANOVA

WTW

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.741	2	.371	2.128	.124
Within Groups	18.116	104	.174		
Total	18.857	106			

Table 6. One-way ANOVA of mean WTW distance among 3 groups. The mean WTW distance for each group was calculated and analyzed for presence of statistically difference among the no myopia, low myopia, and high myopia groups. The p value at 0.124 reveals that there was no significant difference. (Note: significance at $p < 0.05$)



Multiple Comparisons

Dependent Variable: WTW

Bonferroni

(I) Myopia	(J) Myopia	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
No myopia	Low myopia	-.00281	.11020	1.000	-.2710	.2653
	High myopia	.16551	.10126	.316	-.0809	.4119
Low myopia	No myopia	.00281	.11020	1.000	-.2653	.2710
	High myopia	.16832	.09486	.237	-.0625	.3991
High myopia	No myopia	-.16551	.10126	.316	-.4119	.0809
	Low myopia	-.16832	.09486	.237	-.3991	.0625

Table 7. Pairwise p-test with Bonferroni correction for pairs of the 3 groups. The high p values for each combination of pairs of the 3 groups confirm that there was no significant difference in mean WTW distance among the no myopia, low myopia, and high myopia groups. No myopia to low myopia: $p = 1.000$, no myopia to high myopia: $p = 0.316$, low myopia to high myopia: $p = 0.237$ (Note: significance at $p < 0.05$)

Another finding that Wei et al. discovered in their WTW measurement of 39,986 eyes was that WTW distance was significantly smaller in female eyes than in male eyes ($p < 0.001$). I was able to repeat these findings with the data that I gathered. The mean WTW distance for female eyes ($N = 59$) and male eyes ($N = 48$) were 12.03 mm and 12.35 mm, respectively. Performing an independent samples t-test with Levene’s test for equality of variances on the 2 groups revealed that the difference in mean was significant ($p < 0.001$). The results of the statistical analysis can be found in Table 8. Though these findings are far from conclusive, it provides a preliminary basis of how WTW distance may correlate with different ocular biometry.

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
WTW (mm)	Female	59	12.0295	.40692	.05298
	Male	48	12.3540	.37094	.05354

Independent Samples Test

		Levene's Test for Equality of Variances		*t-test for Equality of Means*					*95% Confidence Interval of the Difference*	
		F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**Std. Error Difference**	**Lower**	**Upper**
WTW	**Equal variances assumed**	.304	.583	-4.267	105	0.000	-.32447	.07604	-.47525	-.17368
	Equal variances not assumed			-4.308	103.6	0.000	-.32447	.07532	-.47384	-.17510

Table 8. Independent samples t-test summary. Shown in this table are the descriptive statistics of the 2 groups and the results of an independent samples t-test with Levene’s test for equality of variance. Analysis indicated a significant difference ($p < 0.001$) between the mean WTW distance in females ($N = 59$) and that in males ($N = 48$).

DISCUSSION AND CONCLUSION

In the past, white-to-white distance was widely used as a diagnostic tool for ocular disorders such as congenital glaucoma, microcornea, and megalocornea. Today, WTW distance has been proven to be important for successful postoperative outcomes in refractive cataract and ICL surgeries. Its practical implications have become apparent through identifying its use in calculating the refractive power in IOLs for cataract surgery and the size of pIOLs in ICL surgery. However, a few questions still remain unanswered. What is the most accurate way to measure WTW distance? Is WTW distance a suitable tool for estimating internal ocular biometry such as STS and ATA diameters? How accurate is using a WTW-based formula for ICL sizing and how significant are the postoperative complications that arise due to its use? If STS and ATA measurements provide a more accurate calculation for ICL sizing, what is the best way to measure them – UBM or arc-scanning technology? These are some of the unsettled topics of debate in the current literature that need to be taken into consideration when using WTW distance for surgical planning to ensure the best possible postoperative outcome for patients.

In this thesis, a comprehensive analysis of the most commonly utilized methods of WTW measurement in the clinical setting today was performed. This included the Orbscan II, Pentacam, Galiei, IOLMaster, and Lenstar for digital imaging systems and the manual caliper which still appears to be a preferred method in many practices. In general, there seems to be good agreement among the instruments, but there have been varying findings by different studies in the literature. As new instruments continue to be developed, it is important for clinicians to determine whether the claimed advantages of the new technology provide a significant enough benefit to replace existing ones.

The utility of WTW distance in IOL power calculation appears to stir up the least amount of controversy. Its role in calculating the refractive power of IOLs for cataract surgery has been deeply established in the literature. Due to the pseudophakic implantation of IOLs, WTW plays a greater part in calculating the refractive power and is less important for lens sizing. An error in refractive power can later be adjusted through glasses or light adjustable treatment, which is a newer technology that allows correction of refractive error with a light delivery device after the lens is implanted in the eye (Schwartz, 2003).

The greatest amount of disagreement in the literature arises from the role of WTW distance in ICL sizing. Unlike IOL implantation for cataract surgery, ICL implantation is phakic, requiring accurate sizing of the lens to prevent postoperative complications. Previous studies clearly agree on the importance of ICL size in preventing complications that may arise from sub-optimal vaulting, such as premature cataract formation, EC loss, angle closure, and elevated IOP. However, whether other internal ocular measures such as sulcus or angle diameter are required to improve accuracy of size calculation remains ambiguous. The difficulty in accurately defining the corneo-limbal border when measuring WTW distance provides reasoning for those that argue against relying solely on WTW measurements to calculate lens size.

The study conducted by Reinstein et al. in 2013 reported that sulcus diameter had stronger predicting power of postoperative vault height compared to the traditional WTW distance. At first glance, the results of this study seem to provide evidence for the superiority of sulcus diameter to WTW distance in accurate ICL sizing. However, it is important to recognize that the study did not compare actual postoperative outcomes in eyes that underwent ICL surgery with lenses calculated based on *both* sulcus diameter and WTW distance. While the subjects of the study underwent ICL implantation with lenses calculated based on sulcus-diameter, there were no subjects that received lenses calculated based on WTW distance. The results for the predicting power of WTW distance were predictions based on a mathematical formula that calculated the theoretical vault height that would have occurred had the lens size been obtained by the WTW-based formula. The findings from this study should be confirmed by additional studies that compares the actual outcomes of eyes that undergo ICL surgery with lenses calculated by either STS-based or WTW-based formulas. Such a study may be difficult to implement due to confounding variables but could be achievable if all other variables and conditions are matched as much as possible.

In addition to this caveat and the small sample size in Reinstein et al.'s study, other studies with contradicting findings provide reason to be wary of jumping to conclusions. For example, Zhang et al. found that the majority

(64.9%) of the eyes that they evaluated obtained ideal vault post-implantation despite having used the standard method for ICL sizing (adding 0.5 mm to WTW when 2.8 mm < ACD < 3.5 mm and 1.0 mm when ACD > 3.5 mm). While they did report varying positions of the lens haptics, few of these resulted in sub-optimal vault height that could result in unfavorable complications. Together, the results from these studies introduce the question of whether it is cost effective and clinically relevant to endure the process of replacing the standard ICL sizing method if the final results are not significantly different. It would be important for the surgeons to use their discretion in weighing the accuracy versus efficiency of deviating from long-established protocol to ensure the best outcome for patients.

Technology is constantly evolving and striving to improve the efficacy of these procedures. The latest generation ICL is the Visian ICL V4c that has a central hole for better aqueous humor flow between the ICL and the eye’s natural lens (Alfonso et al., 2013). Clinical studies have proven the efficacy, predictability, and safety, including stable postoperative IOP without a preoperative iridotomy which is required for the previous model (Packer, 2018; Tian et al., 2017). In 2017, Nam et al. evaluated 43 eyes implanted with V4c ICLs to investigate the effect of calculating size based on STS diameter. They found that despite some discrepancies between actual ICL size and STS, postoperative vault did not differ significantly and concluded that there is a buffering zone in sizing of V4c ICLs (Nam et al., 2017). In order to assess whether the same applies for WTW-based calculation of V4c ICL sizing, more studies using WTW distance for the new model should be performed. Furthermore, Shen et al. recently applied big data and artificial intelligence (AI) analytics to predict postoperative vault and ICL size in 6,297 eyes that underwent ICL implantation. Comparing vault values measured by Pentacam to those predicted via regression models revealed significant accuracy of applying AI for vault prediction (Shen et al., 2021). From their results, Shen et al. concluded that AI technology has the potential to assist surgeons in ensuring safety by improving surgical strategies and predicting clinical outcomes.

Developing technology and constant improvement of ICL models seem to offer ways to improve the clinical outcomes of surgery without having to weigh in the debate of whether WTW or STS should be used for accurate sizing. If there were a way to utilize ultrasound technology to visualize the posterior chamber during ICL implantation, complications related to faulty haptic position and consequent sub-optimal vault could be improved. Nonetheless, additional studies that produce more repeatable findings are required to settle the debate in the current literature regarding the validity of using WTW distance for ICL sizing. A study that directly compares the outcomes of ICL implantation with lenses calculated with WTW-based versus STS-based formulas should be performed to determine whether traditional methods should indeed be replaced. If attainable, the most accurate study would be a paired eye study where one eye receives a WTW-based ICL and the other a STS or UBM-based ICL and compare the postoperative outcomes. In either case, collecting a large postoperative data set would be necessary for producing results that will help improve clinical outcomes.

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