Accuracy of corneal power measurements for intraocular lens power calculation after myopic laser in-situ keratomileusis
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Introduction
An increasing number of cataract surgeries in eyes after myopic keratorefractive surgery are expected within the next few decades. Although cataract extraction seems to be possible without major technical obstacles, intraocular lens (IOL) power calculation is problematic [1–5]. Determination of the lens implant power to give any desired postoperative refraction for routine cases requires measurement of two key variables: the central average corneal power and the axial length (AL) of the eye. These measurements are then entered into an appropriate formula [6–9]. Feeding of measured average $K$-reading in post–laser in-situ keratomileusis (LASIK) eyes into standard IOL power calculation formulas results in overestimation of keratometric diopters, and thus underestimation of IOL power leading to postoperative hyperopia. Further, because of extremely high patient expectations, accurate IOL power calculation is especially critical in refractive lens exchange [1–5].

Sources of error in estimating the corneal power after excimer laser corneal surgery are due to the fact that current keratometers and topography systems primarily measure the radius of curvature of the anterior surface of the central cornea. Keratometric diopters are derived from this radius of curvature using an effective refractive index to falsely consider a single refractive lens representing anterior and posterior surfaces. This effective refractive index is considered valid as long as the radii of the anterior and posterior surfaces of the cornea are proportionate and resemble that of the model eye. In LASIK, the radius of curvature of the anterior surface is considerably increased and the distance between both refractive surfaces is decreased. Therefore, this method of calculating keratometric diopters from the anterior radius of curvature is not accurate [1,10–14].

The aim of this work was to evaluate the accuracy of corneal power measurements for IOL power calculation after myopic LASIK.

Patients and methods
This is a combined prospective and retrospective clinical study that was conducted on 45 eyes that had undergone previous myopic LASIK and a successful
phacoemulsification cataract surgery. Cases with a complication during cataract surgery that affected the IOL position or required enlargement of the cataract section, as well as cases with corneal pathology, such as corneal opacities, were excluded from the study. The study complied with the Declaration of Helsinki. The protocol was approved by the local ethics committee of the Faculty of Medicine, Alexandria university, Egypt.

Examination of the patients included manual keratometry using a Nidek KM-450 Keratometer (Nidek, Gamagori, Japan), autokeratometry using a Topcon KR-8800 auto-keratorefractometer (Topcon, Tokyo, Japan) and an IOLMaster Optical Biometer (Carl Zeiss Meditec, Jena, Germany). The software version used was 'IOLMaster with Advance Technology V.5.4'. Imaging with a Scheimpflug camera was carried out using Pentacam (software version 1.17r37; Oculus, Wetzlar, Germany). The following K readings were obtained from Pentacam: Sim-K, Holladay equivalent K readings (EKR) at 1, 2, 3, 4, and 4.5 mm, and true net K. AL was obtained from the IOLMaster optical biometer.

IOLMaster assessment of the corneal radii is based on image analysis, in which distances between light reflections on the cornea are measured. Six light spots are projected hexagonally in a 2.3 mm radius on the cornea. The device records the reflection of these spots, measuring the separation of opposite pairs of light spots and calculating the toroidal surface curvature. The mean of three measurements was used as the corneal power to be entered into IOL power calculation formulas [15,16].

The true net corneal power map uses real anterior curvature, posterior curvature, and corneal thickness values and an accordingly modified refractive index. The true net power is based on the Gaussian optics formula and accordingly uses a modified refractive index rather than the real refractive index of air, cornea, and aqueous [5]. The simulated keratometry values are calculated by averaging power obtained from the anterior corneal radius measured along the 3.0 mm central ring. The Sim-K is calculated by means of the keratometric refractive index of 1.3375 [17]. The Pentacam unit was programmed to calculate an EKR (equivalent K), labeled the Holladay report. The software of the unit evaluates the measurements taken at the central corneal front surface and adjusts them to reflect the difference in the back-surface power of the cornea for the mean of the population [18,19].

All cases underwent routine phacoemulsification cataract surgery and foldable IOL in the bag implantation through clear corneal tunnel incision. The power of the implanted IOL was determined according to the method of calculation preferred by the operating surgeon. The implanted IOL type was a hydrophobic acrylic IOL (Acrysof SA60AT; Alcon Surgical Inc., Fort Worth, Texas, USA).

The final refraction was obtained 1–4 months after surgery. Autorefraction using a Topcon KR-8800 autokeratorefractometer (Topcon) was used as a starting point for the examination. Fine adjustment of the refraction was aided by the retinoscopy findings and Jackson cross-cylinder technique.

Haigis formula, SRK/T formula, and SRK/T formula with double-K modification [20] were used with all available K readings for each case. Haigis-L formula [21] (available on IOLMaster) was also used. The Shammas No History Method (Shammas-modified IOLMaster K readings, where modified $K = 1.14 \times K_{post-LASIK}^2 - 6.8$) was used in the Shammas-PL formula [22] (the formula was entered on an Excel sheet by the authors). The authors conducted regression analysis of post-LASIK eyes and deduced a regression formula for the commonly used method using IOLMaster K values with SRK/T formula. IOL power was determined by the deduced regression formula and the results were tabulated in a sheet. Combinations of means of different IOL powers calculated using various formulas were hypothetically calculated and the best outcomes were shown.

The following parameters were used in the different formula calculations (as stored in the IOLMaster software):

1. For the hydrophobic acrylic IOL Acrysof SA60AT (Alcon Surgical Inc.):
   - (a) SRK/T formula: $A$-constant = 118.7.
   - (b) Haigis formula: $a_0 = -0.091$, $a_1 = 0.231$, $a_2 = 0.179$.

For the double-K modification of SRK/T, an average $K$ value of 43.86 D was used as the prerefractive surgery $K$ value (43.86 D is the default value used with the web-based American Society of Cataract and Refractive surgery 'ASCRS' IOL power calculator).

The predictive accuracy of the calculation was analyzed by calculating the refraction prediction error [which equals actual manifest refraction spherical equivalent (MRSE) minus predicted MRSE]. Calculation of the mean absolute error (MAE) of the above-mentioned values was done. The MAE is derived from the algebraic sum of the absolute values of the errors. This shows whether the formula's outcome is far from or near emmetropia. In addition, percentages of correct
refraction predictions within ± 0.50, ± 1.00, and ± 2.00 D were derived.

Statistical analysis
Clinical findings were statistically evaluated using Excel 2007 (Microsoft Corp., Redmond, WA, USA) and SPSS software (version 15.0; SPSS Inc., Chicago, Illinois, USA). Means, SDs, and ranges were calculated. To check for normal distribution, the Kolmogorov–Smirnov test was applied. Comparisons of the means of normally distributed data were performed with the t-test for paired samples and with analysis of variance (ANOVA). The χ²-test and Fisher’s exact test were used to compare different frequencies. A P value less than 0.05 was considered statistically significant.

Results
The study included 45 eyes. The patients' ages ranged from 33 to 65 years (mean 51.27 ± 7.31 years). The mean AL was 28.66 ± 2.78 mm (range 24.01–33.48 mm). The mean anterior chamber depth as measured by IOLMaster was 3.43 ± 0.35 mm (range 2.74–4.86 mm).

Table 1 shows the various K values of the included eyes, measured following different methods. The steepest mean K value with manual keratometry (37.48 ± 2.86 D) followed by automated keratometry (37.31 ± 2.83 D) and the IOLMaster mean K value (37.06 ± 2.98 D) were steeper than any other mean K value measured by the Pentacam. The flattest mean K values were EKR at 1 mm (34.37 ± 3.63 D) and true net power from Pentacam (34.54 ± 3.15 D). The EKR revealed increasing steepness from smaller diameter to larger (i.e. EKR at 1 mm was the flattest mean, which increased progressively to EKR at 4.5 mm, which was the steepest mean).

Using the Haigis formula with different K readings, it was found that the results were significantly more accurate with EKR 3 mm and EKR 4 mm (P < 0.001). The refractive outcome was significantly better on using EKR 4 mm than on using EKR 3 mm (97.8 and 95.6% were within ± 2 D and 37.8 and 35.6% were within ± 0.5 D; P < 0.05). Similarly, the MAEs were significantly different between EKR 3 mm and EKR 4 mm (P < 0.001) (Table 2).

Using the SRK/T formula with different K readings, it was found that using true net K gave the best results (P < 0.001), with 100.0% of cases within ± 2 D, 71.1% within ± 1 D, and 31.1% within ± 0.5 D. The MAE was 1.06 ± 0.70 D (Table 2).

In addition, linear regression analysis was used to deduce the following regression formula (Table 2) to calculate IOL power using SRK/T formula and IOLMaster K readings:

\[
\text{IOL power} = \text{SRK/T calculated power using IOL Master K readings} + (0.181 \times \text{AL}) - 2.151
\]

Using the double-K SRK/T formula with different K readings, it was found that the results were significantly more accurate with EKR 4 mm (P < 0.001), with 97.8% of cases within ± 2 D, 80.0% within ± 1 D, and 42.2% within ± 0.5 D. The MAE was 0.62 ± 0.49 D (Table 2).

### Table 1 K values of the included eyes in the post-laser in-situ keratomileusis group

| K values       | Mean ± SD (D) | Range (D) |
|---------------|---------------|-----------|
| Auto K        | 37.31 ± 2.83  | 31.50–45.25 |
| Manual K      | 37.58 ± 2.86  | 31.75–45.50 |
| IOLMaster K   | 37.06 ± 2.98  | 31.25–44.94 |
| Pentacam      |               |           |
| Sim-K         | 36.55 ± 3.08  | 30.30–44.10 |
| EKR 1 mm      | 34.37 ± 3.63  | 30.20–42.60 |
| EKR 2 mm      | 34.72 ± 3.45  | 30.20–42.70 |
| EKR 3 mm      | 35.35 ± 3.19  | 30.20–43.00 |
| EKR 4 mm      | 36.22 ± 2.90  | 30.20–43.50 |
| EKR 4.5 mm    | 36.73 ± 2.76  | 30.30–43.70 |
| True net K    | 34.54 ± 3.15  | 27.70–41.90 |

EKR, Holladay equivalent K reading.

### Table 2 Refractive outcome of intraocular lens power calculations using various formulations

| Formulas          | ± 2 D [n (%)] | ± 1 D [n (%)] | ± 0.5 D [n (%)] | Mean error (D) [mean ± SD (range)] | Mean absolute error (D) [mean ± SD (range)] | P       |
|-------------------|---------------|---------------|-----------------|-----------------------------------|---------------------------------------------|--------|
| Haigis using EKR 3 mm | 43 (95.6)     | 34 (75.6)     | 16 (35.6)       | -0.37 ± 0.88 (−2.44 to 1.90)     | 0.76 ± 0.57 (0.01–2.44)                     | <0.001*|
| Haigis using EKR 4 mm | 44 (97.8)     | 32 (71.1)     | 17 (37.8)       | 0.46 ± 0.81 (−1.86 to 2.50)      | 0.76 ± 0.54 (0.08–2.50)                     | <0.001*|
| SRK/T true net K   | 45 (100.0)    | 32 (71.1)     | 14 (31.1)       | 0.18 ± 0.88 (−1.90 to 1.67)      | 1.06 ± 0.70 (0.03–1.90)                     | 0.019* |
| Double-K SRK/T using Sim-K | 44 (97.8) | 32 (71.1) | 18 (40)         | 0.44 ± 0.74 (−1.58 to 2.28)      | 0.68 ± 0.52 (0.00–2.28)                     | <0.001*|
| Double-K SRK/T using EKR 4 mm | 44 (97.8) | 36 (80.0) | 19 (42.2)       | 0.10 ± 0.79 (−2.04 to 1.97)      | 0.62 ± 0.49 (0.00–2.04)                     | 0.008* |
| Shammas-PL         | 45 (100.0)    | 38 (84.4)     | 26 (57.8)       | -0.24 ± 0.67 (−1.98 to 1.29)     | 0.54 ± 0.45 (0.03–1.98)                     | 0.007* |
| Haigis-L           | 41 (91.1)     | 33 (73.3)     | 20 (44.4)       | -0.47 ± 0.90 (−2.79 to 1.62)     | 0.74 ± 0.70 (0.00–2.79)                     | 0.001* |
| Regression formula | 44 (97.8)     | 36 (80.0)     | 22 (48.9)       | -0.02 ± 0.87 (−3.21 to 1.60)     | 0.66 ± 0.57 (0.03–3.21)                     | 0.669 |
| Shammas-PL+double-K SRK/T using EKR 4 mm | 45 (100.0) | 42 (93.3) | 30 (66.7)       | -0.07 ± 0.56 (−1.04 to 1.30)     | 0.48 ± 0.41 (0.02–1.30)                     | —      |

EKR, Holladay equivalent K reading; *Statistically significant; Mean absolute error of different combinations is compared with that of ‘Shammas-PL+double-K SRK/T using EKR 4 mm’. **
Using Haigis-L, the MAE was 0.74 ± 0.70 D, with 91.1% of cases within ± 2 D, 73.3% within ± 1 D, and 44.4% within ± 0.5 D. Using Shammas-PL, the MAE was 0.54 ± 0.45 D, with 100% of cases within ± 2 D, 84.4% within ± 1 D, and 57.8% within ± 0.5 D (Table 2).

The data derived from IOLMaster and Pentacam with the Holladay report were used in various combinations of formulas, with statistically significantly good results. The mean of the IOL power by each formula is calculated. To avoid confusion, only the results of the best combinations were shown, which included:

(1) ‘Shammas-PL+Haigis using EKR 4 mm’.
(2) ‘Shammas-PL+double-K SRK/T using EKR 4 mm’. 
(3) ‘Shammas-PL+SRK/T using true net K’. This combination is useful when using the Scheimpflug imaging system that does not provide the Holladay report that shows the different EKR.

The combinations mentioned above yielded excellent results (Table 3). On using the \( \chi^2 \)-test to compare the number of cases within ± 1 and ± 0.5 D of the five combinations, the result was not statistically significant (\( \chi^2 = 1.823 \), \( P = 0.986 \)).

The refractive outcome of the combinations of formulas showed strong positive correlation (\( r > 0.8 \), \( P < 0.001 \)) to each other. On using ANOVA to compare the MAEs of the combinations, we found no significant difference (\( P = 0.132 \)). On using multiple paired \( t \)-tests to compare the MAEs of the combinations, the combination of ‘Shammas-PL+double-K SRK/T formula using EKR 4 mm’ was found to have significantly better outcome than the other combinations (\( P = 0.014 \)).

Table 2 shows the summary of the formulas and combinations that yielded the best results. On using the \( \chi^2 \)-test to compare the number of cases within ± 2 D, within ± 1 D, and within ± 0.5 D, we found no statistically significant difference (\( \chi^2 = 21.236 \), \( P = 0.170 \)). On using the \( \chi^2 \)-test to compare the Shammas-PL+double-K SRK/T using EKR 4 mm with other \( K \) values individually, we found significantly better results than those of Haigis using EKR 3 mm (\( \chi^2 = 8.420 \), \( P = 0.015 \)), Haigis using EKR 4 mm (\( \chi^2 = 9.319 \), \( P = 0.009 \)), SRK/T using true net \( K \) (\( \chi^2 = 13.268 \), \( P = 0.001 \)), and double-\( K \) SRK/T using Sim-\( K \) (\( \chi^2 = 8.544 \), \( P = 0.014 \)) but no statistically significantly different results from double-\( K \) SRK/T using EKR 4 mm, Shammas-PL formula, Haigis-L formula, or regression formula. The result of comparison of regression formula with other \( K \) values individually was not statistically significant (\( P > 0.05 \)).

On using ANOVA to compare the different MAEs, we found a statistically significant difference (\( P < 0.001 \)). The different MAEs were compared with those of ‘Shammas-PL+double-\( K \) SRK/T using EKR 4 mm’ and were found to be statistically significant except for the ‘regression formula’ (\( P = 0.669 \)) (Table 2).

### Discussion

Patients who have undergone a previous refractive surgery have high expectations as regards their visual outcome after cataract surgery. Despite the use of many methods for IOL power calculation, the postoperative refractive errors are less predictable in those patients compared with those who have not undergone prior refractive surgery. Unpredicted results are most likely due to inaccurate measurements of the corneal power following keratorefractive surgery (in addition to the error in estimation of ELP by third-generation formulas such as SRK/T) [1,20,23,24].

The major problem noted in the literature on IOL power calculation after corneal refractive surgery was the relatively small number of patients included in the studies. For example, Masket [25] included 30 eyes, Latkany et al. [26] included 21 eyes, Shammas and Shammas [22] studied 15 eyes, and Aramberri [20] studied nine cases. Some newer studies included larger numbers of eyes; for example, Haigis [21] included 187 eyes retrospectively (the author mentioned some limitations, such as that the patient selection may have been biased toward better results and that there was a lack of additional information about the included patients such as age, best corrected visual acuity (BCVA), and time between cataract surgery and refraction measurement). In addition, the exact role of the many \( K \) values reported in the Holladay report was not properly evaluated beforehand.

In the present study, \( K \) readings measured by different instruments were used to calculate IOL power

### Table 3 Comparison between different means of combinations of formulas

| Combinations of formulas                  | ± 2 D [%] | ± 1 D [%] | ± 0.5 D [%] | Mean error (D) | Mean absolute error (D) |
|------------------------------------------|----------|----------|-------------|----------------|------------------------|
|                                           | [n (%)]  | [n (%)]  | [n (%)]     | [mean ± SD (range)] | [mean ± SD (range)]    |
| Shammas-PL+Haigis EKR 4 mm               | 45 (100.0) | 42 (93.3) | 29 (64.4)   | 0.11 ± 0.56 (-0.89 to 1.56) | 0.44 ± 0.36 (0.01–1.56) |
| Shammas-PL+double-\( K \) SRK/T EKR 4 mm | 45 (100.0) | 42 (93.3) | 30 (66.7)   | -0.07 ± 0.56 (-1.04 to 1.30) | 0.45 ± 0.34 (0.03–1.30) |
| Shammas-PL+SRK/T using true net \( K \)  | 45 (100.0) | 40 (88.9) | 25 (55.6)   | -0.03 ± 0.65 (-1.75 to 1.19) | 0.51 ± 0.40 (0.01–1.75) |

EKR, Holladay equivalent \( K \) reading.
after myopic LASIK. The manual $K$ and automated $K$ readings were steeper than that measured by the IOLMaster, and therefore their use in IOL power calculation formulas would have left the patient in a more hyperopic condition. The EKR showed gradual transition from flattest at 1 mm to steepest at 4.5 mm. The various possibilities of incorporating those $K$ values into IOL power calculation were tried. The true net $K$ yielded one of the flattest $K$ values that nearly approached EKR 1 mm. The mean of Sim-$K$ values was slightly flatter than IOLMaster $K$ values. Tang et al. [19] reported that the EKR at 4.5 mm measured a steeper corneal power than true corneal power based on paraxial optics and surgical outcome data.

In the present study, when calculating postrefractive surgery IOL power using IOLMaster only, the best refractive outcome was obtained on using the Shammas-PL formula. The absolute IOL prediction error was $0.77 \pm 0.65$ D, with 100.0% of cases within ± 2 D, 84.4% of cases within ± 1 D, and 57.8% of cases within ± 0.5 D. Shammas and Shammas [22] in their study showed that using Shammas-modified $K$ values yielded the best results with the Shammas-PL formula (mean absolute IOL prediction error $0.55 \pm 0.31$ D, with 93.3% of cases within ± 1 D) and Holladay 2 formula (mean absolute IOL prediction error $0.55 \pm 0.41$ D, with 93.3% of cases within ± 1 D).

Another alternative to using IOLMaster only is the use of Haigis-L formula. However, this formula yielded less accurate results than the Shammas-PL formula [ME was $-0.47 \pm 0.90$ D (range $-2.79$ to 1.62 D), 91.1% of cases were within ± 2 D, 73.3% of cases were within ± 1 D, and 44.4% of cases were within ± 0.5 D]. Haigis [21] published better results for Haigis-L formula in his series of 186 eyes [ME was $-0.04 \pm 0.70$ D (range $-2.30$ to +2.40 D), 98.4% of cases were within ± 2 D, 84.0% of cases were within ± 1 D, and 61.0% of cases were within ± 0.5 D].

Regression analysis was used to deduce a formula to modify the IOL power calculated using the SRK/T formula with the IOLMaster $K$ value. This modification aimed at providing a simple method to calculate the postrefractive surgery IOL power without the need for the Pentacam. The outcome of the regression formula was better than that of the Haigis-L formula but less than that of the Shammas-PL formula. It did not show a statistically significant difference from the mean of the combination of ‘Shammas-PL+double-$K$’ SRK/T formula using EKR 4 mm’.$^2$. However, $R^2 = 0.184$ was not a strong correlation for the prediction formula.

Data from Pentacam without the Holladay report improved the accuracy of IOL power calculation after keratorefractive surgery. The SRK/T formula using true net $K$ yielded good results (100.0% of cases were within ± 2 D, 71.1% of cases were within ± 1 D, and 31.1% of cases were within ± 0.5 D), which were inferior to the results of Kim et al. [5] using the same formula (93% of cases were within ± 1 D, 70% of cases were within ± 0.5 D). The combination of ‘Shammas-PL+SRK/T using true net $K$’ yielded excellent results (100.0% of cases were within ± 2 D, 88.9% of cases were within ± 1 D, and 55.6% of cases were within ± 0.5 D), which was better than the results obtained with Shammas-PL alone. An important limitation that has to be reported is the lack of constant optimization. The true net power and Sim-$K$ from Pentacam require different optimized constants in unoperated eyes and, of course, also in post-LASIK eyes.

Another question to be answered was: Did the use of EKR improve the accuracy of IOL power calculation after keratorefractive surgery? Tang et al. [19] reported that EKR was inaccurate in IOL power calculation in virgin corneas and in those with a history of LASIK, PRK, or RK using current IOL power calculation formulas. They only used EKR at 4.5 mm. In this study we tried to address this issue properly by using EKR at 1, 2, 3, 4, and 4.5 mm.

The most accurate EKR with the Haigis formula was EKR 4 mm (the refractive outcome was modest, with 97.8% of cases within ± 2 D, 71.1% of cases within ± 1 D, and 37.8% of cases within ± 0.5 D). The most accurate EKR with the double-$K$ SRK/T formula was also EKR 4 mm (the refractive outcome was good, with 97.8% of cases within ± 2 D, 80.0% of cases within ± 1 D, and 42.2% of cases within ± 0.5 D). The results of SRK/T using different EKR were less satisfactory. None of the EKR values showed better outcome than the true net power using the SRK/T formula.

The concept of using multiple formulas to improve the accuracy of IOL calculations after myopic LASIK has been published, albeit with older generation formulas [27]. It was found that the means of combinations of formulas yielded excellent results that were better than any single formula alone (100.0% of cases within ± 2 D, 88.9% of cases within ± 1 D, and ±55.6% of cases within ± 0.5 D). The best combination was ‘Shammas-PL+double-$K$’ SRK/T using EKR 4 mm’ (100.0% of cases were within ± 2 D, 93.3% of cases were within ± 1 D, and 66.7% of cases were within ± 0.5 D).

In conclusion, it is recommended to use the Shammas-PL formula or the simple regression formula:
IOL power = SRK/T calculated power using IOL Master K readings + (0.181 × AL) – 2.151 when using the IOLMaster alone (both are better than the Haigis-L formula incorporated in the IOLMaster software). When using Pentacam without the Holladay report, the combination of ‘Shammas-PL+SRK/T formula using true net K’ yielded the best results. When using Pentacam with the Holladay report, it is recommended to use the combination of ‘Shammas-PL+double-K SRK/T formula using EKR 4 mm’.

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Conflicts of interest
None declared.

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