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Validating a New Approach to Quantify Posterior Corneal Curvature in Vivo

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Purpose: Validating a new research method to determine posterior corneal curvature and asphericity(Q) in vivo, based on measurements of anterior corneal topography and corneal thickness. **Methods**: Anterior corneal topographic data, derived from the Medmont E300 corneal topographer, and total corneal thickness data measured along the horizontal corneal meridian using the Holden-Payor optical pachometer, were used to calculate the anterior and posterior corneal apical radii of curvature and Q. To calculate accurate total corneal thickness the local radius of anterior corneal curvature, and an exact solution for the relationship between real and apparent thickness were taken into consideration. This method differs from previous approach.[18,27-30] An elliptical curve for anterior and posterior cornea were calculated by using best fit algorism of the anterior corneal topographic data and derived coordinates of the posterior cornea respectively. For validation of the calculations of the posterior corneal topography, ten polymethyl methacrylate (PMMA) lenses and right eyes of five adult subjects were examined. **Results**: The mean absolute accuracy (±standard deviation(SD)) of calculated posterior apical radius and Q of ten PMMA lenses was 0.053 ± 0.044 mm (95% confidence interval (CI) −0.033 to 0.139), and 0.10 ± 0.10 (95% CI −0.10 to 0.31) respectively. The mean absolute repeatability coefficient (±SD) of the calculated posterior apical radius and Q of five human eyes was 0.07 ± 0.06 mm (95% CI −0.05 to 0.19) and 0.09 ± 0.07 (95% CI −0.05 to 0.23), respectively. **Conclusions**: The result shows that acceptable accuracy in calculations of posterior apical radius and Q was achieved. This new method shows promise for application to the living human cornea.

Key words: Anterior corneal topography, Corneal thickness, Posterior corneal apical radii, Posterior corneal asphericity

INTRODUCTION

Over the last few years, various sophisticated clinical imaging devices have become available, and which claim to be able to measure the parameters of the posterior corneal surface. The device includes instruments based on scanning slit technology such as the Orbscan (Bausch & Lomb Surgical Inc, NY, USA), and instruments that utilize Scheimpflug imaging such as the Pentacam (Oculus Inc, Dutenhofen, Germany) and the Galilei (Ziemer Ophthalmic Systems AG, Switzerland).

Various studies[1-7] have demonstrated that those instruments provide repeatable results when used to characterise parameters of the posterior cornea in normal eyes and following refractive surgery. However, as discussed by Oliviera et al.[8] inter-instrument comparisons of posterior corneal characteristics demonstrate significant differences for normal, post-surgical and keratoconic eyes.[5,9-11] In the absence of a "gold standard" or referent, their result raises concerns about whether these instruments give an accurate or "true" reflection of posterior corneal parameters.

In this paper we describe a "first principles" method for determining posterior corneal curvature and asphericity(Q) in a research setting based on measurements of anterior corneal surface parameters and corneal thickness. The accuracy of this method is determined using test surfaces,

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and the potential for the use of this method in human subjects is also addressed through a small repeatability study. Based on the detailed validation of this method reported here, we suggest that this method may be applicable to studies of changes in posterior corneal parameters in the living human eye.

Several research-based methods have been previously described in the literature for determining posterior corneal curvature in vivo. Lowe and Clark[12] determined the radius of curvature of the posterior cornea using slit-lamp photography with a skew ray-tracing method. Royston et al.[13] introduced a technique for monitoring the shape of the posterior cornea using the first and second Purkinje images with a Zeiss keratometer and a Haag-Streit pachometer. The main drawback of Royston's method was the dimness of the Purkinje images, especially the second Purkinje image. Moreover, in this Purkinje image method, the shape of the anterior and posterior cornea at any meridian was assumed to be a sphere. Another technique used previously to measure posterior corneal curvature is Scheimpflug photography.[14] A potential limitation of this method is the image distortion that occurs as a result of the geometry of the Scheimpflug photography and refraction at the cornea.[14-16]

The slit-lamp photography and Purkinje image methods were only valid for the central region of the cornea because of the assumption of a spherical shape for the anterior and posterior cornea. Both slit-lamp and early Scheimpflug photography methods only allowed the vertical meridian of the cornea to be monitored.[17]

Rivett and Ho[18] proposed another method, which was based on anterior corneal surface topography matched with corneal thickness measurements. Usingthis method, both anterior and posterior corneal shape were described as conic sections. Later, Patel et al.[19] proposed a similar method to that of Rivett and Ho.[18]

Our method described in this paper for calculating posterior apical corneal radius and Q using anterior corneal topography and Holden-Payor optical pachometry is similar to the method proposed previously by Rivett and Ho.[18] However, in this new approach, the local radius of curvature at each measurement point and the exact solution for the relationship between real and apparent corneal thickness as suggested by Brennan et al.[20] were used in order to more accurately calculate real corneal thickness.

SUBJECTS AND METHODS

1. Elliptical curve for anterior cornea

Corneal topographic data (radial distance [mm] and corneal height [mm] across the horizontal meridian) were exported from the Medmont E-300 corneal topographer Version 3.9.8 (Medmont Pty Ltd, Camberwell, Victoria, Australia) and analysed in order to calculate an elliptical curve for the horizontal meridian of the anterior cornea using an Interactive Data Language (IDL) computer program (student version 5.0; Research Systems Inc, USA). The IDL computer program calculate an elliptical curve for the horizontal meridian of the anterior cornea by using best fit algorism of the corneal topographic data which were exported from the Medmont E-300 corneal topographer. An elliptical curve was chosen because the human cornea can be acceptably modelled by ellipses.[21-23] For this study, the simplified mathematical description of corneal shape by Bennett[24] was modified to allow calculation of sagittal depth(z) for different chord lengths (x), as follows:

$$z = \frac{Rc}{p} - \sqrt{\frac{Rc^2}{p^2} - \frac{x^2}{p}} \tag{1}$$

where Rc is the apical radius of curvature, and p is the shape factor.

Three descriptors have been used to describe the shape of the cornea. They are e (eccentricity), p (shape factor) and Q (asphericity). Here the 'e' is the rate of flattening of the cornea, and $e^2 = 1 - a^2/b^2$, where a and b are the major and minor axis lengths of an ellipse, respectively. The following equations show the mathematical relationships between p, Q, and e:

$$\begin{aligned} p &= 1 - e^2 \\ p &= 1 + Q \\ Q &= -e^2 \end{aligned} \tag{2}$$

The shape index e can describe prolate elliptical shape, which is suitable for modelling the normal cornea, but is not adequate to describe oblate elliptical shape where the cornea steepens towards the periphery (for example, the after Orthokeratology therapy cornea). This is because the length of the major axis is longer than the minor axis in the case of an oblate elliptical shape. Therefore the square root of $(1 - a^2/b^2)$ is a negative value which is not mathematically defined in the real number field. In contrast, the indices *p* and *Q* can describe both prolate and oblate elliptical shapes. For the purpose of this study, we used *Q* which is equal to $p - 1$ in equation (1) to describe the shape of the anterior and posterior cornea.

2. Real corneal thickness

For measurement of total corneal thickness, the Holden-Payor optical pachometer was used. The angles of illumination (-48.5 ± 0.1 degrees; clockwise from the reference angle) and observation (25.0 ± 0.2 degrees; anticlockwise from the reference angle) of the optical pachometer, a standard corneal refractive index of 1.376,[20] the local radius of anterior corneal curvature,[25,26] and an exact solution for the relationship between real and apparent thickness were taken into consideration to calculate real corneal thickness at each measurement position along the horizontal meridian.[20] This method differs from those that use a standard value for local radius of curvature of 7.8 mm, and an approximate solution for corneal thickness calculated using the original pachometer software.[18,27-30] Calculating accurate real corneal thickness at each measurement position is essential aspect to define correct coordinates of the posterior cornea.

3. Elliptical curve for posterior cornea

The coordinates of the posterior cornea along the horizontal meridian can be calculated based on the anterior corneal elliptical curve, the positions of corneal optical pachometry measurements (which can be defined using the equation of Brennan et al.),[20] the direction of thickness measurements (which is perpendicular to the anterior corneal surface at the point of measurement),[20] and the real corneal thickness at each measurement position. Using the derived posterior corneal coordinates, an elliptical posterior corneal curve for the horizontal meridian was calculated by the IDL computer program. The IDL computer program calculate an elliptical curve for the horizontal meridian of the posterior cornea by using best fit algorism of the derived coordinates of the posterior cornea along the horizontal meridian.

4. Accuracy and repeatability of calculations of test surface parameters

For validation of the calculations of the posterior surface topography, five repeated measurements of the anterior surface topography of ten polymethyl methacrylate (PMMA) lenses (Capricornia Contact Lens Pty Ltd, Brisbane, Australia) were taken by the Medmont E300 corneal topographer to calculate the anterior elliptical curve of the test surface.

The thicknesses of the test PMMA lenses were measured using the optical pachometer. The test lenses were mounted in a vertical position on the pachometer focussing rod, and rotated in approximate 4 degree steps clockwise and anticlockwise out to approximately 28 degrees in each direction with reference to a protractor. Five repeated measurements of lens thickness were taken at each measurement point across the horizontal meridian for each PMMA lens. The radial distance of the anterior surface topographic raw data spanned 8.0 to 8.5 mm, and 15 pachometry measurement points were consequently measured within the back optic zone of the test lenses.

The data for the anterior elliptical curves and thicknesses of the test lenses across the horizontal meridian were then entered into the IDL program to calculate the posterior elliptical curve of the test surfaces, including central radius of curvature and Q. These data were compared with posterior radius of curvature measured using an American Optical/Reichert radiuscope Model 11200 (Reichert Ophthalmic Instruments, Depew, NY, USA), calibrated according to manufacturer's instructions. Asphericity values were compared with nominal values supplied by the manufacturer of the test surfaces. The posterior Q was derived over an approximate 8.5 mm chord.

5. Repeatability of calculations of human corneal parameters

For validation of the repeatability of calculation of human corneal parameters, five subjects (aged 22 to 40 years) participated in this study. All subjects were non-contact lens wearers and had no history of refractive surgery, ocular injury, or corneal disease. Only right eyes were measured over two days, at approximately the same time of the day. This study was conducted in compliance with the Declaration of Helsinki, and informed consent was gained from subjects prior to their participation.

To determine repeatability of the calculation of human posterior corneal topography, the Medmont E300 corneal topographer and Holden-Payor optical were taken for each

Table 1. Measured angles of fixation LEDs of pachometer (n = 3 measurements). Positive values = anticlockwise from the reference angle, negative values = clockwise from the reference angle

	Angles (degrees)					
LED	R9	R7	R6	R4	R2	C
Mean	−35.2	−27.3	−23.7	−15.5	−7.8	0.3
SD	0.1	0.2	0.1	0.10	0.2	0.1
LED	L9	L7	L6	L4	L2	
Mean	34.3	27.1	23.4	15.7	7.8	
SD	0.1	0.2	0.2	0.2	0.1	

LED: light-emitting diode.
R: right fixation LED for subject.
C: central fixation LED for subject.
L: left fixation LED for subject.
SD: standard deviation.

measurement point and the mean of three measurements was pachometer were used. The horizontal locations of the thickness measurement points from the anterior corneal centre are given in Table 1. Five repeated measurements recorded after the maximum and minimum of the five repeated measurements had been excluded. Corneal topographic and thickness data were entered into the IDL program to calculate the posterior corneal apical radius of curvature and Q. The posterior corneal Q was derived over an approximate 8.5 mm chord.

RESULTS

1. Accuracy and repeatability of calculations of test surface parameters

Table 2. Comparison of measured and calculated posterior apical radii (mm) of test surfaces (mean±SD; n = 5 measurements), and absolute accuracy of calculation

Test surface	Measured posterior apical radius	Calculated posterior apical radius	Absolute accuracy
PMMA lens 1	7.642±0.004	7.685±0.021	0.043
PMMA lens 2	7.322±0.004	7.307±0.018	0.015
PMMA lens 3	7.124±0.005	7.066±0.019	0.058
PMMA lens 4	6.534±0.005	6.553±0.007	0.019
PMMA lens 5	6.516±0.005	6.529±0.021	0.013
PMMA lens 6	6.520±0.000	6.564±0.039	0.044
PMMA lens 7	6.504±0.005	6.435±0.022	0.069
PMMA lens 8	6.500±0.000	6.585±0.020	0.085
PMMA lens 9	6.820±0.000	6.842±0.010	0.022
PMMA lens 10	6.816±0.005	6.651±0.015	0.165
Mean			0.053
SD			0.044

The mean absolute accuracy (±standard deviation(SD)) of the posterior apical radius calculations for PMMA lenses was 0.053±0.044 mm (95% confidence interval (CI) −0.033 to 0.139 mm). Detailed data describing the posterior apical radius of the test surfaces are presented in Table 2. Fig. 1 shows Bland-Altman plots comparing the calculated and measured posterior apical radius of the PMMA lenses.

The mean absolute accuracy (±SD) of the posterior Q calculations was 0.10±0.10 (95% CI −0.10 to 0.31). Detailed data describing the posterior Q are presented in Table 3. Fig. 2 presents Bland-Altman plots comparing the calculated and nominal posterior Q of the PMMA lenses.

2. Repeatability of calculations of human corneal parameters

The mean absolute repeatability coefficients (±SD) of

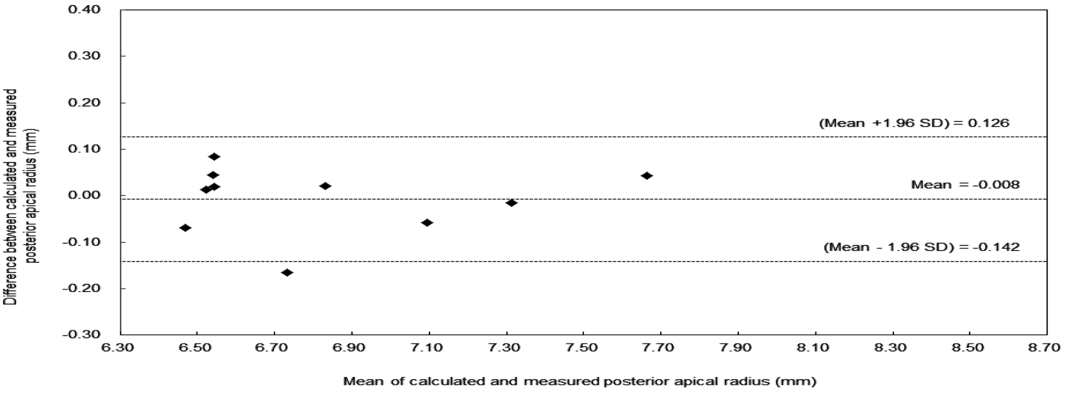

Fig. 1. Bland-Altman plots comparing calculated and measured posterior radius of test surfaces.

Table 3. Comparison of nominal and calculated posterior asphericity of test surfaces (mean ± SD; n=5 measurements), and absolute accuracy of calculation

Test surface	Nominal posterior asphericity	Calculated posterior asphericity	Absolute accuracy
PMMA lens 1	0.00	0.039 ± 0.048	0.039
PMMA lens 2	0.00	0.046 ± 0.042	0.046
PMMA lens 3	0.00	0.026 ± 0.041	0.026
PMMA lens 4	−0.80	−0.659 ± 0.018	0.141
PMMA lens 5	−0.50	−0.436 ± 0.025	0.064
PMMA lens 6	−0.20	−0.131 ± 0.104	0.069
PMMA lens 7	0.20	0.245 ± 0.043	0.045
PMMA lens 8	0.50	0.529 ± 0.051	0.029
PMMA lens 9	0.00	0.183 ± 0.034	0.183
PMMA lens 10	0.00	−0.377 ± 0.042	0.377
Mean			0.102
SD			0.104

Table 4. Differences between Day 1 and Day 2 in calculated posterior apical radius and asphericity of human corneas

	Posterior apical radius (mm)			Posterior asphericity		
	Day 1	Day 2	Absolute Difference	Day 1	Day 2	Absolute Difference
Subject 1	6.11	6.11	0.00	0.75	0.72	0.03
Subject 2	6.82	6.86	0.04	0.71	0.80	0.09
Subject 3	7.09	6.93	0.16	1.19	0.97	0.22
Subject 4	6.74	6.76	0.02	0.60	0.62	0.02
Subject 5	6.98	7.09	0.11	0.97	1.06	0.09
Mean	6.75	6.75	0.07	0.84	0.83	0.09
SD	0.34	0.34	0.06	0.21	0.16	0.07

the posterior apical radius and Q calculations for human subjects were 0.07 ± 0.06 mm (95% CI −0.05 to 0.19) and 0.09 ± 0.07 (95% CI −0.05 to 0.23) respectively. The means of the absolute differences in the posterior apical radius and Q of the human corneas between Day 1 and Day 2 are presented in Table 4.

Fig. 3 and 4 show Bland-Altman plots comparing the calculated posterior apical radius and Q of human corneas on Days 1 and 2 respectively.

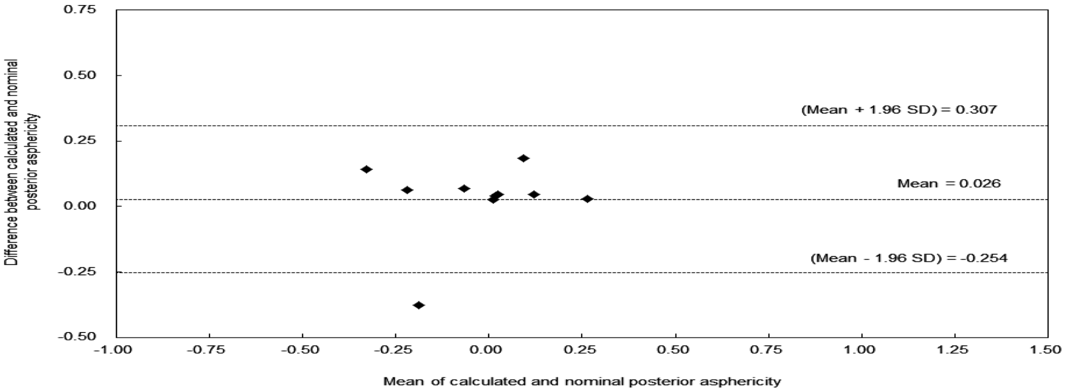

Fig. 2. Bland-Altman plots comparing calculated and nominal posterior Q of test surfaces.

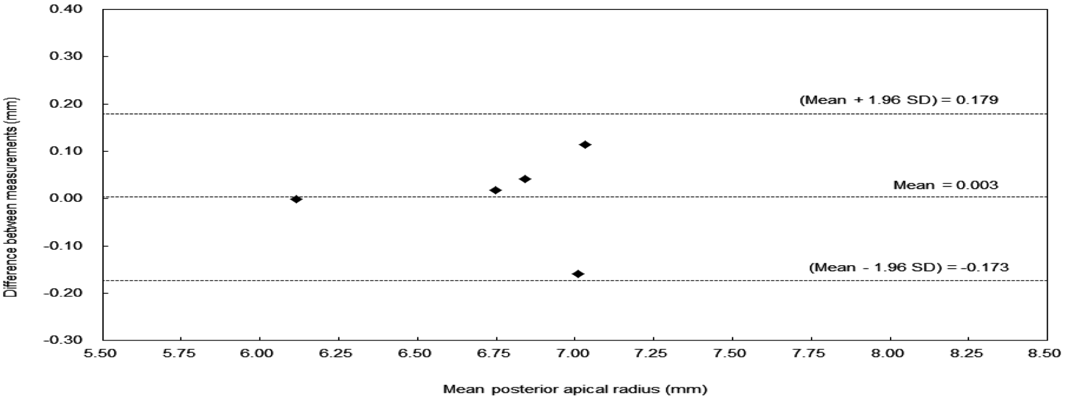

Fig. 3. Bland-Altman plots comparing the calculated posterior apical radius of human corneas on Days 1 and 2.

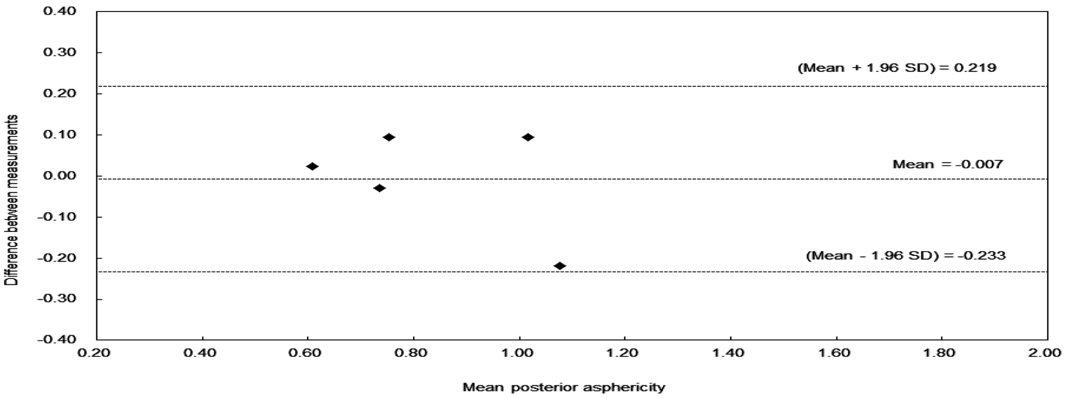

Fig. 4. Bland-Altman plots comparing the calculated posterior Q of human corneas on Days 1 and 2.

DISCUSSIONS

A new "first principles" method based on measurement of anterior corneal topography and thickness was developed to calculate posterior corneal topography. This method for calculation of posterior apical corneal radius and Q is similar to the method previously proposed by Rivett and Ho.[18] However, the local radius of curvature at each measurement point and an exact solution for the relationship between real and apparent corneal thickness as suggested by Brennan et al[20] were used in this study in order to more accurately calculate real thickness.

The method used for calculating posterior corneal topography in this study provides greater accuracy than in the previous study that used more approximate estimates of corneal thickness. In Rivett and Ho's study[18] the method was tested using one RGP lens with 10 repeated measurements for validation. Mean absolute accuracy reported by Rivett and Ho was 0.138±0.104 mm for posterior apical radius (95% confidence intervals −0.065 to 0.341 mm). They did not report the accuracy of posterior asphericity measurements. However in this study, the reliable accuracy of posterior apical radius and asphericity measurements for PMMA lenses were reported. The mean absolute accuracies (±SD) of the posterior apical radius and Q calculations for PMMA lenses were 0.053±0.044 mm (95% CI −0.033 to 0.139 mm) and 0.10±0.10 (95% CI −0.10 to 0.31) respectively.

The purposes of the new method are for research. However, there are commercially available instruments such as the Orbscan, Pentacam and Galilei that can assess the posterior topography of the cornea in vivo. The Orbscan scans the cornea with multiple light slits, and the posterior corneal surface is then calculated by triangulation. The Pentacam and Galilei instruments can also determine posterior corneal curvature in vivo using mono or dual Scheimpflug images of the cornea.

Maldonado et al.[1] reported repeatability of the Orbscan instrument for posterior corneal topography in post-LASIK eyes. The repeatability of posterior best-fit sphere (mm) and eccentricity were 0.09 mm (95% CI 0.08 to 0.10) and 0.65 (95% CI 0.58 to 0.71) respectively. They concluded that reliable intrasession repeatability for posterior best-fit sphere was achieved with the Orbscan, but that the posterior eccentricity results were unreliable. Kawamorita et al also found acceptable repeatability and reproducibility of posterior corneal power measurements calculated from Orbscan data in normal eyes, although this instrument was less repeatable than the Pentacam.[5]

Chen and Lam[2,3] reported that the Pentacam system provides good repeatability of posterior Sim K and best-fit spheres at 5.0 mm and 8.0 mm chords, and posterior corneal curvature. However the extracted positions for peripheral corneal curvature were only 2.0 mm away from the corneal apex. Good repeatability of posterior best-fit spheres at 8.0 mm chords using the Pentacam system has since been reported,[4] as well as excellent repeatability for posterior corneal power.[5] The Galilei system has also shown good repeatability in measuring posterior corneal power.[6,7]

Although there are many reports of good to excellent repeatability of the Orbscan, Pentacam, and Galilei systems in measuring posterior corneal curvature, posterior best-fit sphere, posterior eccentricity, posterior Sim K, and posterior corneal power, none of these reports has determined accuracy or "trueness" of posterior corneal curvature measurement.

Furthermore, statistically significant differences between the Orbscan and the Pentacam in measuring the posterior corneal curvature have been reported in normal, post-surgical and keratoconic eyes.[5,8,10] Posterior corneal elevation data has been shown to differ between Pentacam and Galilei systems.[9] Moreover, the Orbscan tends to measure a steeper value for posterior corneal curvature than the Galilei system in normal and post-surgical corneas.[7] This raises questions about which of these instruments is providing a "true" or accurate measurement of posterior corneal parameters.

In contrast, in this paper, the reliable accuracy of posterior apical radius and asphericity measurements for PMMA lenses using our "first principles" method has been reported. In addition, good repeatability of posterior apical radius and asphericity measurements for the human cornea was reported. The posterior corneal Q was determined over an approximate 8.5 mm chord. The mean absolute repeatability coefficients (±SD) of the posterior apical radius and Q calculations for human subjects were 0.07±0.06 mm (95% CI −0.05 to 0.19) and 0.09±0.07 (95% CI −0.05 to 0.23) respectively.

In our method, the calculation of posterior curvature depends on accurate measurement of thickness of the cornea. There are several potential sources of error when measuring corneal thickness with traditional Holden-Payor optical pachometry. First, it is possible that assumptions for corneal refractive index of 1.376, anterior corneal curvature of 7.8 mm and corneal shape as a sphere (Q = 0) may not be met. The pachometer used in most previous research[27-30] uses these standard values. There is likely to be a range of refractive indices for the human cornea between subjects and corneal regions.[31,32] Anterior and local corneal curvatures may differ markedly from 7.8 mm, and the average Q of the human cornea is approximately −0.20.[33] This may introduce errors into the measurements of apparent thickness of the cornea. However, variations in these factors are likely to be negligible in the normal cornea because the effect of the possible variation in corneal refractive index (1.333 to 1.419) is about 3%.[34] The effect of variation in anterior corneal curvature within the normal range is less than 0.2% of corneal thickness.[35]

Furthermore, the use of a linear scale in optical pachometry can introduce error[36] because the relationship between real and apparent corneal thickness is non-linear. However, this error is also negligible for normal corneal thicknesses of around 0.5 mm.

Optical pachometery requires skill and practice to achieve reliable readings. In particular, the difficulty in recognising the border between the tear film and the corneal layers, which mostly relies on individual judgement, can introduce error into the measurement. Less experienced observers obtain greater variations in measurement (32 m standard deviation) than trained observers (5 to 6 m standard deviation).[37] Holden et al.[28] reported a standard deviation of 5m with ten repeat measurements of stromal and epithelial thickness for an experienced observer. Better repeatability of corneal thickness with the Holden-Payor optical pachometer was claimed by Alharbi and Swarbrick,[29] who reported a standard deviation of 2 m at the central cornea and 4.3 m at the para-central cornea.

The method described in this paper assumes that an elliptical curve can be used to describe corneal shape. However, an elliptical model is not necessarily the best curve for describing individual corneas (for example, the abnormal cornea). This limitation may affect the accuracy of the method in vivo, particularly if corneal shape is significantly altered by treatments such as refractive surgery and orthokeratology (OK). On the other hand it may be argued that the calculation process described here may be applicable in OK because it can take into account changes in local corneal radius and shape such as those induced by overnight OK.[38-40]

Although the published range of posterior corneal Q was fully covered by the range of contact lenses tested in this study, the range of mean posterior corneal apical radius was not. The published ranges of mean posterior central radius and Q of the human cornea are 5.81 to 6.78 mm and −0.48 to −0.26 respectively.[13,14,18,19,41-43] The ranges of posterior apical radius and Q for the contact lenses tested in this study were 6.50 to 7.64 mm, and −0.80 to 0.50. Therefore, measurement of corneas with posterior apical radius of less than 6.50 mm was not validated in this study.

It is anticipated that this new approach for calculating posterior corneal apical radius and Q using anterior corneal topography and topographic corneal thickness can be applied to the human living cornea. More precise descriptions of posterior corneal topography could lead to the refinement of model eyes and provide better understanding of the mechanism of corneal reshaping procedures involved in refractive surgical techniques and contact lens applications. This method may also provide a means to validate the “trueness” of posterior corneal curvature measurements obtained from instruments such as the Orbscan, Pentacam and Galilei.

CONCLUSIONS

A new “first principles” method to determine posterior corneal curvature and asphericity in vivo, based on measurements of anterior corneal topography and corneal thickness, has been developed and validated. Results obtained using this method show better accuracy than previous research methods in calculations of posterior apical radius and Q. Calculation of the posterior apical radius was more reliable than calculations of the posterior Q. This new method shows promise for research applications in the living human cornea.

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각막 후면 지형 측정을 위한 새로운 방법의 신뢰도 분석 및 평가

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목적: 본 연구는 각막 전면의 지형과 각막의 두께를 이용하여 각막 후면 정점 곡률과 asphericity(Q)를 측정하기 위해 고안된 새로운 방법의 신뢰도 평가를 위해서 시행 되었다. **방법**: 각막 후면의 정점 곡률 및 Q는 Medmont E300 corneal topographer로 측정한 각막 전면의 지형 data와 Holden-Payor optical pachometer로 측정한 각막 수평 경선의 두께 data를 이용하여 계산 되었다. 정확한 각막 두께를 계산 하기위하여 각막 전면 측정 위치의 곡률반경과 각막의 겉보기 두께로부터 각막의 실제 두께를 계산 할 때 정확한 방정식을 이용하였으며, 이는 선행 연구와 구별되는 점이다. 그리고 각막 전면과 후면의 지형은 각막 전면의 지형 data와 계산된 각막 후면의 좌표를 best fit 알고리즘을 이용하여 계산 되었다. 각막 후면의 지형 측정의 신뢰도는 10개의 polymethyl methacrylate(PMMA) lens와 성인 5명의 각막을 측정 하여 평가 하였다. **결과**: 10개의 PMMA lens를 이용한 평가에서는 후면 정점 곡률과 후면 Q의 mean absolute accuracy(±SD)는 각각 0.053±0.044 mm(95% 신뢰구간(CI) −0.033~0.139)와 0.10±0.10(95% CI −0.10~0.31)이였다. 그리고 5명의 각막을 이용한 평가에서의 각막 후면 정점 곡률과 후면 Q의 mean absolute repeatability coefficient(±SD)는 각각 0.07±0.06 mm(95% CI −0.05~0.19)와 0.09±0.07(95% CI −0.05~0.23) 이였다. **결론**: 새로운 방법을 이용하여 신뢰할 수 있는 각막 후면의 지형(정점 곡률과 Q)을 계산 할 수 있었다. 이러한 새로운 방법은 살아있는 인체 각막의 정확한 후면 지형 계산에 적용 될 수 있다.

주제어: 각막 전면의 지형, 각막 두께, 각막 후면의 정점 곡률, 각막 후면의 Q