Keratometric Index Obtained by Fourier-Domain Optical Coherence Tomography

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Abstract

Purpose

To determine the keratometric indices calculated based on parameters obtained by Fourier-domain optical coherence tomography (FD-OCT).

Methods

The ratio of anterior corneal curvature to posterior corneal curvature (Ratio) and keratometric index (N) were calculated within central 3 mm zone with the RTVue FD-OCT (RTVue, Optovue, Inc.) in 186 untreated eyes, 60 post-LASIK/PRK eyes, and 39 keratoconus eyes. The total corneal powers were calculated using different keratometric indices: Kcal based on the mean calculated keratometric index, K1.3315 calculated by the keratometric index of 1.3315, and K1.3375 calculated by the keratometric index of 1.3375. In addition, the total corneal powers based on Gaussian optics formula (Kactual) were calculated.

Results

The means for Ratio in untreated controls, post-LASIK/PRK group and keratoconus group were 1.176 ± 0.022 (95% confidence interval (CI), 1.172–1.179), 1.314 ± 0.042 (95%CI, 1.303–1.325) and 1.229 ± 0.118 (95%CI, 1.191–1.267), respectively. And the mean calculated keratometric index in untreated controls, post-LASIK/PRK group and keratoconus group were 1.3299 ± 0.00085 (95%CI, 1.3272–1.3308), 1.3242 ± 0.00171 (95%CI, 1.3238–1.3246) and 1.3277 ± 0.0046 (95%CI, 1.3263–1.3292), respectively. All the parameters were normally distributed. The differences between Kcal and Kactual, K1.3315 and Kactual, and K1.3375 and Kactual were 0.00 ± 0.11 D, 0.21 ± 0.11 D and 0.99 ± 0.12 D, respectively, in untreated controls; -0.01 ± 0.20 D, 0.85 ± 0.18 D and 1.56 ± 0.16 D, respectively, in post-LASIK/PRK group; and 0.03 ± 0.67 D, 0.56 ± 0.70 D and 1.40 ± 0.76 D, respectively, in keratoconus group.
Conclusion

The calculated keratometric index is negatively related to the ratio of anterior corneal curvature to posterior corneal curvature in untreated, post-LASIK/PRK, and keratoconus eyes, respectively. Using the calculated keratometric index may improve the prediction accuracies of total corneal powers in untreated controls, but not in post-LASIK/PRK and keratoconus eyes.

Introduction

Consideration of the keratometric index is essential for the assessment of total corneal power and the prediction of intraocular lens power. [1,2] Historically, because of the lack of information from the posterior corneal surface, the conventional keratometric index (1.3375) [3] or the keratometric index derived from Gullstrand schematic eye (1.3315) [4] combining the anterior corneal curvature were used to calculate the total corneal power. The equation is as follows:

\[ K = \frac{(N-1)}{R} \]

where \( K \) is the total corneal power, \( N \) is the keratometric index, 1 means the refractive index of the air, and \( R \) means the anterior corneal curvature in certain central zone. In theory, these keratometric indices (the conventional 1.3375 or the 1.3315 based on the Gullstrand schematic eye) which are lower than the real corneal refractive index of 1.376, compensate for the negative power of posterior corneal surface. Moreover, the equation above must be based on 2 assumptions: The anterior and posterior corneal curvatures have a constant and linear relationship. [5,6] However, this is not the case. Even in different schematic eyes, the ratio of anterior corneal curvature to posterior corneal curvature are not the same. [6] Furthermore, the ratios obtained by different devices from real human eyes are also vary. [7–9]

Currently, there are three kinds of techniques that can detect the information of the anterior and posterior corneal surface and central corneal thickness (CCT) simultaneously, including Slit-scan system (Orbscan II) [10,11], Scheimpflug camera system (Pentacam or Pentacam HR) [12,13] and optical coherence tomography system (Fourier-Domain OCT, FD-OCT) [14–16]. There have been reports in which the first 2 techniques were applied to obtain the ratio of anterior corneal curvature to posterior corneal curvature, and the keratometric index was calculated regarding the total corneal power based on Gaussian optics formula as a benchmark. [1,5,6,17] However, to the best to our knowledge, until now there have been no reports on the keratometric index calculated by data derived from RTVue FD-OCT (RTVue, Optovue, Inc.).

The commercially available system RTVue FD-OCT with a speed of 26000 axial scans per second has an axial resolution of 5 \( \mu \)m and a transverse resolution of 15 \( \mu \)m. [16] The corneal mapping model had 6.0 mm line scans on 8 meridians with 1019 axial scans centered on the pupil, and the whole scan model was finished within 0.32 seconds. [16] Previous work from our research group showed that RTVue FD-OCT had good repeatability in measurements of corneal parameters (corneal curvature and CCT) from untreated eyes and eyes after corneal refractive surgery. [18,19] In this study, we used the RTVue FD-OCT system to measure the anterior and posterior corneal curvature and the CCT within central 3 mm zone in untreated controls, post-LASIK/PRK and keratoconus groups. The ratio of anterior corneal curvature to posterior corneal curvature and keratometric indices were then calculated, and the total corneal powers were assessed using these keratometric indices in each group.
Patients and Methods

Inclusion criteria were patients who didn’t receive prior corneal or ocular surgery in the untreated controls, or received uneventful LASIK at least 3 months or PRK at least 6 months previously in the post-LASIK/PRK group, or was diagnosed with keratoconus in the keratoconus group. All the results obtained by RTVue FD-OCT had good reliability (Measurement Reliability Rating GOOD displayed on the Pachymetry + CPwr map). Three groups of subjects were included in this study:

1. 186 eyes of 186 subjects in the untreated group; the mean age was 26.1 ± 5.6 years; the mean spherical equivalent was -2.53 ± 1.32 D; these subjects were selected from the patients examined before corneal refractive surgery in Wenzhou Eye Hospital (Wenzhou, China) from July 2011 to April 2012.

2. 60 eyes of 39 patients in the post-LASIK/PRK group; the mean age was 27.3 ± 6.2 years; the mean spherical equivalent before the laser surgery was -4.81±1.22 D; the mean spherical equivalent after the laser surgery was 0.02±0.33 D; these subjects were selected from the patients who received LASIK at least 3 months previously or PRK at least 6 month previously in Wenzhou Eye Hospital from July 2011 to April 2012.

3. 39 eyes of 27 patients in the keratoconus group; the mean age was 34.93 ± 11.41 years; the data were selected from the patients who were diagnosed as keratoconus in Synslaser Clinic (Tromso, Norway) from September 2012 to January 2013. All the patients did not receive any eye surgery previously. And 4 of them had apical scars, 5 of them had Vogt striae, and all the others had clean corneas.

The study was conducted at the Eye Hospital of Wenzhou Medical University and Synslaser Clinic (Tromso, Norway). The research was performed in accordance with the principles stated in the Declaration of Helsinki. The untreated controls and post-LASIK/PKR group from Wenzhou Eye Hospital was approved by the Office of Research Ethical Committee, Wenzhou Medical University; and the keratoconus group from Synslaser was approved by the National Committee for Medical and Health Research Ethics in Norway. All participants provided written informed consent after the nature of the study had been explained to them.

We obtained the anterior corneal curvature (R_{anterior}), posterior corneal curvature (R_{posterior}) and CCT within central 3 mm zone for each tested eye using RTVue FD-OCT. The ratio of the anterior and posterior corneal curvature in each eye was calculated as follows:

\[
\text{Ratio} = \frac{R_{anterior}}{R_{posterior}}
\]

The Gaussian optics formula calculates the actual total corneal power \(K_{actual}\) within central 3 mm zone by assuming the central cornea as a thick lens. And \(K_{actual}\) in each eye was calculated as follows:

\[
K_{actual} = \frac{(n_0 - n_2)R_{anterior} + (n_2 - n_1)R_{posterior} - (CCT/n_1) \times ([n_2 - n_0]/R_{anterior}) \times ([n_2 - n_1]/R_{posterior})}{(n_2 - n_0)/R_{posterior}}
\]

where \(n_0\) (1.000), \(n_1\) (1.376) and \(n_2\) (1.336) are the refractive indices of the air, the cornea and aqueous, respectively. We used the following equation to compute the real keratometric index \(n\) in each eye:

\[
(n - 1)/R_{anterior} = K_{actual}
\]
The mean of \( n \) in each eye was computed and defined as \( N \), next \( N \) was used to estimate the total corneal power (\( K_{\text{cal}} \)) in each eye as follows:

\[
K_{\text{cal}} = \frac{(N - 1)}{R_{\text{anterior}}}
\]

The total corneal power estimated using the keratometric index obtained from Gullstrand model eye (1.3315) and the conventional keratometric index (1.3375) were calculated as follows:

\[
K_{1.3315} = \frac{(1.3315 - 1)}{R_{\text{anterior}}}
\]

\[
K_{1.3375} = \frac{(1.3375 - 1)}{R_{\text{anterior}}}
\]

All the data were entered into MedCalc Version 11.4.2 for Windows. Correlation coefficient and paired t-test were used to compare values normally distributed in the three groups. Correlation coefficient and regression analysis were used to analyze the correlations between \( R_{\text{anterior}} \), \( R_{\text{posterior}} \), \( N_{\text{cal}} \) and Ratio. Bland-Altman plots were applied to analyze the agreement between \( K_{\text{cal}} \) and \( K_{\text{actual}} \), \( K_{1.3315} \) and \( K_{\text{actual}} \), and \( K_{1.3375} \) and \( K_{\text{actual}} \). A \( P \) value of 0.05 or less was considered statistically significant.

### Results

Table 1 shows the corneal parameters obtained by RTVue FD-OCT in untreated controls, post-LASIK/PRK group and keratoconus group. All the values conformed to be normally distributed by Kolmogorov-Smirnov test (all \( P > 0.05 \)). The distributions of Ratio and keratometric indices (\( N \)) in untreated controls, post-LASIK/PRK group and keratoconus group are shown in Fig 1A, 1B, 1C, 1D, 1E and 1F, respectively.

Fig 2 shows the multiple variable graphs of the mean \( R_{\text{posterior}} \), Ratio and Keratometric index (\( N \)) in untreated controls, post-LASIK/PRK group and keratoconus group. In Fig 2A, the mean \( R_{\text{posterior}} \) from keratoconus group was significantly smaller than those from untreated and post-LASIK/PRK group (both \( P < 0.05 \)). And there was no statistical significance between the mean \( R_{\text{posterior}} \) values from untreated controls and post-LASIK/PRK group (\( P > 0.05 \)). In Fig 2B, both the mean Ratio from post-LASIK/PRK group and keratoconus group were larger than the mean Ratio from untreated controls (both \( P < 0.05 \)), and the mean Ratio from post-LASIK/PRK group was larger than that from keratoconus group (\( P < 0.05 \)). In Fig 2C, both the mean keratometric indices (\( N_{\text{cal}} \)) from post-LASIK/PRK group and keratoconus group were smaller than the mean Ratio from untreated controls (both \( P < 0.05 \)), and the mean \( N \) from post-LASIK/PRK group was smaller than that from keratoconus group (\( P < 0.05 \)).

In untreated controls, linear regression revealed that there were good correlations between \( R_{\text{anterior}} \) and \( R_{\text{posterior}} \), Ratio and \( N \). The regression equations were \( R_{\text{posterior}} = 0.01021 + 0.8499\times R_{\text{anterior}} \) (\( r = 0.884, r^2 = 0.782, P < 0.05 \)) and \( N = 1.3752 - 0.3852\times \text{Ratio} \) (\( r = -0.997, r^2 = 0.995, P < 0.05 \)) in Fig 3A and 3B. In post-LASIK/PRK group, linear regression revealed that there were good correlation between Ratio and \( N \). The regression equations was \( N = 1.3775 - 0.04054\times \text{Ratio} \) (\( r = -0.999, r^2 = 0.999, P < 0.05 \)) in Fig 3D. In keratoconus group, the regression equations were \( R_{\text{posterior}} = -2.8393 + 1.218\times R_{\text{anterior}} \) (\( r = 0.854, r^2 = 0.728, P < 0.05 \)) and \( N = 1.3759 - 0.03917\times \text{Ratio} \) (\( r = -0.999, r^2 = 0.999, P < 0.05 \)) in Fig 3E and 3F.

Table 2 shows the total corneal power calculated with different keratometric indices in untreated controls, post-LASIK/PRK group and keratoconus group. Table 3 shows the comparisons between \( K_{\text{cal}} \) and \( K_{\text{actual}} \), \( K_{1.3315} \) and \( K_{\text{actual}} \), \( K_{1.3375} \) and \( K_{\text{actual}} \) in the three groups.
were no statistical significances between $K_{\text{cal}}$ and $K_{\text{actual}}$ in all three groups (all $P = 1.00$, paired $t$ test). In untreated controls, $K_{1.3315}$ and $K_{1.3375}$ were $0.21 \pm 0.11$ D and $0.99 \pm 0.12$ D larger than $K_{\text{actual}}$, respectively (both $P < 0.05$).

**Fig 4** shows the Bland-Altman plots comparing the total corneal power calculated with different keratometric indices ($K_{\text{cal}}, K_{1.3315}$ and $K_{1.3375}$) and the actual total corneal power calculated based on Gaussian optics formula ($K_{\text{actual}}$) in untreated controls, and the 95% confidence interval (CI) for $K_{\text{cal}}$ vs $K_{\text{actual}}, K_{1.3315}$ vs $K_{\text{actual}},$ and $K_{1.3375}$ vs $K_{\text{actual}}$ were $-0.22$ to $0.22$ D, $-0.01$ to $0.42$ D and $0.76$ to $1.21$ D, respectively. In post-LASIK/PRK group, $K_{1.3315}$ and $K_{1.3375}$ were $0.85 \pm 0.18$ D and $1.56 \pm 0.16$ D larger than $K_{\text{actual}}$, respectively (both $P < 0.05$).

**Fig 5** shows the Bland-Altman plots of $K_{\text{cal}}$ and $K_{\text{actual}}, K_{1.3315}$ and $K_{\text{actual}}, K_{1.3375}$ and $K_{\text{actual}}$ in post-LASIK/PRK group, and the 95% CI for $K_{\text{cal}}$ vs $K_{\text{actual}}, K_{1.3315}$ vs $K_{\text{actual}}$, and $K_{1.3375}$ vs $K_{\text{actual}}$ were $-0.40$ to $0.38$ D, $0.50$ to $1.19$ D and $1.23$ to $1.86$ D, respectively. In keratoconus group, $K_{1.3315}$ and $K_{1.3375}$ were $0.56 \pm 0.70$ D and $1.40 \pm 0.76$ D larger than $K_{\text{actual}}$, respectively (both $P < 0.05$).

**Fig 6** shows the Bland-Altman plots of $K_{\text{cal}}$ and $K_{\text{actual}}, K_{1.3315}$ and $K_{\text{actual}}, K_{1.3375}$ and $K_{\text{actual}}$ in keratoconus group, and the 95% CI for $K_{\text{cal}}$ vs $K_{\text{actual}}, K_{1.3315}$ vs $K_{\text{actual}}$, and $K_{1.3375}$ vs $K_{\text{actual}}$ were $-1.28$ to $1.34$ D, $-0.82$ to $1.93$ D and $-0.09$ to $2.88$ D, respectively.

**Discussion**

Keratometric index is critical in both the calculation of total corneal power and the prediction of intraocular lens power. Clinically, the commonly used keratometric indices include the conventional $1.3375$ and the $1.3315$ based on the Gullstrand schematic eye. However, the keratometric indices calculated in real eyes using Scheimpflug camera system[1] and Slit-scan system

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Table 1. Summary of corneal parameters in untreated controls, post-LASIK/PRK and keratoconus group.

| Parameter       | Mean(D)±SD | 95% CI       | Range            | $P$ Value* |
|-----------------|------------|--------------|------------------|------------|
| **Untreated controls** |            |              |                  |            |
| $R_{\text{anterior}}$ (mm) | $7.718 \pm 0.275$ | $7.678$–$7.758$ | $7.016$–$8.561$ | $0.994$    |
| $R_{\text{posterior}}$ (mm) | $6.569 \pm 0.265$ | $6.531$–$6.608$ | $5.849$–$7.259$ | $0.674$    |
| CCT (μm)       | $544.98 \pm 33.09$ | $540.82$–$550.10$ | $433.33$–$629.33$ | $0.442$    |
| Ratio          | $1.176 \pm 0.022$ | $1.172$–$1.179$ | $1.12$–$1.25$   | $0.946$    |
| $N$            | $1.3299 \pm 0.00085$ | $1.3272$–$1.3308$ | $1.3271$–$1.3321$ | $0.992$    |
| **Post-LASIK/PRK group** |            |              |                  |            |
| $R_{\text{anterior}}$ (mm) | $8.582 \pm 0.311$ | $8.501$–$8.662$ | $8.050$–$9.283$ | $0.803$    |
| $R_{\text{posterior}}$ (mm) | $6.534 \pm 0.164$ | $6.491$–$6.576$ | $6.158$–$6.844$ | $0.695$    |
| CCT (μm)       | $451.09 \pm 33.56$ | $442.42$–$459.76$ | $374.00$–$536.00$ | $0.425$    |
| Ratio          | $1.314 \pm 0.042$ | $1.303$–$1.325$ | $1.210$–$1.406$ | $0.945$    |
| $N$            | $1.3242 \pm 0.00171$ | $1.3238$–$1.3246$ | $1.3204$–$1.3285$ | $0.972$    |
| **Keratoconus group** |            |              |                  |            |
| $R_{\text{anterior}}$ (mm) | $7.214 \pm 0.647$ | $7.004$–$7.424$ | $5.588$–$8.732$ | $0.500$    |
| $R_{\text{posterior}}$ (mm) | $5.948 \pm 0.924$ | $5.648$–$6.247$ | $3.721$–$7.395$ | $0.692$    |
| CCT (μm)       | $480.23 \pm 41.93$ | $466.64$–$493.82$ | $385$–$572$ | $0.860$    |
| Ratio          | $1.229 \pm 0.118$ | $1.191$–$1.267$ | $1.050$–$1.502$ | $0.884$    |
| $N$            | $1.3277 \pm 0.0046$ | $1.3263$–$1.3292$ | $1.3171$–$1.3348$ | $0.888$    |

$R_{\text{anterior}}$ = the anterior corneal curvature within 3 mm zone; $R_{\text{posterior}}$ = the posterior corneal curvature within 3 mm zone; Ratio = $R_{\text{anterior}} / R_{\text{posterior}}$; CCT = central corneal thickness within 3 mm zone; $N$ = calculated keratometric index based on Gaussian thick lens formula; CI = consistent interval.

*Kolmogorov-Smirnov test.

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were smaller than 1.3375 and 1.3315. To the best of our knowledge, this is the first study to calculate keratometric index based on data derived from RTVue FD-OCT.

In our study, we used the RTVue FD-OCT to measure the anterior and posterior corneal curvature within central 3 mm zone and central corneal thickness in untreated, post-LASIK/PRK and keratoconus eyes. Then we used the data obtained to calculate the mean ratio of the

Fig 1. The distribution of Ratio and keratometric index (N) in the three group. A: The distribution of Ratio (the ratio of the anterior corneal curvature to the posterior corneal curvature in central 3 mm zone) conforms to a normal distribution ($P = 0.946$, Kolmogorov-Smirnov test) in untreated controls. B: The distribution of calculated keratometric index (N) conforms to a normal distribution ($P = 0.992$, Kolmogorov-Smirnov test) in untreated controls. C: The distribution of Ratio conforms to a normal distribution ($P = 0.945$, Kolmogorov-Smirnov test) in post-LASIK/PRK group. D: The distribution of calculated keratometric index (N) conforms to a normal distribution ($P = 0.972$, Kolmogorov-Smirnov test) in post-LASIK/PRK group. E: The distribution of Ratio conforms to a normal distribution ($P = 0.884$, Kolmogorov-Smirnov test) in keratoconus group. F: The distribution of calculated keratometric index (N) conforms to a normal distribution ($P = 0.888$, Kolmogorov-Smirnov test) in keratoconus group.

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[6] were smaller than 1.3375 and 1.3315. To the best to our knowledge, this is the first study to calculate keratometric index based on data derived from RTVue FD-OCT.

In our study, we used the RTVue FD-OCT to measure the anterior and posterior corneal curvature within central 3 mm zone and central corneal thickness in untreated, post-LASIK/PRK and keratoconus eyes. Then we used the data obtained to calculate the mean ratio of the

Fig 2. The multiple variables graphs of $R_{\text{posterior}}$ values, Ratio and keratometric index (N) from the three group. A: The multiple variables graphs of $R_{\text{posterior}}$ values from untreated controls, post-LASIK/PRK group and keratoconus group. B: the multiple variables graphs of Ratio values from untreated controls, post-LASIK/PRK group and keratoconus group. C: The multiple variables graphs of calculated keratometric index (N) from untreated controls, post-LASIK/PRK group and keratoconus group.

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anterior corneal curvature to the posterior corneal curvature (Ratio) and the mean calculated keratometric index (N_cal) in each group. In untreated controls, it was shown that the Ratio was 1.176 ± 0.022, and N_cal was 1.3299 ± 0.00085. Jin et al.[17] calculated a Ratio of 1.223 ± 0.028 and a keratometric index of 1.3280 ± 0.0011 in 352 Chinese untreated eyes, and a Ratio of 1.205 ± 0.027 and a keratometric index of 1.3287 ± 0.0010 in 205 German untreated eyes using data derived from Pentacam HR. Ho et al[5] used the data obtained by Pentacam to calculate a

Fig 3. The scatter diagram & regression line of \( R_{\text{anterior}} \) and \( R_{\text{posterior}} \), Ratio and keratometric index (N) in the three group. A: The scatter diagram & regression line of \( R_{\text{anterior}} \) and \( R_{\text{posterior}} \) in untreated controls. The regression equation was \( R_{\text{posterior}} = 0.01021 + 0.8499 \times R_{\text{anterior}} \) \( (r = 0.884, r^2 = 0.782, P<0.05) \). B: The scatter diagram & regression line of Ratio and keratometric index (N) in untreated controls. The regression equation was \( N = 1.3752 - 0.03852 \times \text{Ratio} \) \( (r = -0.997, r^2 = 0.995, P<0.05) \). C: The scatter diagram & regression line of \( R_{\text{anterior}} \) and \( R_{\text{posterior}} \) in post-LASIK/PRK group. The regression equation was \( R_{\text{posterior}} = 4.3054 + 0.2596 \times R_{\text{anterior}} \) \( (r = 0.492, r^2 = 0.242, P<0.05) \). D: The scatter diagram & regression line of Ratio and keratometric index (N) in post-LASIK/PRK group. The regression equation was \( N = 1.3775 - 0.04054 \times \text{Ratio} \) \( (r = -0.999, r^2 = 0.999, P<0.05) \). E: The scatter diagram & regression line of \( R_{\text{anterior}} \) and \( R_{\text{posterior}} \) in keratoconus group. The regression equation was \( R_{\text{posterior}} = -2.8393 + 1.218 \times R_{\text{anterior}} \) \( (r = 0.854, r^2 = 0.728, P<0.05) \). F: The scatter diagram & regression line of Ratio and keratometric index (N) in keratoconus group. The regression equation was \( N = 1.3759 - 0.03917 \times \text{Ratio} \) \( (r = -0.999, r^2 = 0.999, P<0.05) \).

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Table 2. Mean values and 95%CI of total corneal power calculated with different keratometric indices in untreated controls, post-LASIK/PRK and keratoconus group.

|                      | Untreated controls | Post-LASIK/PRK group | Keratoconus group |
|----------------------|--------------------|----------------------|-------------------|
| \( K_{\text{actual}} \) | 42.80 ± 1.53 (42.58 to 43.02) | 37.83 ± 1.50 (37.44 to 38.22) | 45.77 ± 3.93 (44.50 to 47.05) |
| \( K_{\text{cal}} \)     | 42.80 ± 1.53 (42.58 to 43.02) | 37.83 ± 1.35 (37.48 to 38.17) | 45.80 ± 4.33 (44.40 to 47.20) |
| \( K_{1.3315} \)        | 43.01 ± 1.53 (42.78 to 43.23) | 38.67 ± 1.38 (38.32 to 39.04) | 46.33 ± 4.38 (44.91 to 47.75) |
| \( K_{1.3375} \)        | 43.79 ± 1.56 (43.56 to 44.01) | 39.38 ± 1.40 (39.02 to 39.74) | 47.17 ± 4.46 (45.73 to 48.61) |

\( K_{\text{actual}} = \) actual total corneal power calculated based on Gaussian optics formula; \( K_{\text{cal}} = \) total corneal power calculated with the mean keratometric indices (1.3299 in untreated controls, 1.3242 in post-LASIK/PRK group and 1.3277 in keratoconus group); \( K_{1.3315} = \) total corneal power calculated with the keratometric index of 1.3315; \( K_{1.3375} = \) total corneal power calculated with the keratometric index of 1.3375.

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Ratio of 1.223±0.034 and a keratometric index of 1.328 ± 0.0018 in 221 Chinese untreated eyes. Fam et al.[6] applied Orbscan II to measure 2429 Malaysian untreated eyes, and obtained a Ratio of 1.22±0.03 and a keratometric index of 1.3273 ± 0.0013. It demonstrated that Ratio calculated by parameters derived from RTVue FD-OCT in untreated controls in our study was obviously smaller than those calculated by parameters obtained by Pentacam and Orbscan II, and simultaneously, Ncal in untreated controls in our study was larger than those calculated by parameters obtained by Pentacam and Orbscan II. The main source for the differences was the different Rposterior obtained. The Rposterior from untreated controls in our study was 6.569 ± 0.265 mm, which is larger than 6.30±0.24 mm from Chinese eyes and 6.42±0.25 mm from German eyes in Jin et al’s study, 6.34±0.28 mm in Ho et al’s study and 6.46±0.26 mm in Fam et al’s study. While the anterior corneal curvatures are comparable, a larger posterior corneal curvature will leads to a smaller ratio of anterior curvature to posterior curvature.

### Table 3. The differences between $K_{\text{cal}}$ and $K_{\text{actual}}$, $K_{1.3315}$ and $K_{\text{actual}}$, $K_{1.3375}$ and $K_{\text{actual}}$ in the untreated controls, post-LASIK/PRK and keratoconus group.

| Pairing               | Mean difference ± SD | 95%CI             | P Value |
|-----------------------|-----------------------|-------------------|---------|
| **Untreated controls**|                       |                   |         |
| $K_{\text{cal}}$ vs. $K_{\text{actual}}$ | 0.00 ± 0.11         | -0.02 to 0.02     | 1.000   |
| $K_{1.3315}$ vs. $K_{\text{actual}}$ | 0.21 ± 0.11         | 0.19 to 0.22      | <0.001  |
| $K_{1.3375}$ vs. $K_{\text{actual}}$ | 0.99 ± 0.12         | 0.97 to 1.00      | <0.001  |
| **Post-LASIK/PRK group**|                       |                   |         |
| $K_{\text{cal}}$ vs. $K_{\text{actual}}$ | -0.01 ± 0.20        | -0.06 to 0.05     | 1.000   |
| $K_{1.3315}$ vs. $K_{\text{actual}}$ | 0.85 ± 0.18         | 0.80 to 0.89      | <0.001  |
| $K_{1.3375}$ vs. $K_{\text{actual}}$ | 1.56 ± 0.16         | 1.50 to 1.59      | <0.001  |
| **Keratoconus group**|                       |                   |         |
| $K_{\text{cal}}$ vs. $K_{\text{actual}}$ | 0.03 ± 0.67         | -0.19 to 0.25     | 1.000   |
| $K_{1.3315}$ vs. $K_{\text{actual}}$ | 0.56 ± 0.70         | 0.33 to 0.79      | <0.001  |
| $K_{1.3375}$ vs. $K_{\text{actual}}$ | 1.40 ± 0.76         | 1.15 to 1.64      | <0.001  |

$K_{\text{actual}}$ = actual total corneal power calculated based on Gaussian optics formula; $K_{\text{cal}}$ = total corneal power calculated with the mean keratometric indices (1.3299 in untreated controls, 1.3242 in post-LASIK/PRK group and 1.3277 in keratoconus group); $K_{1.3315}$ = total corneal power calculated with the keratometric index of 1.3315; $K_{1.3375}$ = total corneal power calculated with the keratometric index of 1.3375.

Fig 4. Band-Altman plots comparing the total corneal powers calculated with different indices ($K_{\text{cal}}$, $K_{1.3315}$ and $K_{1.3375}$) and the actual total corneal power calculated based on Gaussian optics formula ($K_{\text{actual}}$) in untreated controls. The solid lines represent mean differences, and the dotted lines represent 95%LoA. A: Comparison between $K_{\text{cal}}$ and $K_{\text{actual}}$. B: Comparison between $K_{1.3315}$ and $K_{\text{actual}}$. C: Comparison between $K_{1.3375}$ and $K_{\text{actual}}$. $K_{\text{cal}}$ was calculated with the mean keratometric index of 1.3299 obtained in this study. $K_{1.3315}$ was calculated with the keratometric index of 1.3315 obtained from the Gullstrand schematic eye. $K_{1.3375}$ was calculated with the conventional keratometric index of 1.3375.
Consequently, a larger total corneal power will be calculated based on a larger posterior corneal curvature (Formula 2), thus a larger $N_{cal}$ will be calculated (Formula 3). The differences of $R_{\text{posterior}}$ obtained by RTVue FD-OCT, Pentacam Scheimpflug camera system and Slit-scan system RTVue maybe caused by distinct measurement principles on which each device is based. RTVue FD-OCT with a speed of 26000 axial scans per second has an axial resolution of 5 $\mu$m. The corneal mapping model contained 6.0 mm line scans on 8 meridians with 1019 axial scans centered on the pupil, and the whole scan model was finished within 0.32 seconds.\cite{16,20} The Pentacam using a rotating Scheimpflug camera to image the anterior segment, provides the anterior and posterior corneal surfaces, pachymetry maps. And it measures 50000 or 125000 data points in less than 2 seconds.\cite{21–23} The Orbscan\ II is based on a slit-scan combining Placido ring technology. The data collected are processed to generate approximately 9000 data points over a 10 mm corneal diameter, and the Placido ring reflections are used to supplement slit-scan data to generate curvature-based map.\cite{6} Furthermore, both ethnicity and average age of subjects in different studies maybe factors which contributed to the different $R_{\text{posterior}}$ obtained.\cite{24}

**Fig 5.** Band-Altman plots comparing the total corneal powers calculated with different indices ($K_{\text{cal}}, K_{1.3315}$ and $K_{1.3375}$) and the actual total corneal power calculated based on Gaussian optics formula ($K_{\text{actual}}$) in post-LASIK/PRK group. The solid lines represent mean differences, and the dotted lines represent 95%LoA. A: Comparison between $K_{\text{cal}}$ and $K_{\text{actual}}$. B: Comparison between $K_{1.3315}$ and $K_{\text{actual}}$. C: Comparison between $K_{1.3375}$ and $K_{\text{actual}}$. $K_{\text{cal}}$ was calculated with the mean keratometric index of 1.3242 obtained in this study. $K_{1.3315}$ was calculated with the keratometric index of 1.3315 obtained from the Gullstrand schematic eye. $K_{1.3375}$ was calculated with the conventional keratometric index of 1.3375.

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**Fig 6.** Band-Altman plots comparing the total corneal powers calculated with different indices ($K_{\text{cal}}, K_{1.3315}$ and $K_{1.3375}$) and the actual total corneal power calculated based on Gaussian optics formula ($K_{\text{actual}}$) in keratoconus group. The solid lines represent mean differences, and the dotted lines represent 95%LoA. A: Comparison between $K_{\text{cal}}$ and $K_{\text{actual}}$. B: Comparison between $K_{1.3315}$ and $K_{\text{actual}}$. C: Comparison between $K_{1.3375}$ and $K_{\text{actual}}$. $K_{\text{cal}}$ was calculated with the mean keratometric index of 1.3277 obtained in this study. $K_{1.3315}$ was calculated with the keratometric index of 1.3315 obtained from the Gullstrand schematic eye. $K_{1.3375}$ was calculated with the conventional keratometric index of 1.3375.

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In our study, it was shown that Ratio from post-LASIK/PRK group (1.314 ± 0.042) was the largest; followed by Ratio from keratoconus group (1.229 ± 0.118); whereas Ratio from untreated controls was the smallest (1.176 ± 0.022) (all P< 0.05). On the contrary, N\text{cal} from post-LASIK/PRK group (1.324 ± 0.0017) was the smallest; followed by N\text{cal} from keratoconus group (1.3277 ± 0.0046); whereas N\text{cal} from untreated controls was the largest (1.3299 ± 0.00085). We further analyzed the correlation and linear regression between Ratio and N\text{cal} in each group. It demonstrated that N\text{cal} was negatively correlated to Ratio in each group (N = 1.3752 – 0.03852 × Ratio (r = -0.997, r\text{2} = 0.995, P< 0.05) (Fig 3B), N = 1.3775 – 0.04054 × Ratio (r = -0.999, r\text{2} = 0.999, P< 0.05) (Fig 3D), N = 1.3759 – 0.03917 × Ratio (r = -0.999, r\text{2} = 0.999, P< 0.05) (Fig 3F). Here, we can try to explain the reason why N\text{cal} was closely negatively correlated to Ratio from the origin of the 2 parameters. We can combine formula 2 and formula 3 in Patients and Methods part. Then we obtained the equation as follows:

\[
\frac{(n_1 - n_0)}{R_{\text{anterior}}} + \frac{(n_2 - n_1)}{R_{\text{posterior}}} - \frac{(CCT)}{n_1} \times \left[ \frac{(n_1 - n_0)}{R_{\text{anterior}}} \right] \\
\frac{[(n_2 - n_1)]}{R_{\text{posterior}}} = \frac{(n - 1)}{R_{\text{anterior}}}
\]

where n\text{0} (1.000), n\text{1} (1.376) and n\text{2} (1.336) are the refractive indices of the air, the cornea and aqueous, respectively.

The equation can be simplified as:

\[
n = 1.376 + \frac{(0.011 \times CCT)}{R_{\text{posterior}}} - 0.04 \times \text{Ratio}
\]

In the simplified formula above, the value of \(\frac{(0.011 \times CCT)}{R_{\text{posterior}}}\) was very small. We assumed that CCT and \(R_{\text{posterior}}\) were 520 um and 6.5mm, respectively, then the value of \(\frac{(0.011 \times CCT)}{R_{\text{posterior}}}\) was calculated as 0.00088, which could be ignored comparing the constant of 1.376 in the same formula. Thus, we obtained a new formula: \(n = 1.376 - 0.04 \times \text{Ratio}\), which was very similar to the regression formulas in untreated, post-LASIK/PRK and keratoconus eyes. It means that N\text{cal} and Ratio obtained from untreated, post-LASIK/PRK and keratoconus eyes have excellent similar linear relationship.

In our study, the total corneal powers were calculated using N\text{cal} in each group (K\text{cal}), the keratometric index of 1.3315 derived from Gullstrand schematic eye (K\text{1.3315}) and the conventional keratometric index of 1.3375 (K\text{1.3375}). And we also compared K\text{cal}, K\text{1.3315} and K\text{1.3375} to the total corneal powers calculated based on Gaussian optics formula (K\text{actual}). In all the 3 groups, K\text{cal} and K\text{actual} were comparable (all P = 1.00). K\text{1.3315} was 0.21 ± 0.11 D larger than K\text{actual} in untreated controls, and the difference increased to 0.56 ± 0.70 D in keratoconus eyes, and the difference was 0.85 ± 0.18 D. Similarly, K\text{1.3375} were 0.99 ± 0.12 D, 1.40 ± 0.76 D and 1.56 ± 0.16 D larger than K\text{actual} in untreated, keratoconus and post-LASIK/PRK eyes, respectively. In Ho et al’s study[5] in which Pentacam Scheimpflug camera system was applied, K\text{cal} and K\text{actual} were also comparable in untreated controls, but the 95% CI was larger than that in our study (-0.46 D to 0.46 D in Ho et al’s, -0.21 D to 0.21 D in ours). The differences between K\text{1.3315} and K\text{actual} K\text{1.3375} and K\text{actual} were larger than those in our study (0.85 D and 1.21 D in Ho et al’s study). And also the 95% CI were larger than ours (-0.03 D to 0.89 D and 0.75 D to 1.67 D in Ho et al’s study; -0.01 to 0.42 D and 0.76 to 1.21 D in ours). It demonstrated that the agreement between K\text{cal} and K\text{actual} obtained by RTVue FD-OCT was better than that the one obtained by Pentacam Scheimpflug camera system in untreated eyes. In Wang et al’s study[25] using Galilei Scheimpflug camerasy system to obtain data from untreated eyes and myopic-LASIK/PRK eyes, K\text{1.3375} was 1.30 D larger than K\text{actual} in untreated eyes, and the difference increased to 1.51 D in eyes after corneal refractive surgery. In Jin et al’s study[17], K\text{1.3375} was 1.26 D larger than K\text{actual} in untreated eyes, and the difference increased to 1.71 D in eyes after corneal refractive surgery. Table 4 showed the differences between K\text{1.3375} and K\text{actual} obtained
by distinct devices in untreated eyes and post-LASIK/PRK eyes. In our study, we found that the trends of the differences between $K_{1.3315}$ and $K_{\text{actual}}$, $K_{1.3375}$ and $K_{\text{actual}}$ coincided with the trend of Ratio, and opposed to the trend of calculated keratometric index in the 3 groups.

The limitations of this study included: 1) a small number of eyes were included in keratoconus group; 2) the repeatability of corneal parameters obtained by RTVue FD-OCT in keratoconus group has not been proved; 3) For post-LASIK/PRK group, only eyes after myopic-LASIK/PRK were included.

In conclusion, the ratio of anterior corneal curvature to posterior corneal curvature obtained by RTVue FD-OCT in untreated eyes is smaller than those obtained from Scheimpflug camera system and Slit-scan system in published studies, and also the calculated keratometric index obtained by RTVue FD-OCT in untreated eyes is larger than those obtained from Scheimpflug camera system and Slit-scan system in published studies. The calculated keratometric index was negatively related to the ratio of anterior corneal curvature to posterior corneal curvature in untreated, post-LASIK/PRK, and keratoconus eyes. Using the calculated keratometric index may improve the prediction accuracies of total corneal powers in untreated eyes, but not in post-LASIK/PRK and keratoconus eyes.

Author Contributions

Conceived and designed the experiments: YH JH QW. Performed the experiments: YH JH. Analyzed the data: YH AS TPU JH. Contributed reagents/materials/analysis tools: AS TPU XC SR. Wrote the paper: YH JH QW.

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