· Clinical Research ·

Comparison of total corneal power measurements obtained with different devices after myopic keratorefractive surgery

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Abstract

● **AIM:** To analyze the differences, agreements, and correlation among total corneal power parameters generated by different instruments after myopic keratorefractive surgery.

● **METHODS:** The prospective cross-sectional study included patients who underwent myopic keratorefractive surgery and received measurements of corneal power 3mo after surgery. Automated keratometer was used for the measurement of simulated keratometry (SimK), swept-source optical coherence tomography (SS-OCT) based biometer for total keratometry (TK), anterior segment-OCT for real keratometry (RK), and Scheimpflug keratometer for the true net power (TNP), the total corneal refractive power (TCRP) and equivalent K-readings (EKR). The differences among these parameters were analyzed, and the agreements and correlation between SimK and other total corneal power parameters were investigated.

● **RESULTS:** A total of 70 eyes of 70 patients after myopic keratorefractive surgery were included. The evaluated corneal power parameters were as follows: SimK 38.32±1.93 D, TK 37.54±2.12 D, RK 36.64±2.09 D, TNP 36.56±1.97 D, TCRP 36.70±2.01 D, and EKR 37.55±2.00 D. Pairwise comparison showed that there were significant differences ($P<0.001$) among all parameters except for between TK and EKR, RK and TNP, RK and TCRP ($P=1.000$, 1.000, 1.000, respectively). The limits of agreement between SimK and TK, RK, TNP, TCPR, and EKR were 1.08, 1.08, 1.43, 1.48, and 1.73 D, respectively. All parameters showed good correlation with SimK, and the correlation coefficients were 0.995, 0.994, 0.983, 0.982, and 0.975.

● **CONCLUSION:** Among the corneal power parameters after myopic keratorefractive surgery, the value of SimK is the largest, followed by TK and EKR, with TCRP, RK, and TNP being the smallest. The differences among the parameters may be attributable to the different calculation principles. Correct understanding and evaluation of corneal power parameters can provide a theoretical basis for taking advantage of the total corneal power to improve the accuracy of intraocular lens calculation after keratorefractive surgery.

● **KEYWORDS:** total keratometry; keratorefractive surgery; corneal power

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INTRODUCTION

Accurate intraocular lens (IOL) power calculation after keratorefractive surgery remains a challenge, in which the precise evaluation of postoperative corneal power plays a key role[1]. Traditionally, the equipment only measured the anterior cornea curvature radius ($R_{anterior}$), in which, the cornea is considered as a single refractive sphere, the ratio of the anterior to posterior curvature radius (A/P ratio) is assumed to be a constant, and a revised refractive index of 1.3375 is used to calculate the total power, namely, simulated keratometry (SimK)[2]. However, the keratorefractive surgery changes the anterior cornea surface but not the posterior, thus the A/P ratio is no longer a constant. After myopia surgery the A/P ratio increases and the traditional SimK will lead to an overestimation of the corneal power, thus resulting in hyperopia after cataract surgery[3].

With development in technology, the current equipment enables direct measurement of the total corneal power. According to different calculation principles, the total corneal power could be classified as keratometry based on Gaussian optic formula (K_{GOF}) and keratometry obtained by ray tracing method (K_{ray})[4-5].

According to the theory of Gaussian paraxial imaging for thick lenses, K_{GOF} could be calculated using the curvature radius of both anterior and posterior surface, the true refractive index, and the central corneal thickness (CCT) with the following formula:

$$K_{GOF} = \frac{n_1-n_0}{R_{anterior}} + \frac{n_2-n_1}{R_{posterior}} - \frac{CCT}{n_1} \times \frac{n_1-n_0}{R_{anterior}} \times \frac{n_2-n_1}{R_{posterior}} \quad \text{(a)}$$

where n_0=refractive index of air (=1.000), n_1=refractive index of the cornea (=1.376), n_2=refractive index of the aqueous humor (=1.336).

The ray tracing method follows the Snell's law. The parallel light refracts when passing through the anterior and posterior cornea surfaces. K_{ray} could be obtained by tracing the rays and measuring the actual focal length with the following formula:

$$K_{ray} = \frac{n}{f} \quad \text{(b)}$$

At present, a variety of devices can generate the abovementioned corneal power parameters, such as the swept-source SS-(OCT)-based IOLMaster 700 (Carl Zeiss Meditec AG, Germany), the anterior segment OCT-based CASIA 2 (Tomey, Nagoya, Aichi, Japan), and the Scheimpflug imaging-based Pentacam HR (OCULUS, GmbH, Wetzlar, Germany). The comparison of corneal power in normal non-operated cornea has been reported[6]. However, at present, there is no widely recognized standard for the evaluation of corneal power after keratorefractive surgery. The current study aims to analyze the differences, agreements, and correlation among total corneal powers generated by the above three devices.

SUBJECTS AND METHODS

Ethical Approval The current study complies with the principles of the Declaration of Helsinki. The study protocol was approved by the Ethics Committee of Beijing Tongren Hospital, Capital Medical University (TREC2022-KY006). The signed informed consent form was obtained from all participants.

Patients The prospective cross-sectional study enrolled patients who underwent myopic keratorefractive surgery three months ago in the refractive department in April 2022. All keratorefractive surgeries were performed by the same physician (Zhai CB). Inclusion criteria: 1) 18-45y, no ocular organic lesions, no history of ocular trauma or other surgeries; 2) The surgical technique adopted was laser *in situ* keratomileusis (LASIK) or small incision lenticule extraction (SMILE); 3) The postoperative visual acuity reached 1.0 without additional correction, and there were no complications such as dry eye or corneal opacity; 4) The intraocular pressure was within the normal range.

All enrolled participants received examinations by automated keratometer, IOLMaster 700, CASIA 2, and Pentacam HR under the same natural light. The examinations took no more than half an hour. The image quality for all eyes was checked and only one examination with a high-quality factor was documented.

Parameters 1) SimK: from Canon RK-F2. $R_{anterior}$ on the 3.0 mm ring was measured. According to the thin lens formula for paraxial imagery, SimK was calculated using the standard corneal index *n*=1.3375, with the formula below:

$$\text{SimK} = \frac{n-1.000}{R_{anterior}} \quad \text{(c)}$$

2) Total keratometry (TK): from IOLMaster 700, based on Gaussian thick lens optic formula. The anterior corneal curvature is measured by telecentric keratometry, and then the posterior corneal surface is fitted based on CCT measured by SS-OCT[7]. Therefore, the posterior surface measurement depends on the front surface to some extent.

3) Real keratometry (RK): from CASIA 2, based on Gaussian thick lens optic formula. The anterior and posterior corneal elevation maps are obtained using SS-OCT, and then the curvature radius and CCT are deduced according to the elevation map[8]. The measurement range was 3.0 mm zone.

4) True net power (TNP): from Pentacam HR, based on Gaussian thick lens optic formula. Pentacam HR uses a rotating Scheimpflug camera to obtain the elevation of both the anterior and posterior corneal surface. In addition, CCT is not taken into account in the calculation of TNP[9].

5) Total corneal refractive power (TCRP): from Pentacam HR, based on the ray tracing method. According to Snell's law, the incident parallel light refracts when passing through the anterior and posterior cornea surfaces. The measurement of TCRP does not rely on paraxial optics and considers the real status of the cornea, including asphericity[10].

6) Equivalent K-readings (EKR): generated by the Holladay Report of Pentacam HR. The simulated corneal refractive power is revised to reflect different posterior surfaces according to the distribution of posterior/anterior corneal surface ratio in the population and can be used in the conventional 1.3375-based IOL calculation formula[11] as follows:

$$\text{EKR} = \frac{0.376}{R_{anterior}} - \frac{0.03165}{R_{posterior}} \quad \text{(d)}$$

In order to ensure the consistency of the measurement range, the latter three parameters in 3.0 mm zone was recorded for analysis, TNP and TCRP with apex-centered and EKR with pupil-centered.

Statistical Analysis SPSS 22.0 and MedCalc 15.7 were used for the statistical analysis. Kolmogorov Smirnov test was carried out to test the normality of the data, and the measurement results were described as mean±standard deviation (SD). The single-factor repeated measures analysis

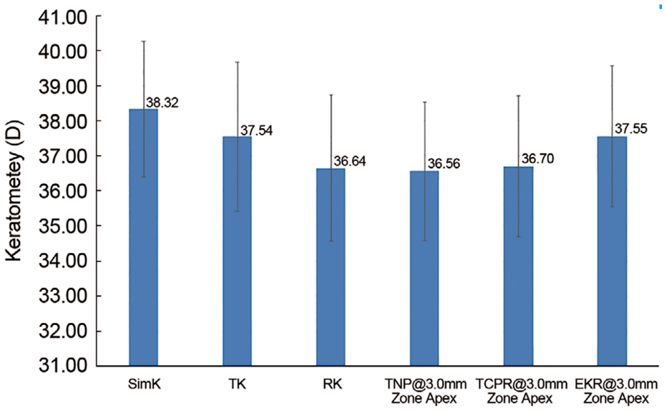

Figure 1 Histogram of different corneal power parameters SimK: Simulated keratometry; TK: Total keratometry; RK: Real keratometry; TNP: True net power; TCRP: Total corneal refractive power; EKR: Equivalent K-readings.

of variances (ANOVA) was used for the comparison of corneal powers, and the Bonferroni post hoc test was adopted for the pairwise comparison. The agreement between SimK and other corneal total powers was evaluated with the Bland-Altman method, and the 95% limits of agreement (LoA) were calculated. The Pearson correlation method was used to evaluate the correlation among parameters, calculate the correlation coefficient, and generate the scatter diagram. P<0.05 was considered statistically significant.

RESULTS

The current study enrolled a total of 70 patients (19 males and 51 females) who underwent keratorefractive surgery, with an average age of 28±6.00 (18 to 45)y. The preoperative spherical equivalent was -6.15±2.01 diopters (D; -13.25 to -2.50 D). Only the data of the right eye of all patients were included.

Differences Among Corneal Powers The corneal power parameters measured by the four devices were as follows: SimK was 38.32±1.93 (33.45 to 42.13) D, TK was 37.54±2.12 (31.78 to 41.58) D, RK was 36.64±2.09 (31.31 to 40.65) D, TNP was 36.56±1.97 (30.40 to 40.30) D, TCRP was 36.70±2.01 (30.45 to 40.50) D, and EKR was 37.55±2.00 (31.46 to 41.35) D (Figure 1).

The single-factor repeated measures ANOVA showed that there were significant differences among these parameters (F=522.526, P<0.001). Further pairwise comparison (Table 1) showed that there were significant differences (P<0.001) among these parameters except for between TK and EKR, RK and TNP, and RK and TCRP (P=1.000, 1.000, 1.000).

Agreement and Correlation Between SimK and Other Total Powers The Bland-Altman plot (Figure 2) of SimK and total power parameters showed that when compared with SimK, the percentage of data points within the 95% LoA were 95.7% (67/70) for TK, 97.1% (68/70) for RK, 94.3% (66/70) for TNP, 92.9% (65/70) for TCPR, and 94.3% (66/70) for EKR, indicating their strong consistency with SimK, with a 95% LoA range of 1.08, 1.08, 1.43, 1.48 and 1.73 D. Besides, all parameters had a significant correlation with SimK, and the correlation coefficients were r=0.995, 0.994, 0.983, 0.982, and 0.975 respectively (Table 2).

Table 1 Pairwise comparison of corneal power parameters

Parameters	Mean difference	P	95% confidence interval for difference	
			Lower bound	Upper bound
SimK				
TK	0.78±0.03	0.000	0.680	0.880
RK	1.68±0.03	0.000	1.580	1.779
TNP	1.76±0.04	0.000	1.630	1.895
TCRP	1.62±0.05	0.000	1.483	1.758
EKR	0.78±0.05	0.000	0.615	0.936
TK				
SimK	-0.78±0.03	0.000	-.880	-0.680
RK	0.90±0.03	0.000	0.824	0.974
TNP	0.98±0.05	0.000	0.847	1.118
TCRP	0.84±0.04	0.000	0.708	0.972
EKR	-0.01±0.06[a]	1.000	-0.172	0.162
RK				
SimK	-1.68±0.03	0.000	-1.779	-1.580
TK	-0.90±0.03	0.000	-0.974	-0.824
TNP	0.08±0.06[a]	1.000	-0.085	0.251
TCRP	-0.06±0.06[a]	1.000	-0.226	0.108
EKR	-0.90±0.06	0.000	-1.097	-0.711
TNP				
SimK	-1.76±0.04	0.000	-1.895	-1.630
TK	-0.98±0.05	0.000	-1.118	-0.847
RK	-0.08±0.06[a]	1.000	-0.251	0.085
TCRP	-0.14±0.01	0.000	-0.171	-0.114
EKR	-0.99±0.03	0.000	-1.072	-0.903
TCRP				
SimK	-1.62±0.05	0.000	-1.758	-1.483
TK	-0.84±0.04	0.000	-0.972	-0.708
RK	0.06±0.06[a]	1.000	-0.108	0.226
TNP	0.14±0.01	0.000	0.114	0.171
EKR	-0.85±0.03	0.000	-0.937	-0.753
EKR				
SimK	-0.78±0.05	0.000	-0.936	-0.615
TK	0.01±0.06[a]	1.000	-0.162	0.172
RK	0.90±0.06	0.000	0.711	1.097
TNP	0.99±0.03	0.000	0.903	1.072
TCRP	0.85±0.03	0.000	0.753	0.937

[a]The mean difference is not significant. SimK: Simulated keratometry; TK: Total keratometry; RK: Real keratometry; TNP: True net power; TCRP: Total corneal refractive power; EKR: Equivalent K-readings.

DISCUSSION

The accurate corneal power assessment is crucial for IOL calculation in cataract patients. While many devices allow the measurement of corneal power, nonetheless, there is no

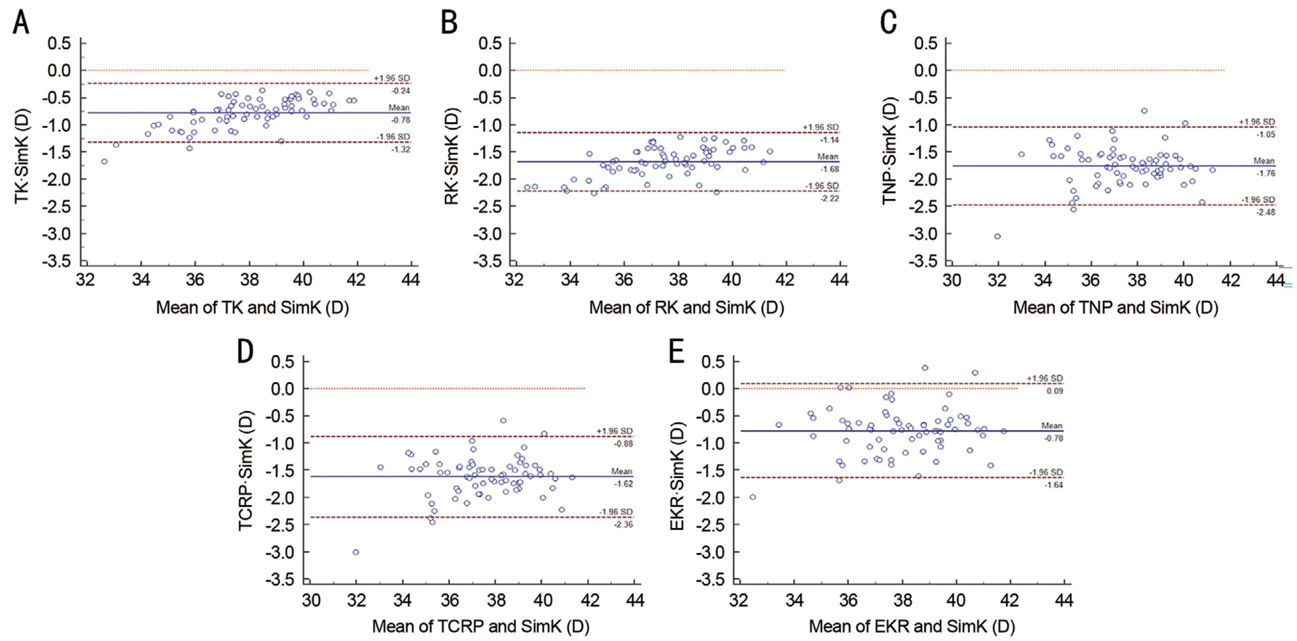

Figure 2 Bland-Altman plot between SimK and total power parameters A: TK and SimK; B: RK and SimK; C: TNP and SimK; D: TCRP and SimK; E: EKR and SimK. SimK: Simulated keratometry; TK: Total keratometry; RK: Real keratometry; TNP: True net power; TCRP: Total corneal refractive power; EKR: Equivalent K-readings.

Table 2 Agreement and consistency between SimK and other total corneal power parameters

Parameters	95% LoA (D)			Pearson correlation coefficient *r*
	Lower	Upper	Size	
SimK				
TK	-1.32	-0.24	1.08	0.995
RK	-2.22	-1.14	1.08	0.994
TNP (3.0 mm, zone, apex)	-2.48	-1.05	1.43	0.983
TCRP (3.0 mm, zone, apex)	-2.36	-0.88	1.48	0.982
EKR (3.0 mm, zone, pupil)	-1.64	0.09	1.73	0.975

SimK: Simulated keratometry; TK: Total keratometry; RK: Real keratometry; TNP: True net power; TCRP: Total corneal refractive power; EKR: Equivalent K-readings; LoA: Limits of agreement.

"gold standard"[12]. The underlying reason for the lack of unified evaluation criteria is that the human cornea is not a regular sphere, and the power of each point on the cornea varies. Therefore, the corneal power is not a fixed single value, but rather, it varies with different diameters, reference planes, and measurement methods. According to different calculation principles, corneal power could be classified as SimK and directly measured total power. The differences in these measurements have been reported before[13-14]. However, to the best of our knowledge, the relationship between SimK and total powers after keratorefractive surgery has not been fully clarified. Thorough clarification of such a relationship will help us have a deeper understanding of corneal refractive parameters and how to make the best of them to improve the accuracy of IOL calculation.

The current study found that the values of RK (36.64±2.09 D) and TNP (36.56±1.97 D) based on Gaussian thick lens formula were smaller than SimK (38.32±1.93 D) by 1.68±0.03 D and 1.76±0.04 D respectively, which was consistent with a difference of 1.71 D between SimK and K_{GOF} previously reported by Jin *et al*[15]. Here are a few explanations for the difference: 1) the reference plane is distinct. Norrby[16] pointed out that SimK referenced to the posterior vertex of cornea, and K_{GOF} to the second principal plane, in front of cornea, which is approximately 0.8 D less than at the posterior vertex; 2) K_{GOF} is further reduced by about another 0.9 D when the larger A/P ratio after corneal refractive surgery is used instead of the SimK ratio of 1.132 (7.7/6.8). In addition, the difference between RK and TNP was about 0.08±0.06 D, and the reason may be related to the fact that TNP did not include the corneal thickness factor. The corneal thickness contributes about 0.1 D in the Gaussian formula[4].

Although TK is also based on the Gaussian thick lens formula, the difference between TK (37.54±2.12 D) and SimK was only -0.78±0.05 D, and there was no significant difference between TK and EKR (37.55±2.00 D) obtained with Pentacam. The TK generated by IOLMaster 700 is a revised value. The manufacturer stated that the revised TK allows the direct use of the existing formula and IOL constant provided by the ULIB website without further optimization[17]. EKR is obtained by Holladay by revising the SimK in order to reflect the real posterior/anterior corneal surface ratio[18]. Although different principles are adopted for the two parameters, they are both generated to be used in the conventional IOL calculation formula based on the index 1.3375. Therefore, the difference between the revised TK and SimK would be smaller compared with other K_{GOF}. Many studies have reported that TK performs well in IOL calculation after keratorefractive surgery[19-20] and it is a parameter with great potential.

The current study found that after myopic keratorefractive surgery, TCRP based on the ray tracing method (36.70±2.01 D) is slightly higher than RP and TNP by 0.06±0.06 and 0.14±0.01 D. The finding was inconsistent with Wang *et al*'s[4] previous report that K_{ray} is 0.55 D smaller than K_{GOF}. The difference between K_{ray} and K_{GOF} mainly comes from the difference in posterior corneal calculation. K_{GOF} complies with the principle of paraxial optics, assuming that the incident light to posterior surface is parallel, while K_{ray} follows Snell's law, namely, the rays propagating to the posterior surface have already been refracted by the anterior surface, therefore, the real posterior refractive power would be smaller than the value based on paraxial optics and parallel light[4]. Therefore, theoretically, K_{ray} should be larger than K_{GOF}[6,12,14], which was consistent with our current study. After myopic keratorefractive surgery, the anterior surface flattens with the ability of refract light weakened, and the difference in posterior corneal calculation would be reduced. As a result, the differences between TCRP and RP, and TCRP and TNP were only 0.06 D and 0.14 D in the current study.

Theoretically, compared with SimK, the total corneal powers obtained based on Gaussian optic formula and ray tracing method are more accurate as they factor in both anterior and posterior corneal surfaces and the true refractive index, which would help improve the accuracy of IOL calculation. However, at present, the widely used IOL calculation formulas are all based on SimK, and various revised formulas based on SimK are still commonly used after keartorefractive surgery, such as Shammas[21], Haigis-L[22], and Maloney[23]. Apart from TK and EKR, other total power parameters are rarely used in IOL power calculation directly. Studying and exploring the relationship among these parameters, establishing the evaluation criteria for keratometry, and further developing specialized IOL calculation formulas for total corneal power will greatly improve the accuracy of IOL calculation after keratorefractive surgery.

There are two limitations to the current study. First, both LASIK and SMILE are eligible surgical techniques for inclusion. As the underlying rationale of both techniques is the change of the anterior cornea surface, which will lead to A/P ratio change, the authors did not further carry out subgroup analysis based on the surgical techniques. Whether different surgical techniques will affect the coefficient conversion among corneal powers needs further research with a larger sample. Second, lack of actual clinical result after cataract surgery in patients with a history of refractive surgery is the other limitation. Theoretically, ray tracing method can best reflect the real corneal refractive status compared with the Gaussian thick lens optic formula. But it still relies on feedback after cataract surgery to make the final conclusion.

In conclusion, the value of SimK was the largest, followed by TK and EKR, with TCRP, RK and TNP ranking at the last. The differences among the parameters may be attributable to the different calculation principles. The development of IOL power calculation formulas based on the proper use of total corneal power parameters should be the next step in future research.

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