The T2 Formula

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Introduction

The SRK/T formula was first described in 1990 [1] and has subsequently become one of the most widely used formulas used to predict the intraocular lens (IOL) power for implantation following cataract surgery. The original article contained errors, which were later corrected [2]. In 1993, Haigis reported a further problem with the published version of the SRK/T formula in which, for particular combinations of axial length and corneal power, the formula algorithm may attempt to take the square root of a negative number leading to erroneous results [3]. This is "the imaginary anterior chamber depth (ACD) problem", and in their reply, the SRK/T authors suggested a solution. In the same response, they also discussed that, under certain circumstances, a non-physiological irregularity in the predicted IOL power is observed [3]. The authors called this the "SRK/T cusp" (Fig. 54.1) and invited colleagues to send examples of cases in which this phenomenon was observed to investigate it further.

Our study was the first to investigate the cause of the SRK/T cusp and to systematically evaluate its clinical significance [4]. We then developed a modification of the formula to eliminate the cusp phenomenon and evaluated its performance. We refer to the new formula algorithm as the T2 formula [4].

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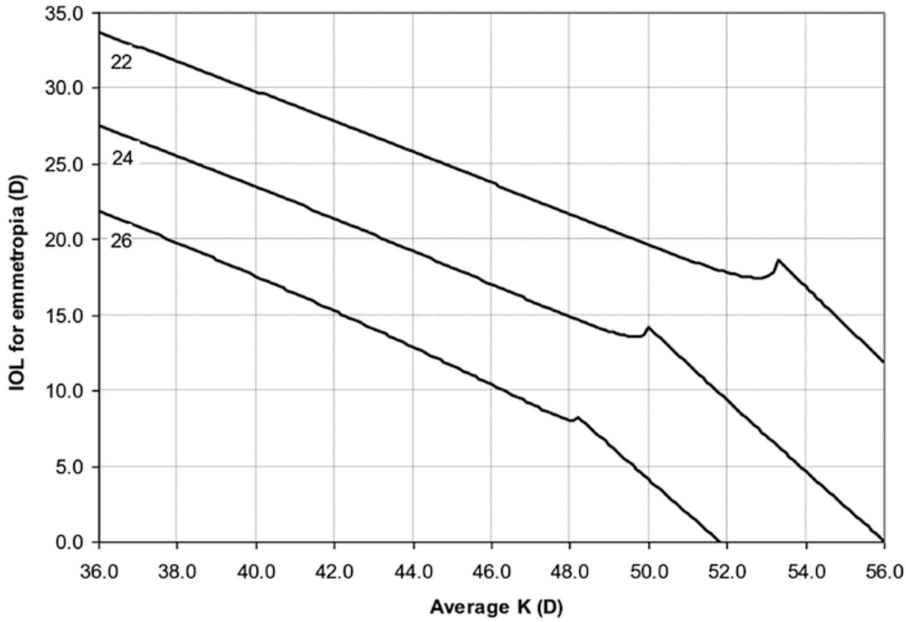

Fig. 54.1 Graph showing non-physiological discontinuity in the IOL power for emmetropia calculated by the SRK/T formula with varying corneal power (K) at three different axial lengths (22, 24 and 26 mm). Reproduced with permission from [4]

Non-physiological Behaviour in the SRK/T Formula

The SRK/T formula determines the required IOL power (in dioptres) for a desired post-operative refraction from the pre-operative average corneal power, *K* (dioptres), and axial length, *L* (millimetres).

Our study examined each of the steps of the SRK/T formula algorithm for non-physiological behaviour by varying the input variables and plotting a graph of the output value. For physiological behaviour, one would expect to see a smooth curve over the physiological range of input variables. We defined non-physiological behaviour as an unexpected or illogical discontinuity in the curve, and we observed such non-physiological behaviour in the calculation of corrected axial length and corneal height.

We investigated the possible impact of the non-physiological behaviour of the SRK/T formula with reference to a large cataract surgery database. The reference database records the full biometric data (measured with the IOL Master) and refractive outcome in 11,189 eyes, using ten different models of posterior chamber IOL [4].

Non-physiological Behaviour in the Calculation of Corrected Axial Length

Step 2 of the SRK/T formula algorithm derives the corrected axial length, known as *LCOR*, which for axial lengths greater than 24.2 mm entails a quadratic expression [1–3]. As a result, *LCOR* reaches its maximal value of 27.62 mm at an axial length of 36.20 mm. For axial lengths above this value, *LCOR* progressively decreases, a behaviour which is illogical. We refer to this phenomenon as the "*LCOR* reversal". The LCOR reversal affects only extremely long eyes with axial lengths greater than 36.20 mm. These eyes are very uncommon; in the reference database, we found no such examples [4].

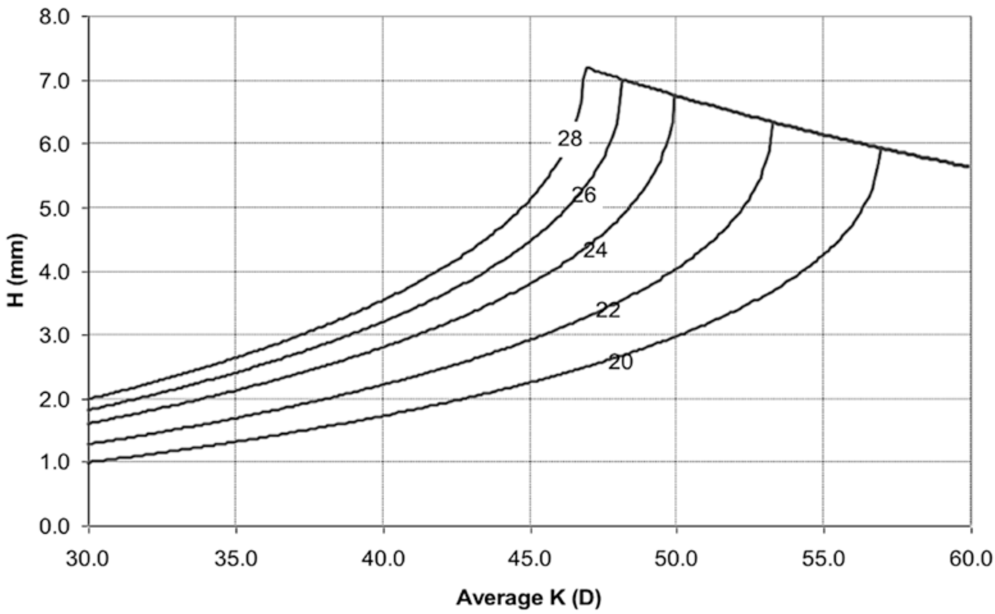

Fig. 54.2 Graph showing the non-physiological variation of the SRK/T calculated corneal height (H) with corneal power (average K) for different axial lengths as indicated (mm). Reproduced with permission from [4]

Non-physiological Behaviour in the Calculation of Corneal Height

Step 4 of the SRK/T formula algorithm calculates the corneal height, *H* [1–3]. Fig. 54.2 shows the variation of *H* with various combinations of *L* and *K*. The shape of the curve is clearly non-physiological in all cases, with *H* increasing rapidly to a peak with increasing *K*, after which the gradient reverses. The shape of the curve resembles the non-physiological irregularity of the SRK/T cusp phenomenon (Fig. 54.1). We therefore refer to the peak of the curve as the corneal height cusp. For a given axial length, *L*, there is a unique corneal power, K_{cusp}, at which the corneal height, *H*, is maximal.

Clinical Significance of the Corneal Height Cusp

The shape of the corneal height curves suggests that, in the vicinity of the cusp, the SRK/T formula may over-estimate the corneal height (Fig. 54.2). In consequence, the estimated effective IOL position will be further from the cornea and closer to the retina, resulting in an over-estimate of IOL power. This hypothesis fits empirically with the original observation of the SRK/T cusp (Fig. 54.1) [3].

Figure 54.3 plots the axial length and corneal power of the eyes in the reference database. The figure also plots K_{cusp} against *L* and, for ease of interpretation, indicates five dioptre-wide bands below the cusp. Two eyes have measured corneal powers greater than K_{cusp} for their axial length ("above the cusp"). 1234 eyes (11.0%) fall into the band within 5 dioptres below the cusp, 9593 (85.7%) are between 5 and 10 dioptres below the cusp and 360 (3.2%) between 10 and 15 dioptres below [4]. The eyes above or close to the cusp may be affected by the SRK/T corneal height error, but it is not possible to determine from these data how many and to what degree.

We applied the SRK/T formula "backwards" to each eye in the reference database to determine the value of *H* that would be required to give the observed refractive outcome. We refer to this as the back-calculated corneal height, H_{back}. We then calculated the corneal height error, $H - H_{back}$, for

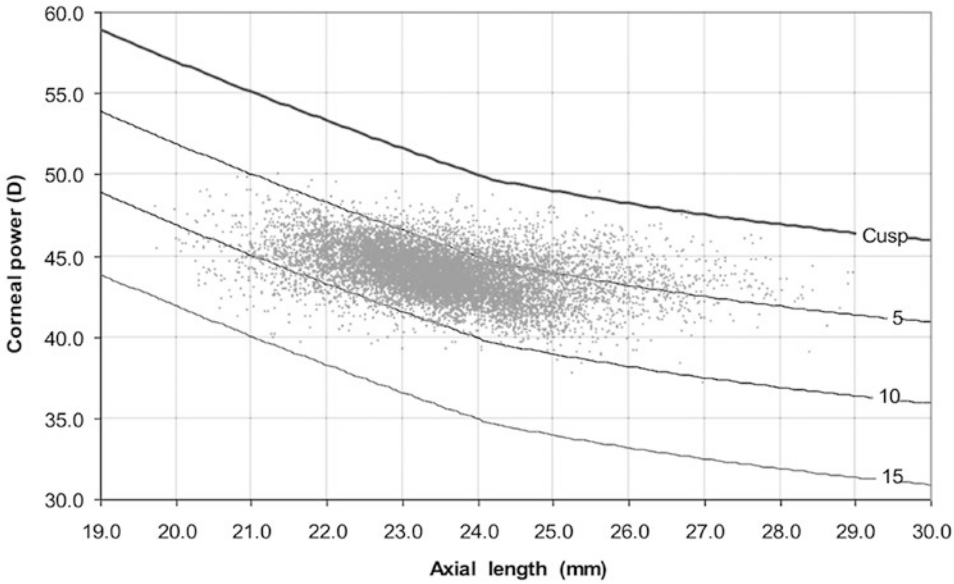

Fig. 54.3 Graph showing the combination of axial length and corneal power at which the SRK/T corneal height cusp occurs (heavy line). The light lines highlight bands 5, 10 and 15 dioptres below the cusp. The points plotted represent the axial length and corneal power combination of the 11,189 eyes from the reference database. Reproduced with permission from [4]

each eye. We segregated eyes from the database into one dioptre bands below the cusp, and Fig. 54.4 shows the mean corneal height error within each band. The graph confirms that the SRK/T formula tends to over-estimate the corneal height as the corneal power approaches the cusp. The SRK/T error in corneal height prediction appears to be systematic, progressively decreasing with increasing distance below the cusp such that, for corneal powers 7 D or more below the cusp, the predicted corneal height tends to be an under-estimate. The differences in corneal height error between the bands were highly statistically significant (one-way ANOVA: $p < 0.0001$) [4].

As we hypothesized, the SRK/T formula tends to over-estimate the corneal height for eyes with a combination of L and K close to the cusp and, as a result, potentially over-estimates the IOL power. However, Fig. 54.4 also shows that SRK/T under-estimates the corneal power for eyes more than 7 D below the cusp with a likely under-estimate of IOL power. These systematic errors, being in opposite directions, will cancel out across a dataset and have therefore not previously been identified. The corneal height error is the most likely explanation for the observation in several studies that the optimized SRK/T A-constant varies with corneal power and, indirectly, axial length [5–8].

The clinical significance of the corneal height error in an individual eye depends on its geometry, but for an average eye (axial length 23 mm and corneal power 44 D) a 0.3 mm error in corneal height prediction results in an IOL power prediction error of 0.25 D. In the reference dataset, 3485 eyes (31.1%) had a corneal height error of more than 0.3 mm [4].

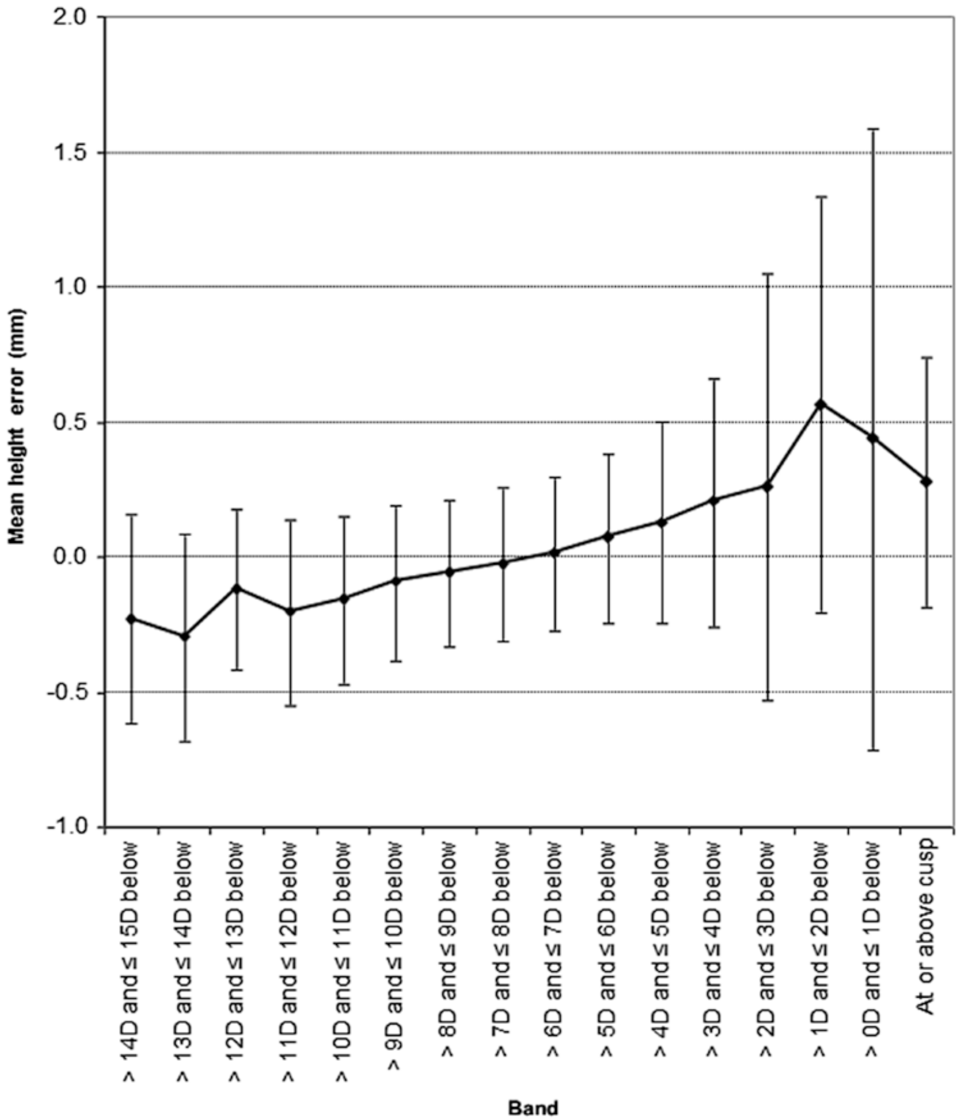

Fig. 54.4 Mean difference between the SRK/T formula's predicted corneal height and the back-calculated corneal height in 11,189 eyes, banded according to their proximity to the cusp (bars indicate standard deviation). Reproduced with permission from [4]

Solution to the SRK/T Cusp: The T2 Formula

The SRK/T cusp arises from the equations employed to predict the corneal height [1–3]. Elimination of the cusp, therefore, requires a new method for corneal height calculation. One solution is to use a regression formula derived from real data, and if a linear regression model is employed, the resulting formula will be free of non-physiological anomalies.

We randomly divided the reference dataset of 11,189 eyes into a development subset used to derive a regression formula for corneal height calculation (5588 eyes), and an evaluation subset to assess its performance in comparison with the standard SRK/T formula (5601 eyes) [4].

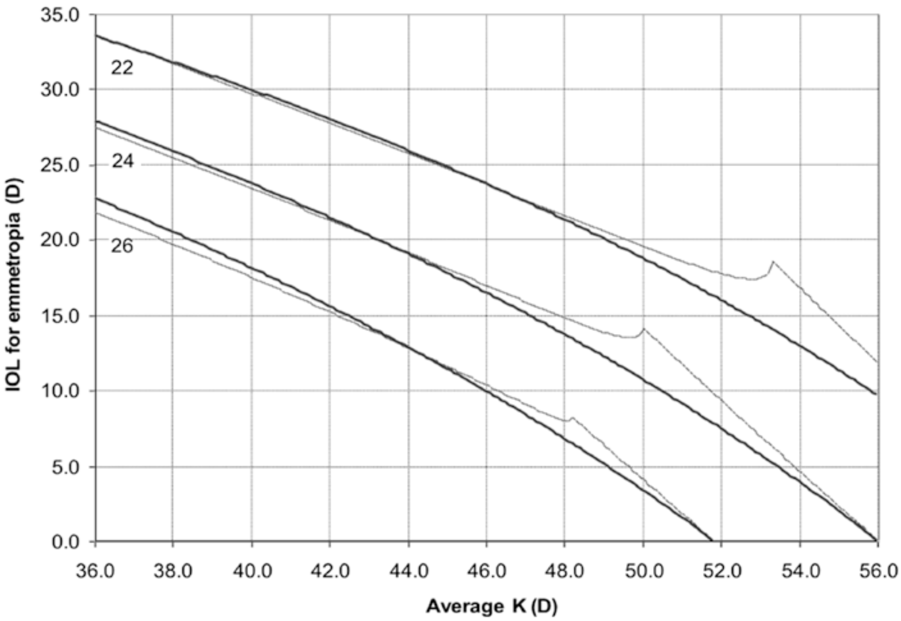

Fig. 54.5 Graph showing IOL power for emmetropia with varying corneal power (K) at three different axial lengths (22, 24 and 26 mm). The heavy lines show the T2 formula and the light lines the SRK/T. Reproduced with permission from [4]

To develop the new corneal height regression formula, we determined H_{back} for each eye in the development subset as described earlier. Multiple linear regression was performed using H_{back} as the dependent variable and corneal power (K) and either axial length (L) or corrected axial length ($LCOR$) as independent variables. Two regression equations were derived for H_2, the estimated corneal height, are as follows:

$$H_2 = -10.326 + 0.32630 \cdot L + 0.13533 \cdot K \tag{54.1}$$

$$H_2 = -11.980 + 0.38626 \cdot LCOR + 0.14177 \cdot K \tag{54.2}$$

Equation (54.1) showed a higher correlation coefficient ($R^2 = 0.5566$ vs. 0.5404) and lower standard error (0.3147 vs. 0.3204) and was therefore selected for further investigation. Since the SRK/T formula only uses *LCOR* as an intermediate step in the corneal height calculation, the use of Eq. (54.1) renders a solution for the *LCOR* reversal unnecessary. We programmed a new version of the SRK/T formula by simply replacing the corneal height calculation step with Eq. (54.1). We refer to the modified version as the **T2 formula** [4], and Fig. 54.5 confirms the elimination of the SRK/T cusp phenomenon.

Evaluation of the T2 Formula

We compared the clinical performance of the T2 formula with the SRK/T by calculating the spectacle prediction error (PE) of each formula in the evaluation subset of eyes, using separate IOL-specific A-constants optimized for each formula (mean PE: SRK/T 0.0019 D, T2 0.0004 D). When compared to the SRK/T, the T2 formula results demonstrate a significantly lower standard deviation (SD: SRK/T 0.4167 D, T2 0.3960 D; F-test: $p < 0.0001$) and mean absolute error (MAE: SRK/T: 0.3217 D, T2: 0.3052 D; t-test: $p < 0.0001$). Table 54.1 shows the number and proportion of eyes within ±0.25 D, ±0.5 D and ±1 D of prediction for the two formulas; in all cases, the T2 formula shows a statistically significant improvement over the SRK/T.

Table 54.1 Proportion of eyes in the evaluation subset (n = 5601) within ±0.25 D, ±0.5 D and ±1 D of prediction

	SRK/T	T2 formula	McNemar's test
Within ±0.25 D	2710 (48.4%)	2818 (50.3%)	$p = 0.0002$
Within ±0.50 D	4416 (78.7%)	4516 (80.9%)	$p < 0.0001$
Within ±1.00 D	5487 (98.0%)	5510 (98.5%)	$p = 0.0003$

A small number of subsequent studies have evaluated the performance of the T2 formula [9–11]. These confirm that, across the full range of axial lengths, the T2 formula is significantly more accurate than the SRK/T formula and the other third-generation IOL formulas. When analysed according to subgroups of axial length, the T2 formula matches or exceeds the performance of other third-generation formulas for the short-, medium- and medium-long groups [9]. For long eyes (axial length > 26 mm), the results are conflicting. Cooke and Cooke confirmed that the T2 formula is more accurate than the SRK/T in this subgroup also [10], but other series show that the SRK/T formula may be more accurate than the T2 formula [9, 12].

Conclusion

Our study set out to understand the cause of the SRK/T cusp phenomenon and, in doing so, identified a systematic error in corneal height calculation. Our large reference dataset allowed us to evaluate the importance of the corneal height error and to propose a solution. The development of the T2 formula achieved its goal of eliminating the SRK/T cusp and, in consequence, delivered a statistically and clinically significant performance improvement in what was, at the time, the largest independent study to examine the performance of the SRK/T formula. The A-constants required by the T2 formula are almost identical to those of the SRK/T; in our study, they differed by no more than ±0.03 D. The T2 formula can therefore be used as a direct substitute for the SRK/T.

More recent fourth-generation formulas using more ocular measurements (e.g. phakic anterior chamber depth, lens thickness and horizontal corneal diameter in addition to keratometry and axial length) or algorithms employing ray tracing and artificial intelligence paradigms are more accurate than the third-generation formulas, of which the T2 formula is one [13]. It is likely that in routine clinical practice third-generation formulas are now obsolete, but they may retain a role in circumstances where the parameters required by the more modern formulas cannot be measured. For example, phakic anterior chamber depth (ACD) and lens thickness, required by many of the newer formulas, cannot be obtained in aphakic eyes requiring secondary intraocular lens implantation or in pseudophakic eyes requiring IOL exchange, and the measured phakic ACD is likely to be anomalous in eyes with a subluxated crystalline lens. It can be shown that the performance of the fourth-generation formulas is degraded by missing input parameters (personal communication, David Cooke). Li et al. studied refractive outcomes of lens implantation in eyes with insufficient capsular support and demonstrated that the SRK/T formula was the most accurate, including in comparison with the Haigis (requires phakic ACD) and Barrett Universal II formulas (requires phakic ACD and lens thickness) [14]. The authors did not evaluate the T2 formula in their study, but there is no reason to expect that it would not perform better than the SRK/T in this context, similar to the findings in the setting of standard cataract surgery.

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