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CLINICAL STUDY

# Correlational study of central corneal thickness measurements on Hong Kong Chinese using optical coherence tomography, Orbscan and ultrasound pachymetry

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## Abstract

*Background* **Central corneal thickness (CCT) of 74 eyes from 39 normal Hong Kong Chinese subjects with ages ranging from 39 to 86 years were studied.**
*Aim & Purpose* **To compare the measurements of different devices and to compare the results of ethnic groups in other studies.**
*Methods* **Non-contact measurements by Orbscan and Optical Coherence Tomography (OCT) were first carried out, followed by contact measurement using Ultrasound Pachymetry. The results of five measurements of Ultrasound Pachymetry and three measurements of OCT and Orbscan were each averaged and compared using correlation, linear regression and one-way analysis of variance methods.**
*Results* **The measurements of three devices were significantly correlated ($P < 0.01$). The mean CCT in our study group measured by Orbscan (with an acoustic factor set at 0.92), Ultrasound Pachymetry and OCT were $555.96 \pm 32.41$, $555.11 \pm 35.30$ and $523.2 \pm 33.54$ $\mu$m respectively. A linear regression model (using ultrasound measurements as standard) was presented.**
*Conclusions* **When a correction factor of 32 $\mu$m was applied to OCT measurements, the means of three devices became significantly equal. The adjusted OCT measurements were less precise within subjects but more accurate than Orbscan when compared with ultrasound pachymetry as a reference standard. The mean CCT measurement of our sample was comparable to some studies on Hong Kong Chinese, Caucasians and Japanese but higher than those on some Europeans, Asian and North Americans of African origin.**

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*Keywords:* central corneal thickness; Orbscan; ultrasound pachymetry; optical coherence tomography; Chinese

## Introduction

Central Corneal Thickness (CCT) can affect the measurement of applanation tonometry. It also affects the decision to perform some keratorefractive surgical procedures. Various methods have been used in past studies to measure central corneal thickness. They include Optical Pachymetry,[1] Ultrasound Pachymetry,[1] Orbscan,[1,2] Optical Coherence Tomography (OCT),[3,4] Laser Interferometry[5] and Ultrasound Biomicrocscopy.[6] Ultrasound Pachymetry is considered to be the standard of measuring central corneal thickness. The advantage is that it is fast and very convenient to repeat several measurements to minimize measurement error. It can also be

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used to measure peripheral corneal thickness.
Orbscan was considered the second most popular device to measure corneal thickness. It is a non-contact method and can give additional information on the peripheral corneal thickness, anterior and posterior curvature of the cornea. It is also a very useful machine for preliminary measurements before performing some refractive procedures such as astigmatic keratectomy, corneal graft, laser in-situ keratomileusis, intrastromal corneal rings and phototherapeutic keratoplasty.

Some studies have been conducted to compare different devices. CCT measured by Marsich MW[1] *et al* using optical pachymetry, ultrasound pachymetry and Orbscan were found to be 539 ± 33 $\mu$m, 542 ± 33 $\mu$m and 596 ± 40 $\mu$m respectively. The study showed that the Orbscan system was the most repeatable technique for measuring corneal thickness but showed a significant bias towards greater corneal thickness measurement than both ultrasound and optical pachymetry. Liu *et al*[2] also found that the central cornea had the lowest average thickness (0.56 ± 0.03 mm) and the superior cornea had the greatest average thickness (0.64 ± 0.03 mm). Bechmann[3] used Retinal Optical Coherence Tomography (OCT) to measure CCT (530 ± 32 $\mu$m) and found that the measurements were significantly correlated with the Ultrasound Pachymetry results (581 ± 34 $\mu$m).[3]

In our study, we measured the central corneal thickness of normal Hong Kong Chinese subjects using three devices: Orbscan vers 3.10.31 (Orbtek Inc, Salt Lake City, UT, USA), Ultrasound Pachymetry DGH-1000 (DGH Technology Inc, Exton, PA, USA) and Optical Coherence Tomography (Humphrey Instruments, Carl Zeiss, Dublin, CA, USA). The purpose of this study was to compare the measurements of these three devices. The results of this study were analysed and compared with other studies especially on the results of OCT and measurements in other ethnic groups.

## Materials and methods

Central corneal thickness (CCT) measurements of 74 eyes (36 right eyes and 38 left eyes) from 39 Hong Kong Chinese subjects (17 males and 22 females) were studied. The subjects, with informed consent, were recruited at our clinics with the inclusion criteria of having no ocular abnormality, contact lens wear or ocular surgery and refractive errors less than or equal to −6.0 D. Subject age ranged from 39 to 86 years with a mean age of 65.5 ± 11.8 years. Non-contact central corneal thickness measurements by Orbscan ($CCT_{ORB}$) and Optical Coherence Tomography ($CCT_{OCT}$) were first carried out, followed by contact measurement using Ultrasound Pachymetry ($CCT_{PACH}$). As ultrasound measurements were treated as a reference standard, the results of five measurements of $CCT_{PACH}$ and three measurements of $CCT_{OCT}$ and $CCT_{ORB}$ were each averaged to minimise measurement error.

### *Instruments*

The Orbscan Corneal Topography system measures anterior and posterior corneal surface curvature as well as corneal thickness with a scanning optical slit device. The optical acquisition head scans the eye using light slits that are projected at a 45-degree angle. Twenty slits are projected sequentially on the eye from the left and 20 slits from the right side for a total of 40 slits. The instrument software analyses up to 240 data points per slit and calculates the elevation of the anterior and posterior surface of the cornea relative to a best-fit sphere. Pachymetry is determined by the difference in elevation between the anterior and posterior surface of the cornea with the readings averaged in a 2 mm diameter circle in the centre of cornea and in eight 2 mm diameter circles located 3 mm from the visual axis in the mid-peripheral cornea.[2,7] Our Orbscan version 3.10.31 is an experimental version and the basic software is the same as Orbscan II. The software measures corneal thickness by calculating the orthogonal distance between the anterior and posterior corneal surface tangents, ie, in the direction perpendicular to the anterior surface. Central corneal thickness was measured by calculating the points within the central 2 mm zone. Our version has the acoustic factor already set at 0.92 as shipped from the factory.

Optical coherence tomography is a relatively new method for high axial resolution (10–14 $\mu$m) cross-sectional imaging of the retina that directly measures changes in the $z$-plane (depth of the retina).[8] It uses light to detect relative changes in reflection at optical interfaces by use of the method of low-coherence interferometer. A super-luminescence diode is used as a low coherence light source, emitting light with a 20- to 25-nm bandwidth centred at 830 nm. Some studies extended the use of OCT to examine cornea and anterior segment.[4] Bechmann[3] *et al* used the retinal OCT device to measure central corneal thickness. Similarly in our study, we used the same device to conduct single line measurements on CCT, with the minimum scan length of 1.13 mm. The high detection sensitivity was used to measure the distance between the optical signals with the highest reflectivity at the anterior and posterior corneal tissue boundaries.[9] Three measurements between the most outer spike and inner spike of scan profile were recorded and averaged.

DGH-1000 Ultrasound Pachymetry had been used in a previous study.[10] After topical anaesthesia with novesin (0.4% benoxinate hydrochloride), an average of five contact measurements was made with the probe perpendicular to the cornea as similar to a previous study.[10] The ultrasonic A-scan velocity was set at 1640 m/s for all measurements. In our study, these contact measurements were recorded after performing non-contact examinations using Orbscan and OCT.

Statistical data analysis was carried out using SPSS for windows, version 10.0 (SPSS Inc). Measurements of cornea thickness with optical coherence tomography, ultrasound pachymetry and Orbscan were analysed using regression and correlation methods. Their means were compared using Analysis of Variance (ANOVA). Bonferroni and Tukey's Honestly Significant Difference (HSD) tests were used for pairwise comparisons on the difference between the measurements by three devices.

## Results

### *Intra-subject comparison*

With regards to the intra-subject variability (ie precision or measurement error) of the three instruments under study, 10 measurements in each of 10 eyes were performed. The variance in each individual was calculated and the mean variances of Orbscan, OCT and ultrasound were 21.04, 22.06 and 21.06 (mean standard deviation were 4.33, 4.91, 4.40 $\mu$m) respectively. Orbscan has the highest precision in the intra-subject measurements when compared with OCT and ultrasound pachymetry.

### *Inter-subject comparison of three different devices*

Normality tests on the data by the three devices showed that they all follow the normal distribution at a significance level of 0.05. Figure 1 shows a histogram of data gathered using ultrasound pachymetry.

Figure 2 (Box and whisker plots) shows that the data distributions of CCT were similar for different devices. The means and standard deviations of CCT measurements using Orbscan, ultrasound pachymetry and OCT were 555.96 ± 32.41 $\mu$m (range 608.3–474 $\mu$m), 555.11 ± 35.30 $\mu$m (range 633.8 –491.8 $\mu$m) and 523.21 ± 33.54 $\mu$m (range 601–455 $\mu$m) respectively. The ratio of inter-subject to intra-subject standard deviation of Orbscan, ultrasound pachymetry and OCT were 7.5:1, 7.1:1 and 6.8:1 respectively. The mean difference between ultrasound pachymetry and Orbscan was 0.85 (95% CI ± 18.94) while the difference between

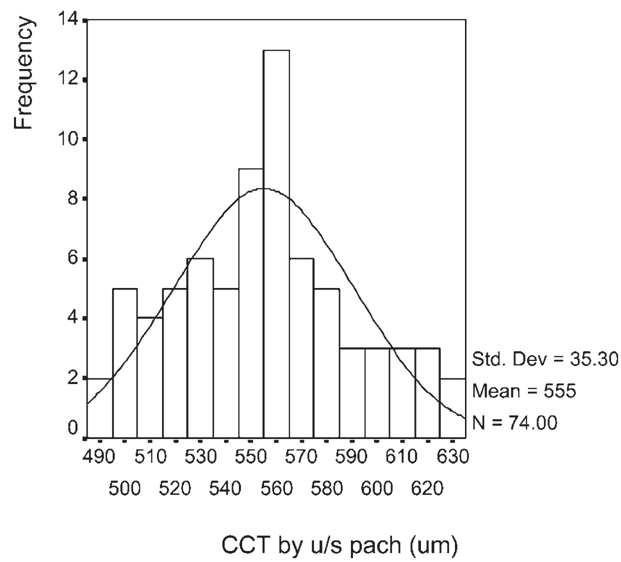


**Figure 1** Histogram of ultrasound pachymetry measurements.

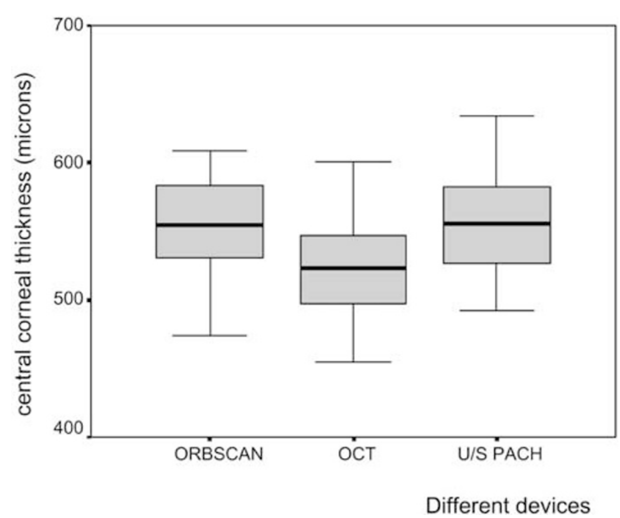


**Figure 2** Boxplot of central corneal thickness ($\mu$m) in relation to three different devices: Orbscan, optical coherence tomography and ultrasound pachymetry (No. of samples = 74).

ultrasound pachymetry and OCT was 31.9 (95% CI ± 11.59).

$CCT_{PACH}$ was found to be highly correlated with $CCT_{OCT}$ ($r = 0.945$, $P < 0.01$) and $CCT_{ORB}$ ($r = 0.835$, $P < 0.01$). Since most studies use ultrasound pachymetry as standard instrument, the results were treated as 'true' values and the relationships between instruments were evaluated using linear regression analysis (Figure 3). The respective slopes of regression lines of Orbscan and OCT were 0.808 and 0.897, and were found to be not significantly different from each other ($P > 0.05$). The results of the analysis can be represented by:

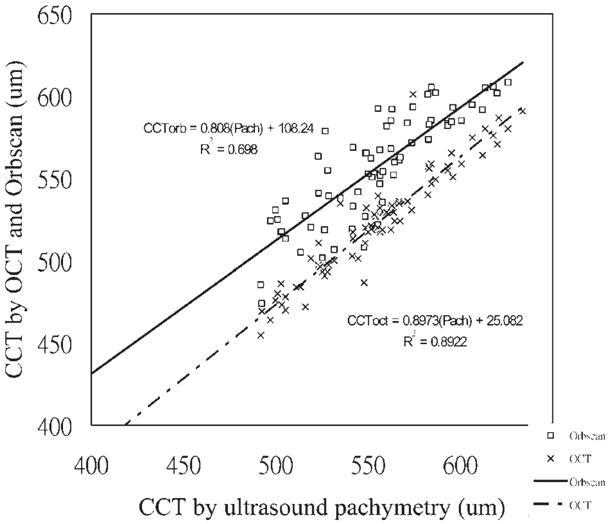


**Figure 3** Linear regression of OCT and Orbscan against ultrasound pachymetry measurements ($P < 0.01$).

$CCT_{ORB} = 0.808(CCT_{PACH}) + 108.24$ and $CCT_{OCT} = 0.897(CCT_{PACH}) + 25.082$

*Orbscan and OCT* $CCT_{ORB}$ and $CCT_{OCT}$ were analysed in a similar way and were highly correlated with each other ($r = 0.845$) ($P < 0.01$). The mean of $CCT_{OCT}$ was found to be lower than $CCT_{ORB}$ and $CCT_{PACH}$ with the mean differences 32.75 and 31.9 $\mu$m respectively. Using linear regression analysis, the correlation can be seen as follows ($P < 0.01$):

$CCT_{ORB} = 0.8523(CCT_{OCT}) + 110.83$ and $CCT_{OCT} = 0.8373(CCT_{ORB}) + 56.767$

To test if all means were significantly equal, one way Analysis of Variance (ANOVA) was used. The measurements were tested in pairs. Results showed that the $CCT_{OCT}$ measurement was different from $CCT_{ORB}$ and $CCT_{PACH}$ while the latter two were significantly equal at the significance level of 0.05. Pairwise comparisons on the differences between the three gave similar results using Tukey HSD and Bonferroni correction.

### *Analysis after adjustment of OCT*

When the data of OCT were adjusted by a correction factor of 32 $\mu$m (about the mean measurement difference between ultrasound pachymetry and OCT) and analysed again using ANOVA, the mean of adjusted $CCT_{OCT}$ was found to be significantly equal to $CCT_{ORB}$ and $CCT_{PACH}$ at a significance level of 0.05. The mean difference between $CCT_{PACH}$ and adjusted $CCT_{OCT}$ was –0.1 $\mu$m (with 95% CI $\pm$ 11.59). With a smaller confidence interval of mean difference, the adjusted $CCT_{OCT}$ was more accurate than $CCT_{ORB}$ (with 95% CI $\pm$ 18.94). Using the regression model, the relationship of ultrasound and OCT measurements can be represented by $CCT_{PACH} = 0.9973(CCT_{OCT} + 32) + 2.9227$.

### *Analysis of the relationship between CCT with age, gender and left/right eyes*

*Ultrasound pachymetry* Mean CCT measurements using ultrasound pachymetry were 554.0 $\pm$ 32.5 and 560 $\pm$ 34.6 $\mu$m in male and female subjects respectively. Mean CCT measurements were 558.2 $\pm$ 35.4 and 555.6 $\pm$ 33.41 $\mu$m in right and left eyes respectively. Associations of CCT using ultrasound pachymetry with other factors such as age, gender and left/right eyes were tested with the regression model. Gender and left/right eyes were found to have no correlation while age showed negative correlation ($r = –2.37$, $P < 0.05$) with $CCT_{PACH}$.

*Orbscan and OCT* Age, gender and left/right eyes were not correlated with CCT measurements using the other two methods ($CCT_{ORB}$ and $CCT_{PACH}$).

## Discussion

While Yaylali[11] and Marisch[1] showed that Orbscan consistently provided measurements greater than ultrasonic pachymetry with the difference of 28 and 54 $\mu$m respectively, our study showed a difference of only 0.85 $\mu$m. This may be due to an acoustic factor set at 0.92 on our device (all Orbscan pachymetry readings were automatically multiplied by a factor of 0.92). Thus our Orbscan measurements were more comparable to ultrasound results. With its advantage of having the best repeatability compared with ultrasound pachymetry and optical pachymetry,[1] Orbscan pachymetry can be a good alternative in measuring central corneal thickness. However, performing Orbscan may not be suitable in certain circumstances. In our experience, patients with small palpebral fissure, unsteady eye gaze, frequent blinking, squeezing, poor tear films and excessive tearing can pose difficulties in obtaining good measurements.

The mean CCT measurement using the optical coherence tomography device in our group was 31.9 $\mu$m lower than ultrasound pachymetry, compared with the mean difference of 49.4 $\pm$ 5.9 $\mu$m in the study by Bechmann. Wirbelauer[9] also found a mean difference of 24 $\mu$m between these two devices in his high myopic group. That means the ultrasound measurements of corneal thickness were on average higher than optical coherence tomography values. The mean differences can be 24–49 $\mu$m in different sample groups using different scan lengths, and the mean difference in our group was within this range (31.9 $\mu$m). Differences of refractive indexes in retina and cornea and possibly higher measurement by DGH ultrasound pachymetry were considered,[3,10] but none of them could satisfactorily explain such a discrepancy.

In our sample the OCT device could be considered as a non-contact, non-invasive alternative to measure the central corneal thickness, provided that a correction factor is applied. At present not many studies were conducted using the OCT device to measure corneal thickness. Also, there is no standardized way to measure CCT by OCT. Take the scan length for example, some studies use 3 mm scan length while others use 1 mm. We adopted the minimum scan length that can be reached on our device, ie, 1.13 mm. This may minimise measurement error by obtaining a better and maximal magnification of the corneal image. However, performing OCT with a scan length of 1.13 mm is quite skill demanding and time consuming. It needs an experienced operator and cooperative patients to get good results.

Precision of OCT (mean variance of 22.06) was lower than Orbscan (mean variance of 21.04). However, the measurement error can be reduced by taking three measures and the averaged value of OCT has a higher coefficient of determination ($r^2 = 0.89$) than Orbscan ($r^2 = 0.70$) when compared with ultrasound as a standard. The results of CCT measured by our method were comparable to other studies[3,12] (Table 1). The OCT device has the added advantage of providing qualitative assessment of corneal layers. It is most suited to measure and assess the cornea of very localized lesions and is particularly useful in documenting diseases like corneal scars, corneal ulcers and even minute intra-corneal foreign bodies. It has been used to assess corneal cap and stromal bed after laser in situ keratomileusis.[12] So, further studies can be considered by comparing normal corneas with those that are affected by pathological diseases.

When comparing with other ethnic groups in some studies, ultrasound pachymetry measurements ($555 \pm 35$ $\mu$m) in our sample were comparable to the Caucasian group measured by La Rosa *et al*.[15] Orbscan measurements ($556 \pm 32$ $\mu$m) were comparable to the subjects recruited in the study by Liu Z *et al*.[2] OCT measurements ($523 \pm 34$ $\mu$m) were comparable to Bechmann *et al*,[3] but when compared with some African Americans,[15] Black Canadians,[16] Danish[18] and Dutch,[19] our sample was found to be higher (Table 2).

Compared with studies on other Asians using different devices (Table 3), CCT measurements in our study group were higher than some Indians,[20] Asian Canadians[16] and some myopes in Korea[21] but were comparable to Japanese[22] and Hong Kong Chinese[23] in other studies.

Previous studies have attempted to compare CCT measurements between Asians and Westerners. Cho[23] found that CCT measurements from Hong Kong Chinese were significantly higher than those from Caucasians. This finding was different from Dohadwala[16] whose measurements showed that Asians had the lowest CCT on average among the Canadians. Foster[25] compared his results by optical pachymetry with Wolfs[19] by ultrasound pachymetry and found that Mongolians had lower CCT measurements. Similar results were found in Singaporeans.[26] Zhang[27] found that Northern Chinese ($515 \pm 4$ $\mu$m) were comparable to Japanese ($518 \pm 20$ $\mu$m). Our measurements were comparable to some Caucasians in other studies.[1,9,10,11,15,18]

It seems that the CCT measurements could be quite different in various localities even within an Asian region. One possible reason is that different devices are used for measuring. CCT measurements using optical pachymetry were generally lower in previous studies

**Table 1** Summary of various studies on central corneal thickness (CCT) measurements using optical coherence tomography (OCT)

| *Authors* | *Year* | *Location* | *No. of subjects (no. of eyes)* | *Age (range or mean ± SD)* | *Scan length* | *CCT using OCT (μm) (mean ± SD)* | *Refractive error of sample subjects (mean ± SD)* |
|---|---|---|---|---|---|---|---|
| Present study | 2001 | Hong Kong | 39 (74 eyes) | 65.5 ± 11.8 | 1.13 mm | 523 ± 34 | |
| Bechman M *et al*[3] | 2001 | Germany | 36 (36 eyes | 52.0 ± 19.7 | | 530 ± 32 | |
| Wirbelauer C *et al*[9] | 2000 | Germany | 24 (24 eyes) | 41 ± 14 | 6 mm | 534 ± 36 | –6.7 ± 3.6 D |
| Ustundag C *et al*[12] | 2000 | Turkey | 11 (11 eyes) | 29.4 ± 69 | 1.12–3.8 mm | | |
| Feng Y *et al*[13] | 2000 | Canada | 10 | 26–43 | 1 mm | 498.25 ± 11.81 | |
| Maldonado MJ *et al*[14] | 2000 | Spain | (63 eyes) | | 3 mm | 538.9 ± 26.2 | –9.25 ± 2.24 D |

Table 2 Summary of various studies on CCT measured by different devices (mean ± SD)

| Authors | Year | Location | No. of subjects | Age | Optical (μm) | U/S pachymetry (μm) | Orbscan (μm) | OCT (μm) |
|---|---|---|---|---|---|---|---|---|
| Present study | 2001 | Hong Kong, China | 39 (74 eyes) | 65.5 ± 11.8 | | 555 ± 35 | 556 ± 32 | 523 ± 34 |
| Marsich M et al[1] | 2000 | Ohio, USA | 20 | 33.3 ± 9.0 | 539 ± 33 | 542 ± 33 | 596 ± 40 | |
| Liu Z et al[2,7] | 1999 | Miami, USA | 51 (94 eyes) | 47.32 ± 14.06 | | | 560 ± 30 | |
| | 1999 | Miami, USA | 21 (34 eyes) | 61.2 ± 11.71 | | | 571 ± 28 | |
| Wheeler NC et al[10] | 1992 | California, USA | 18 | 22–57 | | 549 ± 37 | | |
| Yaylali et al[11] | 1997 | Louisiana, USA | 31 (61 eyes) | | | 543.3 ± 7.49 | 571 ± 6.21 | |
| La Rosa FA et al[15] | 2001 | Texas, USA (Caucasian) | 51 | 65.2 ± 10.3 | | R: 555.9 ± 33.2<br>L: 555.7 ± 31.6 | | |
| | | (Afr American) | 26 | 63.1 ± 11.8 | | R: 533 ± 33.9<br>L: 534.1 ± 31.8 | | |
| Dohadwala AA et al[16] | 1998 | (White Canadians) | 227 | | | 552.5 ± 34.7 | | |
| | | (Black Canadians) | 32 | | | 529.7 ± 30 | | |
| | | Asian Canadians) | 24 | | | 532.8 ± 34.3 | | |
| Bechmann M et al[3] | 2001 | Munich, Germany | 36 (36 eyes) | 52.0 ± 19.7 | | 581 ± 34 | | 530 ± 32 |
| Wirbelauer C et al[9] | 2000 | Berlin, Germany | 24 | 41 ± 14 | | 558 ± 44 | | 534 ± 36 |
| Olsen T et al[17] | 1984 | Arhus, Denmark | 115 | 48.9 ± 18.2 | 515 ± 33 | | | |
| Nissen J et al[18] | 1991 | Arthus, Denmark | 68 | 78.9 ± 7.2 | 531 ± 40 | 524 ± 39 | | |
| Wolfs RC et al[19] | 1997 | Amsterdam, Holland | 352 | 72 | | 537.4 ± 1.8 | | |

Table 3 Summary of CCT in Asian sample groups measured by different methods

| Authors | Year | Location | No. of subjects | Age | Method | CCT in Asians (μm) (mean ± SD) | Remarks |
|---|---|---|---|---|---|---|---|
| Present study | 2001 | Hong Kong | 39 (74 eyes) | 65.5 ± 11.8 | U/S pach. | 555 ± 35 | |
| Thomas R et al[20] | 2000 | India | 50 | | U/S pach. | 537 ± 34 | |
| Kang SW et al[21] | 2000 | Korea | 61 (103 eyes) | 28.4 | U/S pach. | 527 ± 30 | –7.09 ± 2.04 D |
| Wu LL et al[22] | 2000 | Japan | 50 | | U/S pach. | 552 ± 36 | |
| Cho P et al[23] | 1999 | Hong Kong | 151 | 28.6 ± 1.3 | U/S pach. | R: 575 ± 32<br>L: 575 ± 31 | |
| Lam AK et al[24] | 1998 | Hong Kong | 240 | 19–65 | U/S pach. | 541.7 ± 28.5–560.8 ± 34.3 | |
| Foster PJ et al[25] | 1998 | Mongolia | (R: 1127 eyes)<br>(L: 1129 eyes) | 10–87 | Optical pach. | R: 495 ± 32<br>L: 514 ± 32 | |
| Foster PJ et al[26] | 2000 | Singapore | 23 | 35–82 | Optical pach. | 529 ± 48 | |
| Zhang SF[27] | 1981 | Beijing | 466 (900 eyes) | 6–73 | Optical pach. | 515 ± 4 | |

(515–539 μm). Wheeler[10] showed that DGH 1000 pachymetry consistently produced values statistically significantly higher than the other models of pachymeters. The limitations of these comparisons are that most studies had small sample sizes. Further studies of larger sample-size with standardisation of devices would be useful for more accurate comparison.

In our study, there was no significant correlation between CCT and sex, regardless of the device that we used. This matches the conclusions in previous studies.[17,18,19,23,27] There was no significant difference between CCT measurements in the right or left eyes, which was also found by Nissen[18] and Wolfs.[19] Furthermore, the negative correlation of CCT using ultrasound pachymetry and age was found in our study and previous studies.[23,24] This finding is also consistent with Olsen[17] ($r = -0.23$, $P < 0.05$), Foster[25] and Alsbirk[28] using optical pachymetry. When we compared CCT measurements using OCT with previous studies, the lack of correlation between $CCT_{OCT}$ with age, sex and left/right eyes in our sample is in agreement with the Bechmann study.[3]

## Conclusion

In conclusion, the measurements of the three devices were significantly correlated ($P < 0.05$). CCT measurements using Orbscan pachymetry with an acoustic factor set at 0.92 were comparable to those using ultrasound pachymetry in our study group. The mean difference was only 0.85 $\mu$m, compared with a high difference of 21–58 $\mu$m seen in other studies. With a correction value of 32 $\mu$m added to the OCT measurements, the mean became significantly equal to the other two devices. The adjusted OCT measurements were less precise within subjects but more accurate than Orbscan measurements when compared with ultrasound measurements as a reference standard. They also have higher correlation value with ultrasound measurements. CCT measurements using ultrasound pachymetry in our group were comparable to some studies on Caucasians and Japanese but higher than those on African Americans, Danish, Dutch, Indians, Koreans, Blacks and Asian Canadians. Also the ultrasound measurements of our sample were higher than measurements by optical pachymetry on Mongolians and Singaporeans. However, further studies having larger sample size and standardization of equipment are recommended for more accurate comparisons.

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