Corneal coupling of astigmatism applied to incisional and ablative surgery

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PURPOSE: To redefine measures of corneal coupling for use with incisional and ablation procedures for astigmatism.

SETTING: Private clinics, Melbourne, Victoria, Australia.

DESIGN: Retrospective nonrandomized study.

METHODS: The measures known as the coupling ratio (CR) and coupling constant (CC) were redefined to ensure validity in most cases of incisional procedures and laser vision correction procedures. In addition, a new measure—the coupling adjustment (CAdj)—was developed to quantify the amount of spherical adjustment that must be applied to compensate for coupling that occurs as a result of astigmatism treatment. These quantitative measures of coupling were applied to retrospective data to show their applicability.

RESULTS: Pure myopic, compound myopic, and compound hyperopic astigmatism excimer laser treatments showed a CR close to zero, a CC close to 0.5, and a CAdj close to zero. Incision LRIs showed a CR close to 1.0 and a CC close to zero. In all cases, the coupling measures were consistent for treatments with a larger astigmatic component (>1.0 diopter) but variable when the astigmatic component of the treatment was smaller.

CONCLUSIONS: The revised definitions of CR and CC can be used with incisional and ablative surgery. Incorporating the CAdj into the planning of spherocylindrical treatments allows one to factor in the effect of the astigmatic treatment on the spherical component and thus to more accurately target the desired spherical equivalent.

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The term *coupling* was introduced in the 1970s to quantify the relative corneal steepening that occurs 90 degrees from the primary corneal flattening induced by corneal incisions. It is unknown who first used the term in this manner, although several authors used the concept or term in the early literature.[1–7]

Rowsey and Fouraker[8] quantified coupling using the 2 measures, which allowed planning of surgical change to the cornea on the basis of the spherocylindrical refraction. The first measure was coupling (C_{RF}), which is "the ratio of the magnitude of corneal flattening or steepening in the axis of surgery divided by the magnitude of flattening or steepening 90 degrees away." The second was the coupling ratio (CR_{RF}), which is "the sphere component in the plus-cylinder refraction divided by the sphere component in the minus-cylinder refraction."

Faktorovich et al.[9] later defined 2 other measures to quantify coupling in arcuate astigmatic keratotomy. The first was the coupling ratio (CR_{FMP}), which is "the flattening of the incised meridian to the steepening of the opposite meridian" (where the opposite meridian is at 90 degrees to the incised meridian). The second was the coupling constant (CC_{FMP}), which is "the ratio of the change in spherical equivalent to the magnitude of the vector change in astigmatism."

Most studies in the recent literature that report coupling use the coupling ratio CR_{FMP} as their reporting measure,[10–13] although the coupling constant CC_{FMP} has also been used.[14] The coupling ratio CR_{FMP}

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described by Faktorovich et al.[9] is the same concept as the coupling C_{RF} defined by Rowsey and Fouraker,[8] meaning that existing terminology applied to coupling is historically inconsistent.

Both the coupling ratio CR_{FMP} and identical coupling C_{RF} were designed to describe corneal changes as a result of the incision effect. Here, it is expected that the amount of flattening at the incision meridian has the same magnitude as the steepening 90 degrees away in accordance with Gauss' law of elastic domes.[4] This means that CR_{FMP} and C_{RF} should have a value close to 1. However, in the context of laser refractive surgery, it is possible that there is no change in corneal curvature 90 degrees from the meridian of treatment. Because the CR_{FMP} and C_{RF} would then require division by a zero denominator, this single parameter of coupling ratio is not suitable for use in evaluating laser refractive surgery.

It is essential to consider corneal coupling in the modern era of laser ablation treatments in which the surgeon and the patient have high expectations that the postoperative spherical and astigmatic results will be on target and excellent.

In this paper, we define a coupling paradigm that is valid for all forms of incisional and ablative astigmatism treatments and show how it performs using actual patient data.

MATERIALS AND METHODS

The following 3 coupling measures for pure astigmatic surgical treatments were defined: coupling ratio (CR), coupling constant (CC), and coupling adjustment (CAdj). The first 2 measures are adaptations of 2 previously defined quantitative measures of coupling and can be used universally for eyes treated with incisional or laser refractive surgery. The third measure functions as the necessary spherical adjustment for an astigmatic treatment. Also considered was how to calculate these measures for compound astigmatic surgical treatments that are intended to concurrently steepen or flatten the cornea in addition to treating astigmatism.

In this paper, the meridian at which the primary curvature change is intended to occur is referred to as the treatment meridian. The meridian 90 degrees from the treatment meridian is then the opposite meridian. If the treatment is intended to cause local corneal steepening, the treatment meridian is exactly the axis of the target induced astigmatism vector (TIA)[15]; if the intended treatment is to cause local corneal flattening, the treatment meridian is 90 degrees from the axis of the TIA. Figure 1 shows a simplified double-angle schematic representation of the change in corneal power at the treatment meridian (ΔK_T) and change in corneal power at the opposite meridian (ΔK_O), where the vertical direction represents the corneal power along this meridian.

New Definitions of Coupling Measures

Coupling Ratio The proposed CR is $-\Delta K_O/\Delta K_T$, where ΔK_O is the change in corneal power at the opposite meridian and ΔK_T is the change in corneal power at the treatment meridian. This CR is the reciprocal of those described by CR_{FMP} and C_{RF} and was chosen specifically so that it would be meaningful when there is no change at the opposite meridian; that is, $\Delta K_O = 0$, which is the usual aim of laser ablation astigmatism treatment.

In the case of regular astigmatism, it is possible to determine the preoperative and postoperative keratometric values at the treatment meridian and opposite meridian by vectorially resolving the measured keratometric astigmatism to these meridians.[16] For a cornea with average keratometry of K_{Av}, astigmatism of C, and a steep meridian of M, the resolved value K(θ) at meridian θ is calculated as.

$$K(\theta) = K_{Av} + \frac{C}{2}\cos 2(\theta - M)$$

For example, given a cornea with regular astigmatism, where the keratometric measurement is 42.1 diopters (D)

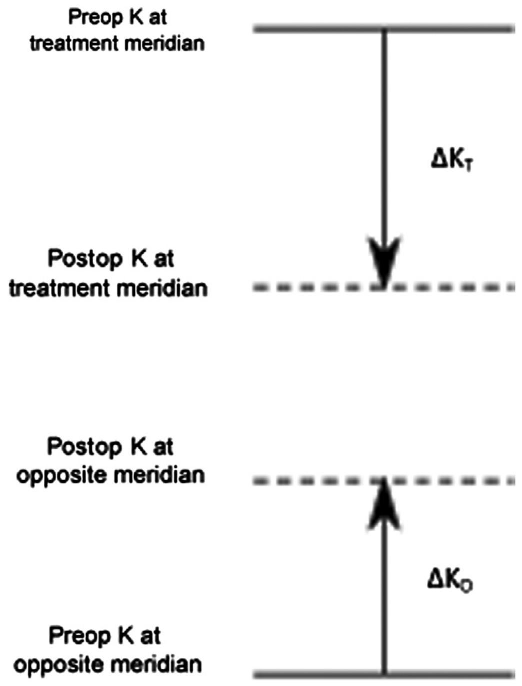

Figure 1. Schematic of changes in corneal power caused by an incisional treatment for simple myopic astigmatism. In this example, there is flattening at the treatment meridian and steepening at the opposite meridian (K = keratometry).

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(flat @ 170 degrees) and 46.7 D (steep @ 80 degrees), the keratometric value at a meridian of 90 degrees can be calculated in the following way:

$$K_{Av} = 44.4\,D,\ C = 4.6\,D,\ M = 80\ \text{degrees},\ \theta = 90\ \text{degrees}$$

$$K(90^\circ) = 44.4 + \frac{4.6}{2}\cos 2(90^\circ - 80^\circ) = 46.56\,D$$

Again assuming regular astigmatism, the relationship between the preoperative and postoperative keratometric values can also be described in terms of the surgically induced astigmatism vector (SIA),[16] angle of error (AoE),[16] and change in the mean keratometry (ΔK_{Mean}). This is described later when the maximum treatment effects are away from the treatment meridian.

Coupling Constant The proposed CC is $\Delta K_{Mean}/(\Delta K_T - \Delta K_O)$, where ΔK_{Mean} is the change in the mean corneal power and $\Delta K_T - \Delta K_O$ is the difference between the change in corneal power at the treatment meridian and the change in corneal power at the opposite meridian.

The proposed CC differs from CC_{FMP} in that the CC depends on the flattening/steepening effect of the SIA at the intended treatment meridian, which may be less than the total SIA change in corneal astigmatism at a different axis. In contrast, CC_{FMP} uses only the magnitude of the total change in corneal astigmatism; that is, the whole SIA. To accurately measure corneal astigmatism postoperatively, a keratometric reading at the actual treatment meridian would be required to calculate the CR and the CC.

Using the concepts of the SIA and the AoE,[16] the expected difference between CC and CC_{FMP} can be calculated. Assuming regular astigmatism and a flattening treatment,

$$CC = \frac{-\Delta K_{Mean}}{\|SIA\|\cos 2AoE}$$

and

$$CC_{FMP} = \frac{-\Delta K_{Mean}}{\|SIA\|}$$

When the SIA axis coincides with the TIA axis, the AoE is zero and the 2 measures are the same. As the magnitude of the AoE increases, so does the difference between these 2 parameters.

When the cornea being treated has regular astigmatism, the CC can be determined from the CR as follows:

$$\Delta K_{Mean} = \frac{1}{2}(\Delta K_T + \Delta K_O)$$

This can be substituted into the definition of CC to obtain

$$CC = \frac{1}{2}\left(\frac{\Delta K_T + \Delta K_O}{\Delta K_T - \Delta K_O}\right)$$

Assuming there has been a change at the treatment meridian (ie, ΔK_T is not zero), the numerator and denominator can be divided by ΔK_T to obtain

$$CC = \frac{1}{2}\left(\frac{1 + \Delta K_O/\Delta K_T}{1 - \Delta K_O/\Delta K_T}\right) = \frac{1}{2}\left(\frac{1 - CR}{1 + CR}\right)$$

This equation shows that the CC is closely linked to the CR for surgical treatments of regular astigmatism. Thus, an increase in CR should result in a decrease in CC and vice versa.

Coupling Adjustment The CR and CC are useful measures for characterizing coupling; however, it is difficult to use them directly during the planning of spherocylindrical treatments because these parameters provide no insight into the effect of the astigmatic treatment on sphere. For this reason, another measure is proposed. This measure is intended for use during treatment planning to allow accurate targeting of the desired spherical equivalent (SE) when astigmatism is treated.

The coupling adjustment (CAdj) is CC – CC_{EXP}, where CC is the calculated CC that occurred and CC_{EXP} is the expected CC for this type of surgery. The CAdj is the spherical adjustment per diopter cylinder of astigmatic treatment that has to be incorporated into the spherical part of the treatment to reach the expected spherocylindrical outcome. In this paper, the CAdj is calculated only for laser refractive treatments, with $CC_{Exp} = 0.5$. For incision procedures, CC_{Exp} would be 0.0.

In myopic astigmatism and hyperopic astigmatism, if there is positive coupling, the spherical treatment is reduced (ie, less magnitude is treated). In cases of negative coupling, the spherical treatment is increased.

Examples

Incision Surgery with 100% Coupling In this example, we consider incision surgery using arcuate relaxing incisions, where there is flattening at the treatment meridian and an equal amount of steepening 90 degrees away at the opposite meridian (Figure 2, *a*).

Preoperative corneal power : 42.0 / 46.0 @ 90
Treatment meridian : 90 degrees
Postoperative corneal power : 43.8 / 44.2 @ 90
$CR = -(1.8)/(-1.8) = 1.0$
$CC = (0.0)/(-1.8 - 1.8) = 0.0$

The CR of 1.0 shows that the changes in corneal power at the treatment meridian and the opposite meridian are equal in magnitude (100% coupling) and opposite in sign. The CC of zero means that this treatment of corneal astigmatism had no effect on the SE.

Incision Surgery with Partial Coupling This example is the case of an incisional surgery using tangential relaxing incisions with a radial flattening component of the incision, where the amount of flattening induced at the treatment meridian is more than the amount of steepening induced at the opposite meridian (Figure 2, *b*).

Preoperative corneal power : 42.0/46.0 @ 90
Treatment meridian : 90 degrees
Postoperative corneal power : 43.2/43.6 @ 90
$CR = -(1.2)/(-2.4) = 0.5$
$CC = (-0.6)/(-2.4 - 1.2) = 0.17$

The CR of 0.50 indicates that the change in corneal power at the opposite meridian was one half the change at the treatment meridian (50% coupling). The CC of 0.17 means that each diopter change in astigmatism produced a 0.17 D change in SE.

Laser Refractive Surgery Treating Pure Myopic Astigmatism with No Coupling In laser refractive surgery, ideally an astigmatic ablation will cause no coupling because the manufacturers should have calibrated the laser according to past performance to produce the expected amount of

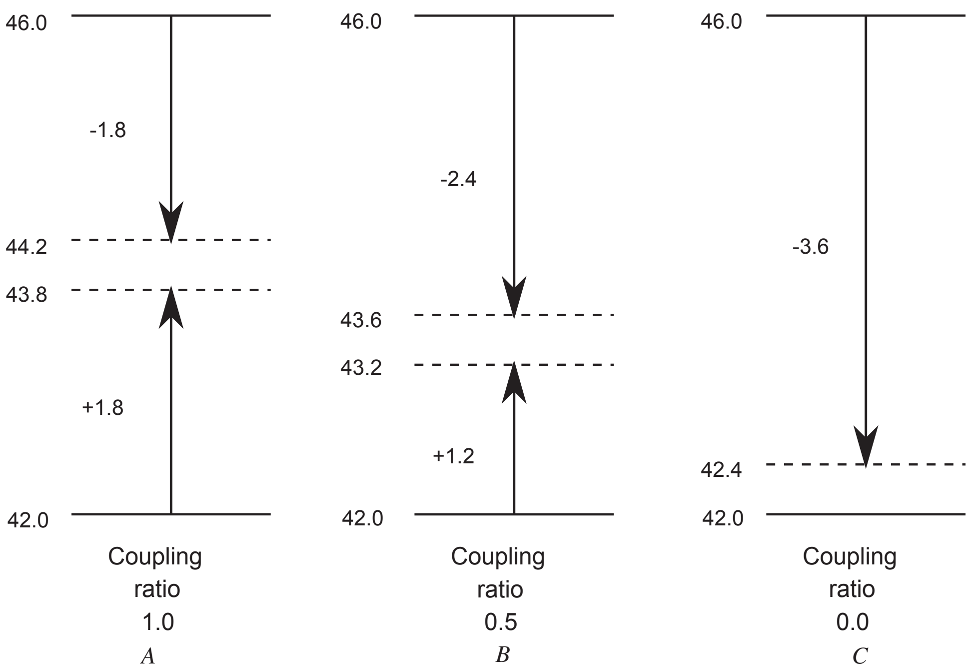

Figure 2. Examples of different amounts of coupling associated with a pure myopic astigmatic treatment of −3.6 DC. *a*: When there is a coupling ratio of 1.0, the amount of flattening at the treatment meridian is matched by an equal amount of steepening at the opposite meridian. *b*: With a coupling ratio of 0.5, the treatment induces some flattening at the treatment meridian and half as much steepening at the opposite meridian. *c*: In the absence of coupling, the corneal power at the opposite meridian remains unchanged.

correction. An example of zero coupling is given here (Figure 2, *c*).

$$\begin{aligned}&\text{Preoperative corneal power: } 42.0/46.0 @ 90\\&\text{Treatment meridian: } 90 \text{ degrees}\\&\text{Postoperative corneal power: } 42.0/42.4 @ 90\\&\text{CR} = -(0.0)/(-3.6) = 0.0\\&\text{CC} = (-1.8)/(-3.6-0.0) = 0.5\\&\text{CAdj} = 0.5-0.5 = 0.0\end{aligned}$$

The CR of zero shows that there was no change in corneal power at the opposite meridian (0% coupling). The CC of 0.5 means that for every diopter change in astigmatism, there was a 0.5 D change in SE. The zero CAdj indicates that the surgery went as planned and resulted in no unexpected spherical change.

Treatment of Myopia with Maximum Effect away from the Treatment Meridian The maximum effect of an astigmatic treatment will not always be aligned exactly with the actual treatment meridian. In such a case, only part of the effect of the treatment will be seen at the treatment meridian and opposite meridian. When regular astigmatism has been induced, the changes at the treatment meridian and the opposite meridian can be calculated from the coupling-induced change in mean keratometry, the magnitude of the SIA, and the AoE. For a flattening treatment, the changes at the treatment meridian and opposite meridian are

$$\begin{aligned}\Delta K_T &= \Delta K_{Mean} - \|\text{SIA}\| \cos 2\text{AoE}\\ \Delta K_O &= \Delta K_{Mean} + \|\text{SIA}\| \cos 2\text{AoE}\end{aligned}$$

while for a steepening treatment, the changes in corneal power are

$$\begin{aligned}\Delta K_T &= \Delta K_{Mean} + \|\text{SIA}\| \cos 2\text{AoE}\\ \Delta K_O &= \Delta K_{Mean} - \|\text{SIA}\| \cos 2\text{AoE}\end{aligned}$$

Figure 3 shows these calculations in a double-angle vectorial form.

Coupling in Ablation Treatments of Compound Astigmatism Most laser ablation treatments are combinations of spherical and astigmatic treatments, also known as compound astigmatism treatments. In this case, the effect of the spherical treatment on the cornea has to be removed before the coupling effect of the astigmatic treatment alone can be determined (Figure 4). However, it is not possible to separate the effects of the 2 treatments exactly because no intermediate corneal curvature reading is taken after the spherical treatment is applied and before the astigmatic treatment is applied. One way to estimate the effect of the spherical treatment is to determine it from historical data for pure spherical ablations. All remaining change in the corneal curvature is then attributed to the astigmatic treatment. The results section shows how to remove the effect of the spherical treatment from the data for spherocylindrical treatments.

Confirming Laser Ablation Coupling Results Via Subjective Refraction Keratometry estimates corneal power from the anterior corneal curvature only, assuming that the posterior corneal power is a fixed percentage of the anterior corneal power. This makes it an ineffective measure of corneal power after laser ablation because this type of surgery changes the curvature of the anterior corneal surface without changing the curvature of the posterior surface.[17,18] Ideally, a measure of total corneal power, calculated from both anterior and posterior corneal curvatures, would be used instead of anterior keratometry. However, we have not conventionally measured both preoperative and postoperative corneal power with a Scheimpflug device. Thus, we decided to use our routinely collected preoperative and postoperative subjective manifest refraction data to confirm the coupling results obtained via keratometry.

To calculate the changes in refraction at the treatment meridian and opposite meridian, it is necessary to vectorially resolve the preoperative and postoperative refractive

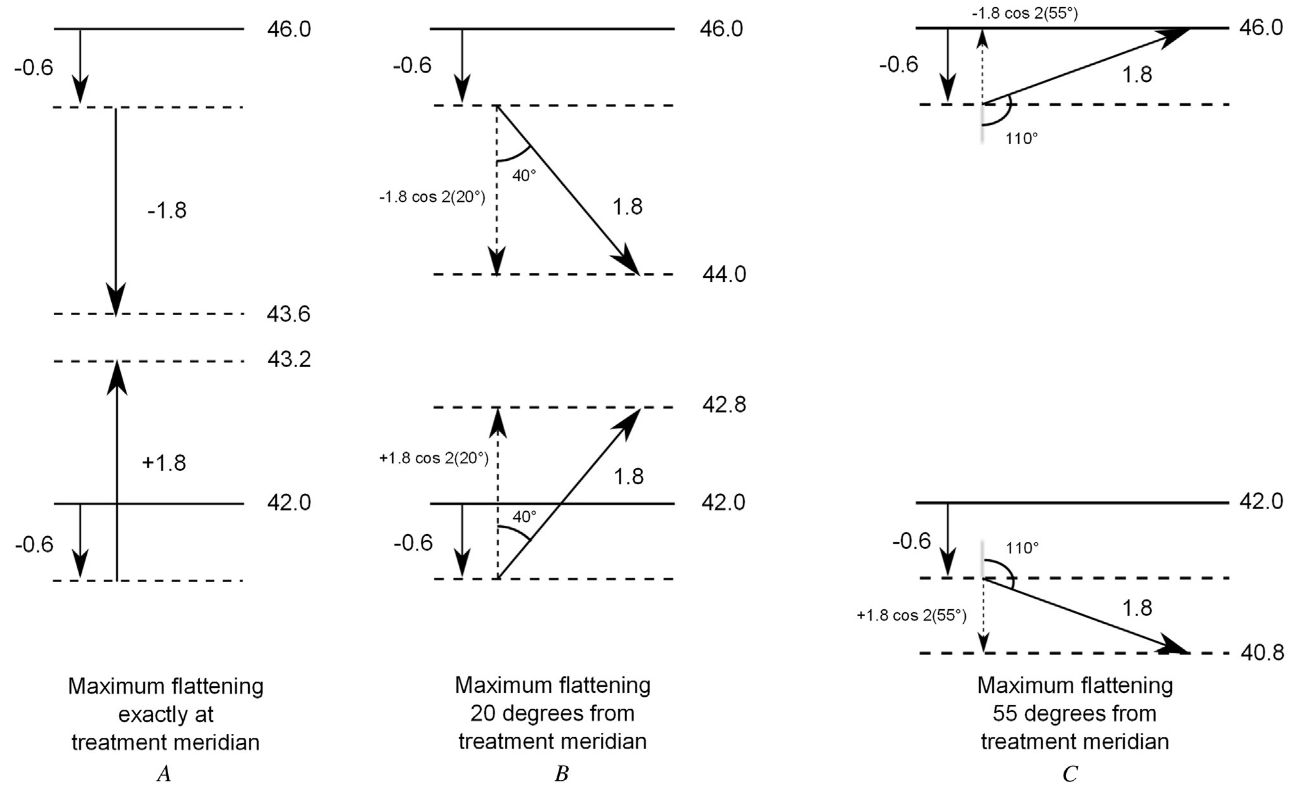

Figure 3. Examples of flattening treatments when the maximum effect is at different angles off the treatment meridian. *a*: All the effect of the SIA is divided between the treatment meridian and the opposite meridian. *b*: Some of the effect of the SIA is seen at the treatment meridian and the opposite meridian. *c*: Here, the effect of the SIA has a net spherical direction opposite to the expected direction, with steepening at the intended flattening meridian and flattening at the intended steepening meridian.

cylinders to these meridians in the same way as for the keratometric values.

At both meridians, the change in refraction is expected to have the sign opposite to the change in keratometry because the manifest refraction is a correction of refractive error, not a measurement of total astigmatism. Because this reversal of sign occurs for both meridians, the formulas to estimate the CR and CC from the manifest refraction have the same form as the formulas used when calculating directly with corneal power.

The CR estimated from refraction is $-\Delta R_O/\Delta R_T$, where ΔR_O is the change in refractive power at the opposite meridian and ΔR_T is the change in refractive power at the treatment meridian. The CC estimated from the refraction is $\Delta R_{Mean}/(\Delta R_T - \Delta R_O)$, where ΔR_{Mean} is the change in the mean refractive power. The CAdj estimated from the refraction is the coupling constant minus the expected coupling constant estimated from the refraction.

Similar to the keratometric case, historical data from spherical laser in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK) treatments were used to estimate the effect of the spherical component of the treatment on refraction.

After the estimated effects of the spherical component are removed, the coupling measures for the astigmatic component can be calculated.

Study Groups

To determine whether the new measures are meaningful in the context of laser refractive and corneal incisional surgery, they were calculated for several refractive surgery types as follows: laser ablation surgery (LASIK or PRK) to correct compound myopic astigmatism; laser ablation surgery (LASIK) to correct compound hyperopic astigmatism; incisional surgery with 1 pair of incisions on the steep meridian.

The excimer laser treatments considered here are based on a combination of manifest refractive cylinder and corneal parameters using the method of vector planning.[19] Thus, for a treatment of compound myopic astigmatism, the treatment meridian is typically not at the steepest corneal meridian or steepest positive refractive axis but is rather somewhere in between.

Table 1 shows details of the retrospective data used for each group. In each case, all were virgin eyes preoperatively. All analyses were based on the last examination before surgery and the 1-month postoperative (between 3 weeks and 8 weeks) examination. For measurements of corneal power, keratometry values measured using OM-4 keratometers (Topcon Corp.) were used. Because postoperative keratometry measurements after laser ablation surgery have questionable validity, also calculated were the coupling measurements from refractive measurements when laser ablation surgery was performed to determine whether they were more in line with expectations. Regression lines and *P* values were calculated with R,[20] using the robust regression function *lmrob* from the library *robustbase*.[21] When *P* values are stated, the corresponding null hypothesis is given by H_0.

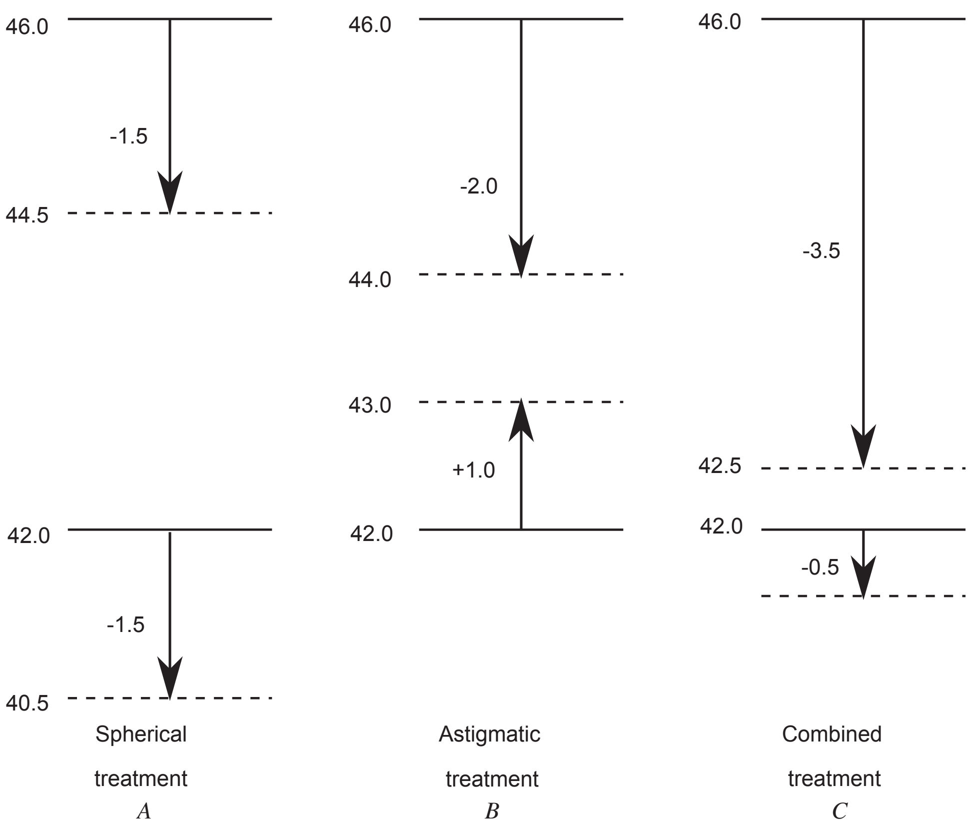

Figure 4. Example of a compound astigmatism treatment. *a*: Pure spherical treatment does not cause any coupling. Here, a −1.5 D myopic treatment is shown. *b*: Pure astigmatic treatment may cause some coupling. In this example, the treatment is plano −3.0 × 90. In this case, coupling causes an overall steepening of +1.0 D. This results in steepening of +1.0 D at the opposite meridian and flattening of −2.0 D at the treatment meridian; thus, the coupling ratio is 0.50. *c*: It is not possible to determine the amount of coupling caused by the astigmatic treatment directly from the combined spherocylindrical changes in corneal power. Rather, it is necessary to first subtract the effect of the spherical treatment. If the value of the coupling ratio is calculated directly from the combined treatment, it would appear to be −0.14 instead of the true value of 0.50.

RESULTS

These results are specific to the excimer laser used (Visx S4 IR, Abbott Medical Optics, Inc.) and thus may not apply to other lasers.

Effect of Spherical Ablation Treatments on Keratometry and Refraction

Before it is possible to calculate the coupling measures for ablation treatments with a spherical component, it is necessary to estimate and remove the effect of the spherical part of the treatment. To estimate the effect of a spherical ablation, retrospective keratometric data pertaining to simple spherical ablations were used. There were more treatments of low refractive error than of high refractive error (Figures 5 and 6); thus, the distributions of treatment magnitude were normalized using a log transform before the statistical analysis was performed.

Table 1. Details of historical data used for each group.

Group	Eyes (n)	Age Range (Y)	Males (%)	Right Eye (%)
Compound myopic astigmatism, treated by LASIK or PRK	3228	18, 61	40	49
Compound hyperopic astigmatism, treated by LASIK	590	18, 71	44	47
Incisional surgery	74	22, 84	27	50

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy

The effect of spherical treatments was calculated by comparing the applied spherical treatment (as input into the laser at the corneal plane) with the resulting changes in keratometric power and refraction. The resulting graphs for myopic spherical treatments are shown in Figure 7, and those for hyperopic spherical treatments are shown in Figure 8. For myopic treatments and hyperopic treatments, the change in mean keratometry appeared to have a nonlinear relationship with the spherical treatment magnitude. In contrast, the change in refractive SE appeared to have a linear relationship with the magnitude of the spherical treatment.

These relationships show that with the excimer laser used in this study, an ablation intended to treat 1.00 D of myopia is expected to change the keratometry by 0.96 D and the refraction by 0.95 D, while an ablation to treat 5.00 D of myopia is expected to change the keratometry by 4.23 D and the refraction by 4.85 D. On the other hand, an ablation to treat

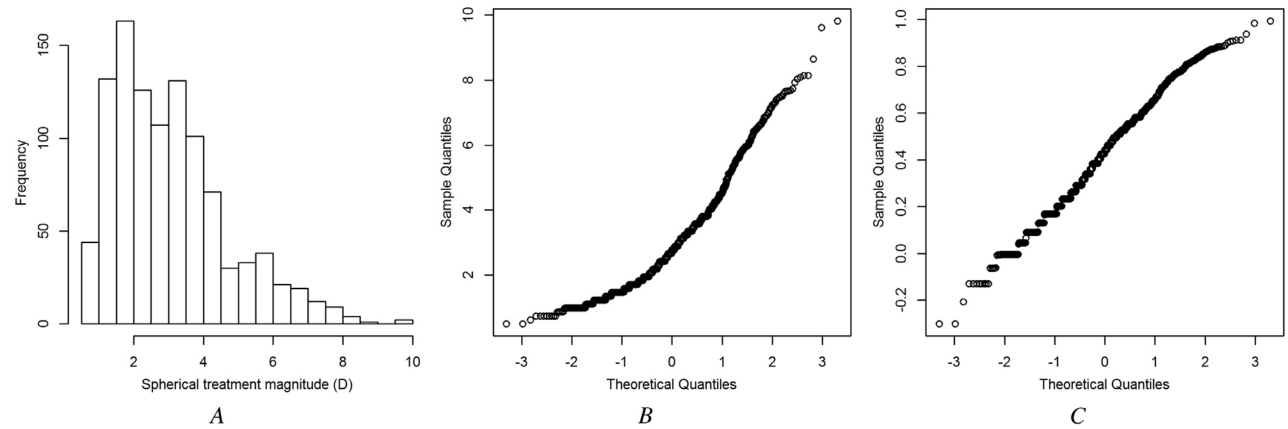

Figure 5. Distribution of spherical myopic treatment magnitudes on the cornea 1 month postoperatively. *a*: Spherical treatment magnitudes. *b*: Normal Q-Q plot of raw data. *c*: Normal Q-Q plot of log-transformed data. The points lie close to the identity line, which shows that the distribution of the log-transformed data is close to normal (Q = quantile).

1.00 D of hyperopia is expected to change the keratometry by 0.61 D and the refraction by 1.01 D, while an ablation to treat 5.00 D of hyperopia is expected to change the keratometry by 3.63 D and the refraction by 5.40 D.

In the following analyses, these relationships are used to remove the expected change caused by the spherical component of the treatment.

Ablation Treatments of Compound Astigmatism

Figure 9 shows the results of treatments for compound myopic astigmatism derived from keratometry. For treatments, the change in keratometry at the treatment meridian was approximately 85% of the intended treatment magnitude and there was a tendency toward a small amount of flattening to occur at the opposite meridian. The CR was negative (median −0.23), reflecting the flattening at the opposite meridian. The CC was close to 0.50 (median 0.55). Thus, the CAdj was close to zero (median 0.05), indicating that the spherical part of the treatment did not have to be adjusted to account for the astigmatic treatment.

Figure 10 shows the results for the same treatments of compound myopic astigmatism, this time derived from refractive data. The change in refraction at the treatment meridian was close to that of the intended treatment magnitude, and there was a tendency toward a small myopic shift at the opposite meridian. The CR was close to zero (median −0.02), which indicates that no coupling occurred. The CC is close to 0.50 (median 0.46). Thus, the CAdj was close to zero (median −0.04), which indicates again that the spherical part of the treatment did not have to be adjusted.

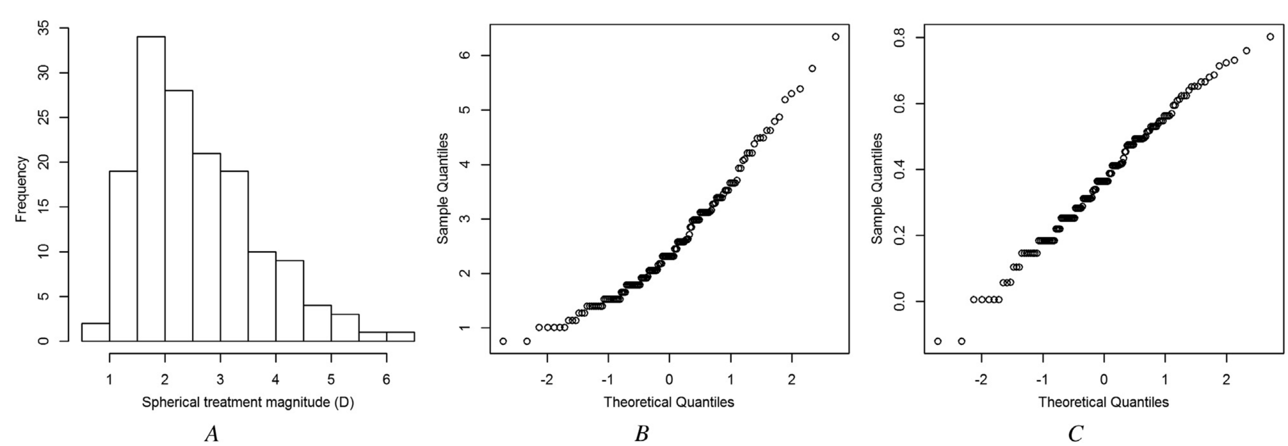

Figure 6. Distribution of spherical hyperopic treatment magnitudes on the cornea 1 month postoperatively. *a*: Spherical treatment magnitudes. *b*: Normal Q-Q plot of raw data. *c*: Normal Q-Q plot of log-transformed data. The points lie close to the identity line, which shows that the distribution of log-transformed data is close to normal.

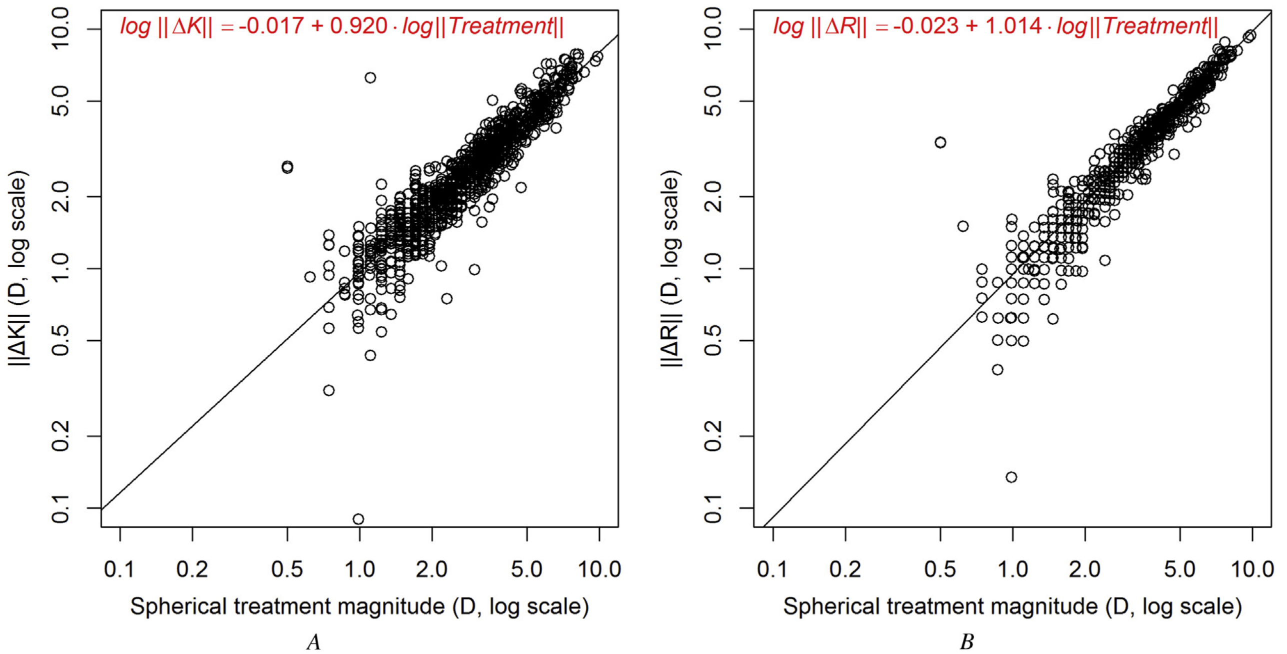

Figure 7. Effect of spherical ablation treatments of myopia on keratometry and refraction 1 month postoperatively. *a*: Keratometric change has a nonlinear relationship to treatment sphere because the slope of 0.920 is significantly different from unity (H_0: slope = 1, $P < .001$). *b*: Refractive change has a linear relationship to treatment sphere because the slope of 1.014 is not significantly different from unity (H_0: slope = 1, $P = .07$) (||ΔK|| = absolute change in keratometric astigmatism; ||ΔR|| = absolute change in refractive cylinder).

Figure 11 shows the results of treatments for compound hyperopic astigmatism derived from keratometry. In this case, the change in keratometry at the treatment meridian was approximately 60% of the intended treatment, while the opposite meridian made up an extra 25% of the treatment. The CR was positive

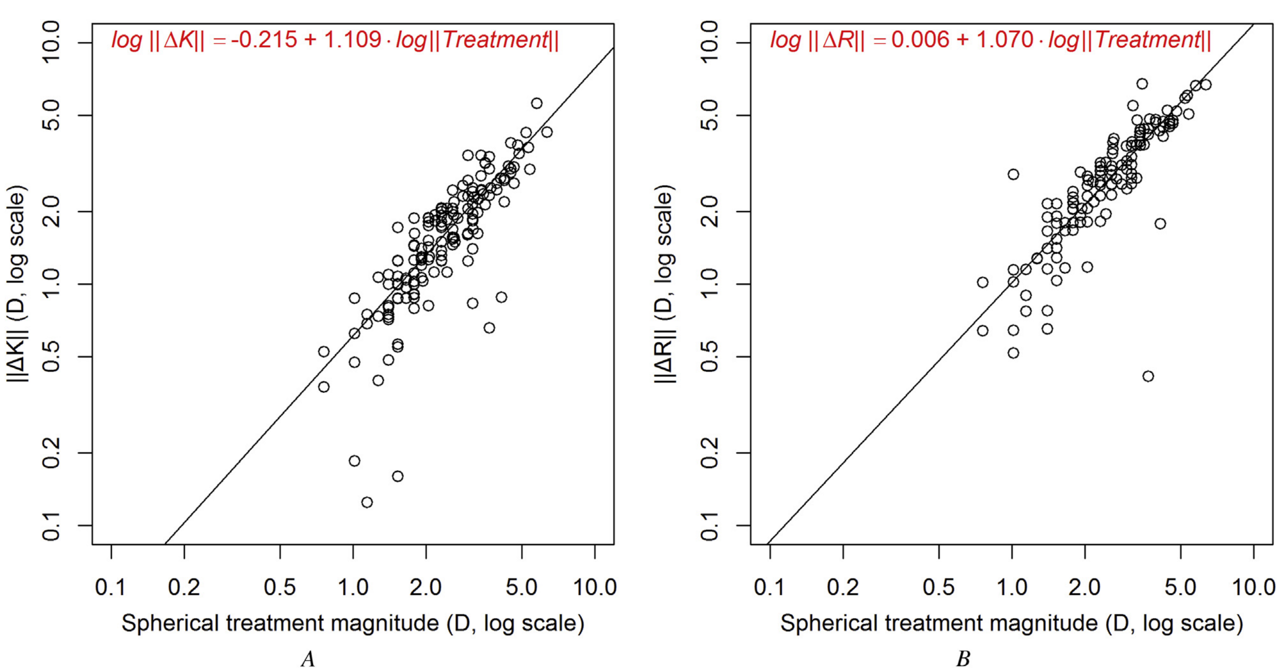

Figure 8. Effect of spherical ablation treatments of hyperopia on keratometry and refraction 1 month postoperatively. *a*: Keratometric change has a nonlinear relationship with treatment sphere because the slope of 1.109 is significantly different from unity (H_0: slope = 1, $P = .012$). *b*: Refractive change has a linear relationship with treatment sphere because the slope of 1.070 is not significantly different from unity (H_0: slope = 1, $P = .10$) (||ΔK|| = absolute change in keratometric astigmatism; ||ΔR|| = absolute change in refractive cylinder).

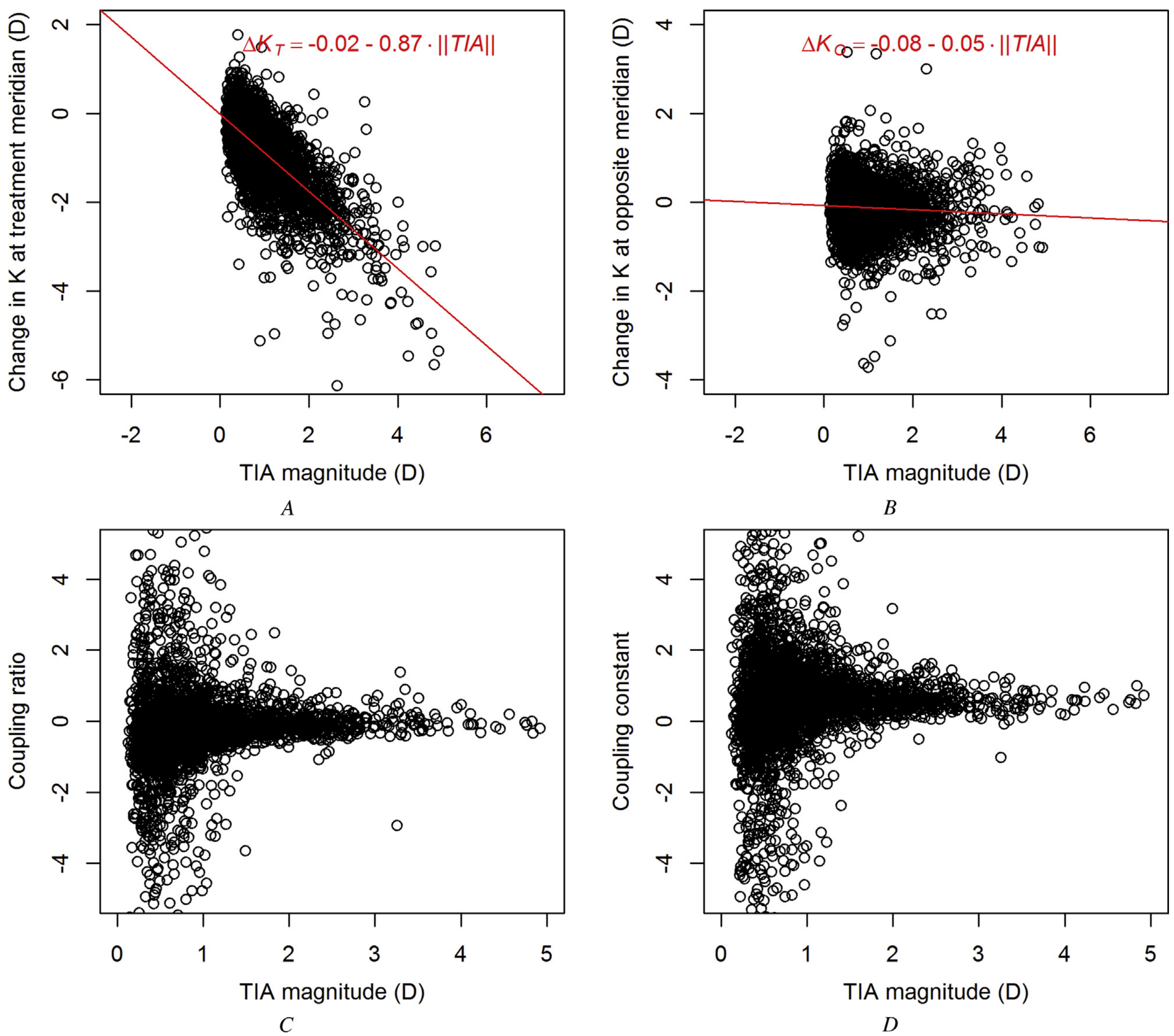

Figure 9. Effect of compound myopic astigmatic treatments on keratometry, 1 month postoperatively. *a*: The amount of flattening at the treatment meridian is about 85% of the TIA magnitude (H_0: slope $= -1$, $P < .001$). *b*: Although there is no intended change at the opposite meridian, individual cases may show steepening or flattening. For large myopic treatments, there is the tendency towards flattening at the opposite meridian (H_0: slope $= 0$, $P = .006$). *c*: The coupling ratio derived from keratometry is negative (median $= -0.23$), which reflects the tendency towards flattening at the opposite meridian. When the astigmatic part of the treatment is small, the coupling ratio is difficult to estimate correctly. *d*: The coupling constant derived from keratometry is slightly above 0.5 (median $= 0.55$) (K $=$ keratometry; ΔK_O $=$ change in corneal power at opposite meridian; ΔK_T $=$ change in corneal power at treatment meridian; TIA $=$ target induced astigmatism vector).

(median 0.30), showing that coupling was occurring. The CC is less than 0.50 (median 0.27) and the CAdj was -0.23, which indicates that the spherical part of the treatment needed to be increased.

The refractive results shown in Figure 12 are quite different. The change in refraction at the treatment meridian was slightly larger than the intended treatment magnitude, with little change occurring at the opposite meridian. The CR was slightly negative (median -0.13), which corresponds to a small myopic shift at the opposite meridian. The CC was close to 0.50 (median 0.44), and the CAdj was close to zero (median -0.06), which indicates that the spherical part of the treatment did not require adjustment.

Incision Treatments Using Limbal Relaxing Incisions

The incision treatments used in this analysis were all performed in conjunction with cataract extraction. There was always 1 penetrating 3.0 mm phacoemulsification incision and 1 limbal relaxing incision (LRI) of

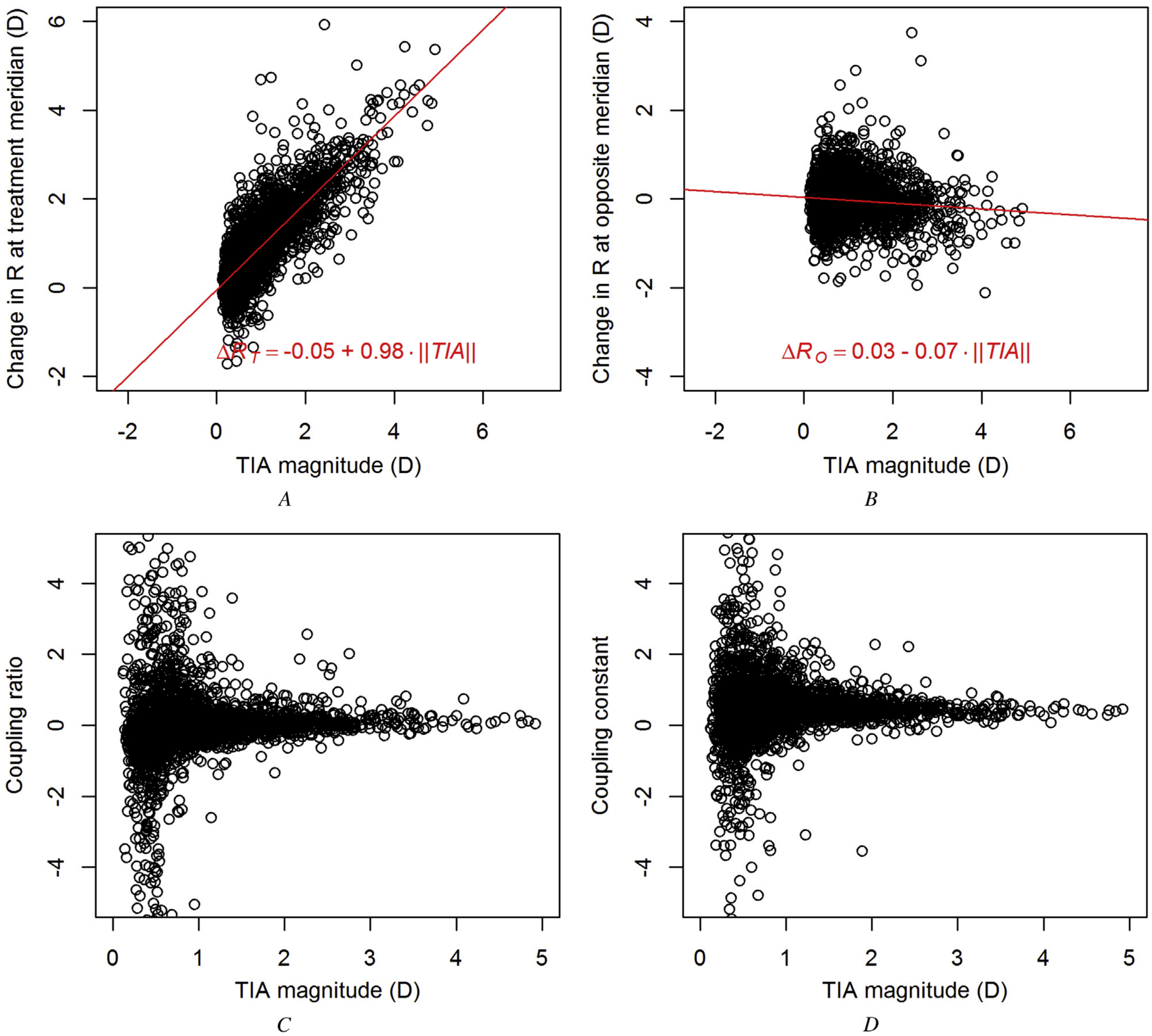

Figure 10. Effect of compound myopic astigmatic treatments on refraction 1 month postoperatively. *a*: The amount of hyperopic change in refraction at the treatment meridian is approximately the same as the TIA magnitude (H_0: slope = 1, P = .24). *b*: There is the tendency toward a small myopic shift at the opposite meridian for large myopic astigmatism treatments (H_0: slope = 0, $P < .001$). *c*: The coupling ratio derived from refraction is close to zero (median −0.02), which indicates almost no coupling. When the astigmatic part of the treatment is small, the coupling ratio is difficult to estimate correctly. *d*: The coupling constant derived from refraction is close to 0.50 (median 0.46) (K = keratometry; ΔR_O = change in change in refractive power at opposite meridian; ΔR_T = change in change in refractive power at treatment meridian; TIA = target induced astigmatism vector).

between 30 degrees and 45 degrees arc length placed opposite (180 degrees) to each other on the preoperative steep meridian of the cornea.

Figure 13 shows results for the incision treatments. In general, there was flattening at the treatment meridian and steepening at the opposite meridian, the CR had a peak near unity, and the CC had a peak near zero, as expected from Gauss' law of elastic domes. However, there was much intersubject variability—so much that the treatment merdian may be steepened 1 month after surgery. This large variability is clearly present in the distributions of CR and CC.

DISCUSSION

In this paper, we redefine quantitative measures of coupling to be meaningful for laser ablation surgery and incisional surgery. This has removed the need for an arbitrary decision that was associated with previous quantitative measures of coupling relating to

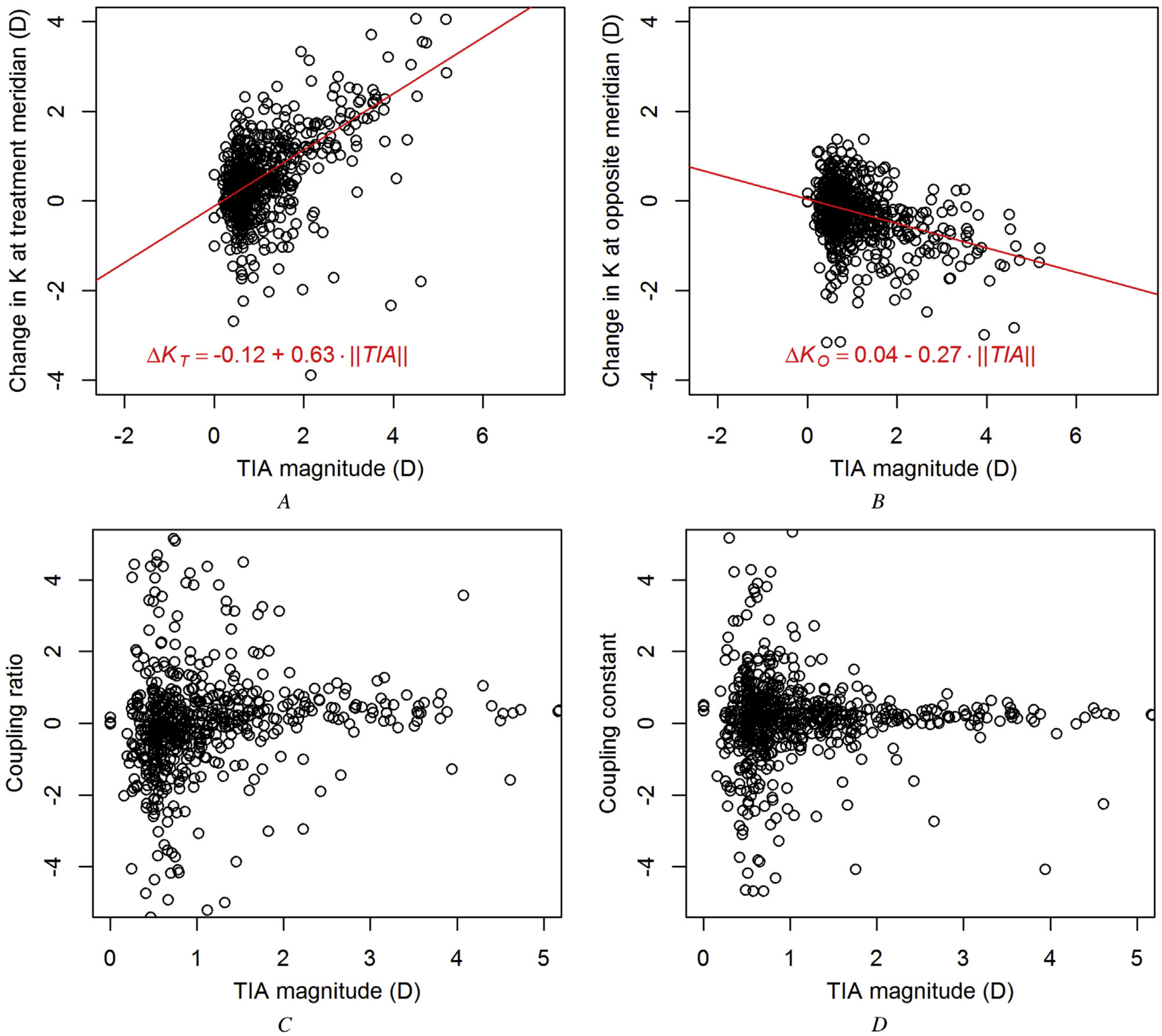

Figure 11. Effect of compound hyperopic astigmatic treatments on keratometry 1 month postoperatively. *a*: The amount of steepening at the treatment meridian is approximately 60% of the TIA magnitude (H_0: slope = 1, P = .06). *b*: The opposite meridian shows flattening of approximately 25% of the TIA magnitude (H_0: slope = 0, P = .003). *c*: The coupling ratio derived from keratometry is positive (median = 0.30), which reflects flattening at the opposite meridian. When the astigmatic part of the treatment is small, the coupling ratio is difficult to estimate correctly. *d*: The coupling constant derived from keratometry is less than 0.50 (median = 0.27) (K = keratometry; ΔK_O = change in corneal power at opposite meridian; ΔK_T = change in corneal power at treatment meridian; TIA = target induced astigmatism vector).

incisions; namely, whether the change at the surgical treatment meridian should be the numerator or denominator of the CR. With the proposed coupling measures, a typical laser ablation treatment of astigmatism would have a CR of zero (0% coupling) and a typical LRI would have a CR of 1.0 (100% coupling). In contrast, CR_{FMP} and C_{RF} produce an infinite value for a typical laser ablation treatment of astigmatism, which makes it difficult to evaluate how much a particular treatment deviates from the norm and complicates subsequent analysis of coupling. A coupling ratio of infinity can still occur with our new definition, although this would be uncommon. It would occur when there is neither a flattening effect nor a steepening effect at the treatment meridian.

The results derived from keratometric measurements are fundamentally different from those derived from manifest refractive measurements. For example, the effect of a spherical myopic ablation is nonlinearly related to keratometric change but linearly related to refractive change. This difference is too systematic to be caused by measurement error alone. Indeed, we know that any post-ablation measurement of corneal power based on anterior corneal curvature only must

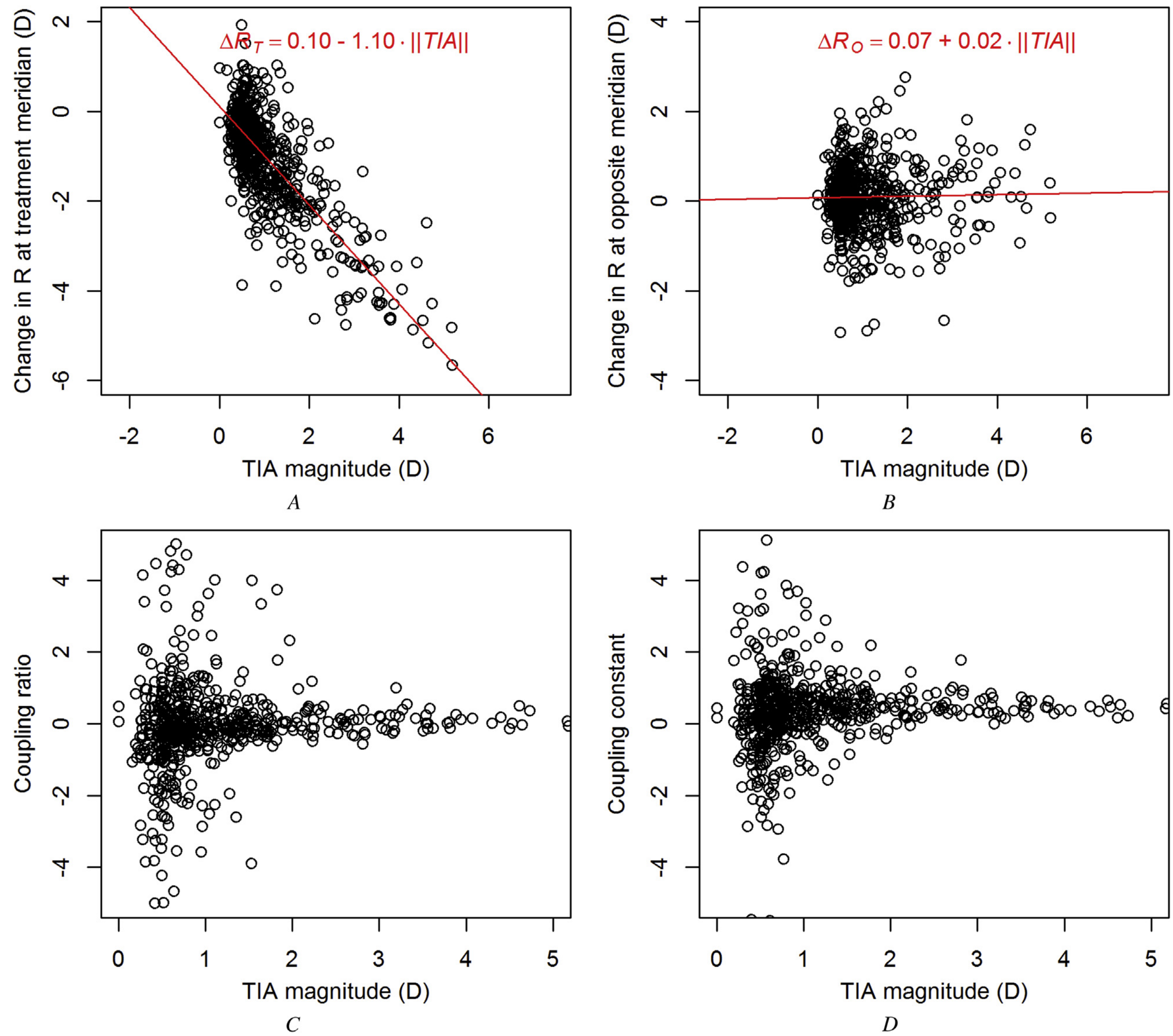

Figure 12. Effect of compound hyperopic astigmatic treatments on refraction 1 month postoperatively. *a*: The amount of hyperopic change in refraction at the treatment meridian is slightly greater than the TIA magnitude (H_0: slope $= -1$, $P = .01$). *b*: In general, there is no change at the opposite meridian (H_0: slope $= 0$, $P = .48$). *c*: The coupling ratio derived from refraction is slightly negative (median $= -0.11$), reflecting the slight myopic shift at the opposite meridian when there are large changes at the treatment meridian. When the astigmatic part of the treatment is small, the coupling ratio is difficult to estimate correctly. *d*: The coupling constant derived from refraction is slightly less than 0.50 (median 0.39) (K = keratometry; ΔK_O = change in corneal power at opposite meridian; ΔK_T = change in corneal power at treatment meridian; TIA = target induced astigmatism vector).

be incorrect because there is now a changed relationship between the curvatures of the anterior corneal surface and posterior corneal surface as the curvature of the posterior surface has not changed.[17,18] This includes any topography-based measurements that rely solely on anterior surface curvature. Because the results from keratometry and refraction are so different, it is important not to mix corneal values and refractive values when calculating coupling measures.

In our analysis of the effects of pure spherical ablations, we found that that the keratometric change is typically less than the refractive change. This effect has been reported by Moshirfar et al.[11] In the future, it might be preferable to analyze total corneal power data that are derived using both the anterior corneal surface and posterior corneal surface. The expectation is that the change in corneal power would be closer to or equal to the refractive change.

One major difference between our measures of coupling and previous measures of coupling is our decision to consider all effects relative to the treatment meridian, including the CR and the CC. For the CR,

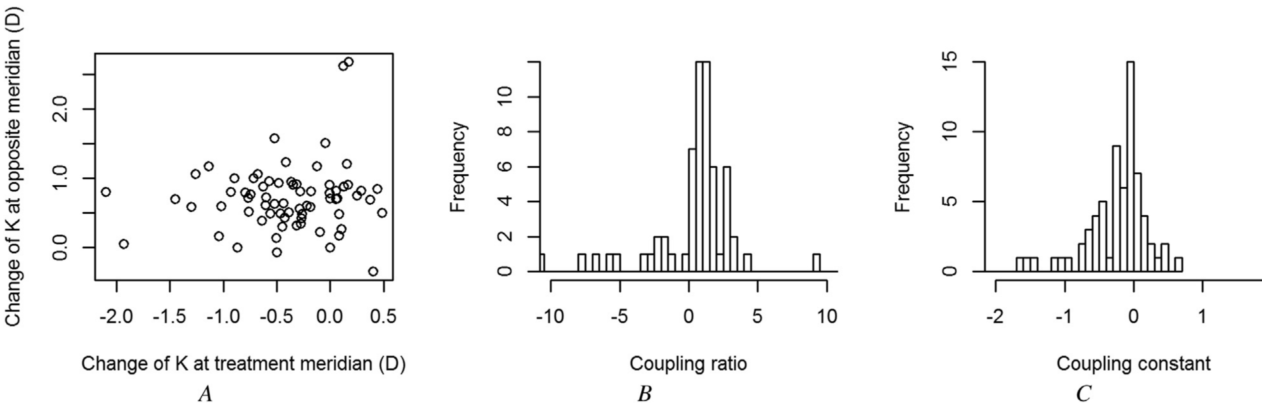

Figure 13. Effect of incisional surgery on keratometry 1 month postoperatively. *a*: In most cases, there is flattening at the treatment meridian (median −0.36) and steepening at the opposite meridian (median 0.70). However, there is no obvious linear relationship between the changes in keratometry as resolved to the treatment meridian and opposite meridian. *b*: The histogram of coupling ratios has a peak close to unity (median 1.00); however, many individual cases have coupling ratios far from unity. *c*: The histogram of coupling constants has a peak close to zero; however, there is a tendency toward negative coupling constants (median −0.12). A negative coupling constant indicates that the surgery has caused overall steepening of the mean corneal curvature as a result of arcuate incisions.

we are interested in the changes at the treatment meridian and opposite meridian so the preoperative measured keratometric astigmatisms and SIA are resolved to each meridian. For the CC, we are interested in the balance between the spherical shift and astigmatic change caused directly by the surgery.

If a treatment causes an astigmatic change that is off axis from the intended meridian, the magnitude of the resolved astigmatic change seen at the treatment meridian and opposite meridian will be less than the magnitude of the whole SIA. When the full astigmatic change is 45 degrees from the intended meridian, there will be no spherical change at the treatment meridian and opposite meridian.

Ophthalmologists are often advised to adjust the treatment parameters input into the laser using nomograms in an attempt to compensate for the tendency of a laser system to overtreat or undertreat. Assuming these nomograms are developed using a data-based analysis, we can consider them to have a similar function to a calibration. The aim is to make the actual treatment as close as possible to the intended treatment.

The use of such a nomogram does not at all invalidate coupling analysis. In fact, only a calibrated laser (with a correct nomogram) will be able to consistently achieve the expected CR of zero. Coupling analysis can determine when a laser produces treatments that have unexpected amounts of coupling.

Similarly, the use of negative cylinder profiles when treating compound hyperopic astigmatism requires the laser to compensate for the fact that the periphery of the cornea is ablated at a different rate than the center of the cornea.[22,23] However, we can normally assume that the profile that is used has been selected to try to achieve the desired refractive treatment effect. Here, coupling analysis can help determine how well a negative cylinder profile treats compound hyperopic astigmatism and how much extra hyperopic spherical treatment it delivers as a result.

For laser ablation refractive surgery, it is the coupling adjustment described in this paper that is most relevant to planning and outcomes. By knowing ahead what effect the astigmatic treatment has on the sphere, adjustments can be made to the spherical treatment to more accurately achieve the target. The expected CC for ablations is 0.5 because this is used in the calculation of CAdj to compare the actual change in the cornea with the expected change.

For surgery using arcuate incisions, there is no planned spherical treatment and therefore the CAdj plays no role. Instead, the CR and the CC are the measures that are of most interest. The expectations for this type of incisional surgery are that the CR is 1.0 and the CC is zero. Anything significantly different from this requires further investigation into what has occurred because the surgery would have caused a change in SE.

Due to the complexity of the coupling calculations the authors have developed a specific calculator to determine the coupling effect when sphero-cylindrical treatments are performed.[A]

In all ablation cases, the coupling measures were consistent for treatments with a larger astigmatic component (>1.0 D) but variable when the astigmatic component of the treatment was smaller.

In a small proportion of our laser ablation data, the change at the treatment meridian attributed to the astigmatic part of the treatment was in the direction opposite that expected from the treatment. For example, ablations to treat myopic astigmatism should result in flattening at the treatment meridian; however, in approximately 10% of cases, the astigmatic part of the treatment appeared to produce steepening. There are 2 obvious explanations for such a paradoxical outcome. The first is that the unexpected change at the treatment meridian is real and caused by a healing response that is so pronounced that it reverses the surgically induced change to the cornea. The second explanation is that the paradoxical change at the treatment meridian occurs because we estimate the effect of the spherical part of the treatment incorrectly, which then causes the effect of the astigmatic part of the treatment to be incorrect. Any such errors will be most evident when the treatment has a large spherical component and a relatively small astigmatic component. We believe that the 2 explanations together account for the large spread of CRs for low TIA magnitudes (<1.0 D) but not for higher TIA magnitudes. Interestingly, the spherical change between 1 month and 6 months postoperatively was not clinically significant.

In our incisional surgery data, the tendency was for flattening at the treatment meridian and steepening at the opposite meridian, consistent with Gauss' law of elastic domes. However, approximately one quarter of our cases showed the opposite behavior, with steepening at the treatment meridian. These results are similar to those in other studies.[24,25] One explanation for the observed steepening is that a pronounced healing effect reversed the flattening caused by the incision. Another possible explanation is that the incision may have caused central steepening (and thus a steeper keratometry reading) even though it achieved its aim of peripheral flattening.[26] Further research is necessary to determine eye-specific factors that influence the amount of coupling in incision surgery.

In this paper, we did not consider treatments for mixed astigmatism in which 1 meridian requires a myopic treatment while the meridian at right angles to it requires a hyperopic treatment. Part of the problem is that different lasers implement mixed astigmatic treatments using differing paradigms. Some perform a spherical treatment followed by a cylindrical treatment, while others calculate a tissue-saving ablation profile to achieve the mixed astigmatic treatment directly with 2 proportional planocylindrical treatments without the spherical component being required.[27] Theoretically, the amount of coupling caused by a treatment of mixed astigmatism could be calculated by combining the individual amounts of coupling caused by each individual ablation. However, this would have to be validated against clinical data.

In conclusion, coupling is a clinically significant phenomenon that affects the visual outcomes of incisional and ablative procedures. By determining coupling, a surgeon can better anticipate the spherical effect of astigmatic treatments. Our results show that the amount of coupling caused by any type of astigmatism treatment can be estimated reliably from historical data as long as small astigmatic treatments (<1.0 D) are excluded from consideration. In the case of laser ablation, the resulting coupling adjustment can then be incorporated into future surgical plans for sphere to improve the accuracy of visual outcomes.

WHAT WAS KNOWN

- The corneal coupling ratio has been traditionally defined as the ratio of flattening at the treatment meridian to the steepening at the opposite meridian.
- The coupling constant has been defined as the ratio of the change in SE to the whole change in astigmatism (SIA).

WHAT THIS PAPER ADDS

- The coupling ratio was redefined to make it meaningful for laser ablation procedures as well as incisions.
- The coupling constant was redefined to consider only the part of the astigmatism caused directly by the surgical procedure. This involves vectorially resolving the SIA vector to the treatment meridian and opposite meridian.
- The coupling adjustment (CAdj) for laser ablation procedures was introduced. This new measure can be used clinically in the surgical planning process to factor in the anticipated spherical effect of an astigmatic treatment, allowing the surgeon to more accurately target the desired SE.

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