Intraocular lens calculation after refractive surgery for myopia: Haigis-L formula

Wolfgang Haigis, MS, PhD

PURPOSE: To describe the Haigis-L formula for the calculation of intraocular lenses (IOLs) after refractive laser surgery for myopia based on current biometry and keratometry and present clinical results.

SETTING: University Eye Hospital, Wuerzburg, Germany, and various clinics and private practices.

METHODS: The basic concepts of the new algorithm were described and summarized. The Haigis formula was analyzed with respect to its usability for eyes after laser surgery for myopia and modified accordingly. Correction curves for IOLMaster keratometry were derived from previous studies. The new formula was checked using the postoperative results of 187 cataract procedures in which 32 IOL types were implanted by 57 surgeons. Input data were current IOLMaster biometry as follows: axial length (AL), anterior chamber depth (ACD), and keratometry (corneal radii) measurements.

RESULTS: Before IOL surgery, the mean spherical equivalent was −7.60 diopters (D) ± 3.90 (SD) (range −20.00 to −1.25 D); the mean AL, 27.02 ± 2.01 mm (range 23.09 to 35.32 mm); the mean ACD, 3.52 ± 0.36 mm (range 2.43 to 4.39 mm); and the mean of the measured corneal radii, 8.70 ± 0.60 mm (range 7.28 to 10.96 mm). The mean arithmetic refractive prediction error was −0.04 ± 0.70 D (range −2.30 to +2.40 D) and the median absolute error, 0.37 D (range +0.01 to +2.40 D). The percentages of correct refraction predictions within ±2.00, ±1.00, and ±0.50 D were 98.4%, 84.0%, and 61.0%, respectively.

CONCLUSIONS: The new formula would produce promising results in eyes without refractive history. Its refractive predictability fulfills the current criteria for normal eyes.

J Cataract Refract Surg 2008; 34:1658–1663 © 2008 ASCRS and ESCRS

Since Harold Ridley first replaced a cataractous lens with a poly(methyl methacrylate) intraocular lens (IOL) in 1949, IOL implantation has become the most frequently performed and successful surgical procedure in medicine. Modern microsurgical techniques, new IOL technologies, sophisticated biometry methods, and advanced methods in IOL power calculation allow most cataract patients to regain high-quality vision. However, problems are encountered in treating the increasing number of patients who have had refractive corneal surgery and are now developing a cataract. Intraocular lens power calculation produces postoperative hyperopic errors in many of these patients because of altered corneal geometry. In the past few years, increasing attention has been given to this problem.[1–15]

Three main sources of error have been identified.[16] First, curvature measurements are erroneous because they are not obtained from the corneal center (radius error). Second, corneal power calculated with the commonly used keratometric index is incorrect (keratometer index error). Third, erroneous IOL positions are derived from the decreased corneal powers in some IOL power formulas (IOL formula error).

The proposed solutions to these problems can be divided into 2 classes: (1) procedures requiring patient

Accepted for publication June 20, 2008.

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The author has no financial or proprietary interest in any material or method mentioned.

Presented in part at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, March 2006.

Warren Hill, MD, provided patient outcomes.

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Published by Elsevier Inc.

0886-3350/08/$—see front matter
doi:10.1016/j.jcrs.2008.06.029

historical data and (2) methods relying only on current measurements. An important member in the first class is the refractive history method,[17,18] which serves as a gold standard. Most of the more recent studies discuss no-history procedures.[1–5,9,10,12] The formula presented here also belongs in the second class. It has been in clinical use for approximately $2^1/_2$ years, with the first experiences published in German.[1,2] It is also included in the operating software of the IOLMaster (version 4.0 and later, Carl Zeiss Meditec AG).

This paper explains the new formula (Haigis-L) in detail and illustrates it with clinical results of cataract surgeries in 187 eyes after laser treatment for myopia.

PATIENTS AND METHODS

Haigis-L Formula

To improve IOL calculation in eyes with former refractive surgery, the 3 basic factors in IOL calculation problems (ie, radius error, keratometer index error, and IOL formula error) errors must be avoided, and if this is not possible, corrected. This is the basic approach of the formula described here.

The error introduced by the radius measurement depends essentially on the instrument used (keratometer, topography system), amount of refractive correction achieved, and laser and ablation types applied. Together with the keratometer index error, the error introduced by the radius measurement can be corrected for a given instrument if a correlation can be found between the wrongly measured corneal radii and the actually effective corneal powers after refractive surgery. Such a correlation has been established for, among other instruments, the IOLMaster (W. Haigis, MS, PhD, et al., “Messung von Hornhautradien bei normalen Augen und Augen nach LASIK,” presented at the 16th Kongress der Deutschen Ophthalmochirurgen, Nürnberg, Germany, August 2003; W. Haigis, MS, PhD, et al., “Bestimmung wirksamer Hornhautradien nach myoper LASIK,” presented at the 103 Kongress der Deutschen Ophthalmologischen Gesellschaft, Berlin, Germany, September 2005).

The anterior corneal radius was measured with the IOLMaster in 40 eyes of 20 patients with a mean age of 37.8 years ± 11.5 (SD) (range 20.0 to 60.9 years) after myopic laser in situ keratomileusis (LASIK) (preoperative refraction −6.30 ± 2.60 diopters [D], range −12.75 to −1.75 D). In addition, the refractive history method[17,18] was applied to calculate the (equivalent) corneal power effective after laser surgery. As a result, a correction curve was obtained, allowing the determination of the effective corneal power from current radius measurements (Figure 1). The correlation coefficient is 0.96; the regression equation ($P < .001$) is shown in the graph

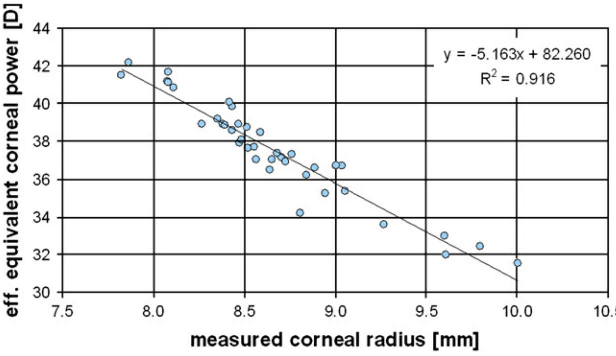

Figure 1. Effective (equivalent) corneal power from the refractive history method as a function of corneal radius measured with the IOLMaster in 40 eyes after LASIK for myopia performed with a Schwind keratome (eff. = effective).

in Figure 1. Corneal powers derived from Figure 1 are free of radius and keratometer index errors.

The formula error can be avoided by using an IOL power algorithm that does not use corneal power as a predictor for the postoperative effective IOL position (such as the Haigis formula[19,20]). In preceding model calculations[16] that simulate laser surgery for myopia in Gullstrand-like theoretical eyes and the performance of popular IOL power formulas in these eyes, the smallest deviations between the necessary and predicted IOL powers were with the Hoffer Q and Haigis formulas in combination with corneal powers from the refractive history method. The smallest residual errors (0.3 to 0.6 D) were with the Haigis formula. Table 1 summarizes the results of the model calculations.[16] Therefore, the Haigis formula can be considered a good candidate for IOL calculations in post-refractive surgery eyes, especially in connection with the correction curve in Figure 1.

Although the effect of a shortening of, for example, the axial length (AL), due to laser ablation was neglected in the model calculations, this is not justified in reality. Although the “correct” AL and anterior chamber depth (ACD) are measured with the IOLMaster in such an eye, the ACD requires special consideration because it enters the effective lens position (ELP) prediction in the Haigis formula. In IOL power calculation, the ACD is defined as the distance from the anterior corneal vertex to the anterior vertex of the crystalline lens, and this distance is shortened by the refractive procedure. This suggests an IOL position that is too anterior and thus, an IOL power that is too small. Thus, the Haigis formula is also subject to an ELP prediction error that stems from the ACD instead of the corneal power, as in the other formulas, but with much less effect, as will be shown in the following estimate.

Table 1. Deviations between necessary IOL power for emmetropia and predicted IOL powers with different formulas for myopic model eyes formerly −5.0 D and −1.0 D (after Haigis[16]).

	IOL Power Formula				
Parameter	SRK II	SRK/T	Holladay 1	Hoffer Q	Haigis
Prediction error (D) for model eye formerly −5.0 D	−1.32	−0.74	−0.40	0.45	0.30
Prediction error (D) for model eye formerly −10.0 D	−2.71	−1.17	−1.07	0.87	0.56

IOL = intraocular lens

The mean decrease in AL in the eyes in the 2003 paper by Haigis et al. (cited above) was 135 ± 119 μm (range −70 to +480 μm), for a mean preoperative refraction of −6.30 ± 2.60 D (range −12.75 to −1.75 D).

A similar reduction in ACD would cause an IOL power too weak by ≈ 0.135 × 1.7 D ≈ 0.22 D. For eyes after refractive surgery, this factor could be added separately to the result of the "normal" IOL calculation or, preferably, incorporated into the correction curve in Figure 1. Because a change of 1.00 D in corneal power is roughly equivalent to a change of −1.40 D in IOL power, an increase of 0.22 D in IOL power can be effected by a decrease of 0.22/1.4 D ≈ 0.16 D in corneal power.

By doubling this value to 0.35 D, to stay on the safe (myopic) side, an additional correction factor for the corneal power that makes allowance for this small ELP prediction error is introduced.

In summary, the Haigis-L formula is characterized by the following stages:

1. Use the correction curve of Figure 1 to correct the current IOLMaster measurement of corneal radius and to derive the effective equivalent corneal power.
2. Subtract 0.35 D from the obtained value to allow for the ELP prediction error.
3. Reconvert this value into an effective corneal radius on the basis of a keratometer index of 1.3315 and enter it into the regular Haigis formula (because this formula calls for a radius input and internally uses the 1.3315 conversion).

Hence, if r_{meas} is the corneal radius (mm) measured with the IOLMaster in an eye after laser surgery for myopia, the corrected radius r_{corr} to be entered into the regular Haigis formula is calculated according to

$$r_{corr} = \frac{331.5}{-5.1625 \times r_{meas} + 82.2603 - 0.35}$$

Clinical Calculations

The new formula was applied to 187 eyes after myopic LASIK, laser-assisted subepithelial keratectomy, or photorefractive keratectomy, the data for which were provided by 57 surgeons from Austria (1), Australia (1), Belgium (1), Canada (1), Germany (35), Switzerland (1), and the USA (17) (Appendix). In most cases, data were sent to the author before cataract surgery and IOL power was calculated prospectively from current measurement data. In the other cases, refraction was derived retrospectively from patient data sets that included biometry and keratometry results, IOL type, and power and refractive outcomes. To the author's knowledge, no eye in the study population had had retreatment.

Personalized IOL constants were used if explicitly provided for the IOL to be implanted by the respective surgeon. In all other cases, which were the majority, optimized lens constants were taken from the User Group for Laser Interference Biometry web site (User Group for Laser Interference Biometry. Optimized constants for the Zeiss IOLMaster. Available at: http://www.augenklinik.uni-wuerzburg.de/eulib/. Accessed July 11, 2008).

All patients had biometry (AL and ACD) and keratometry (corneal radii) measurements with an IOLMaster at the respective centers before cataract extraction; that is, after corneal refractive surgery. The surgeons were asked to report the stable postoperative manifest refraction at best corrected distance visual acuity after cataract surgery.

In all 187 eyes, the predicted refraction (Rx calc) according to the Haigis-L formula was compared with the postoperative manifest refraction (Rx true) by forming the arithmetic prediction error ME = (Rx true − Rx calc) as well as its absolute value (MA). In addition, the percentages of correct refraction predictions within ±0.50, ±1.00, and ±2.00 D were derived. Means and standard deviations were calculated for ME and MA, although statistically this does not make sense for MA, which in general is not normally distributed. These numbers are given to simplify comparison with the literature, in which averages of MA are often found.

The calculations with the Haigis-L formula were then repeated with the regular Haigis formula; that is, all eyes were treated as though they had no previous refractive corneal surgery.

Statistical Analysis

Clinical findings were statistically evaluated using Excel 2000 (Microsoft Corp.) and SPSS software (version 15.01, SPSS, Inc.). Means, standard deviations, medians, 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. A P value less than 0.05 was considered statistically significant.

RESULTS

Current IOLMaster biometry and keratometry data (after refractive surgery for myopia and before cataract surgery) and stable manifest refractions (best corrected distance acuity) after IOL implantation were available for all 187 eyes. The respective mean values were AL, 27.02 ± 2.01 mm (range 23.09 to 35.32 mm); ACD, 3.52 ± 0.36 mm (range 2.43 to 4.39 mm); mean of steep and flat corneal radii, 8.70 ± 0.60 mm (range 7.28 to 10.96 mm), and spherical equivalent (SE) of stable refraction, −0.51 ± 1.14 D (range −5.25 to +4.50 D).

Thirty-two IOL types were implanted as follows: Alcon SN60WF (53); Alcon SA60 (32); Advanced Medical Optics (AMO) AR40e (24); Alcon SN60 (12); AMO Tecnis Z9000 (8); AMO Tecnis ZA9003 (7); Bausch & Lomb LI61SE (6); Eyeonics AT45 (5); Staar Visacryl (4); AMO AR40 (4); Acri.Tec Acri.Smart 46S-5 (4); AMO SI-40 (3); AMO Clariflex (2); Alcon MA60AC (2); Dr. Schmidt MS612 (2); Lenstec Softec (2); Polytech Polylens A62 (2); other IOL models (15). The mean IOL power was 19.4 ± 2.9 D (range 9.0 to 27.5 D).

Although data required for IOL calculation was complete for all 187 eyes, it was not complete for other parameters. The mean patient age (n = 78) was 58.1 ± 8.5 years (range 42.0 to 77.0 years). The mean time elapsed between surgery and date of refraction measurement (n = 82) was 92 ± 103 days (range 1 to 434 days). Twice, refraction was determined on the first postoperative day. Twice, the time between

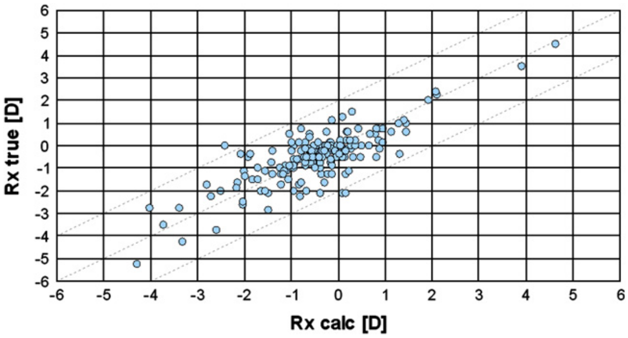

Figure 2. The SE of Rx true versus Rx calc using the Haigis-L formula. Dashed lines show the ±0.00 D and ±2.00 D limits. Regression line: Rx true = m × Rx calc + *t* with slope *m* = 0.817 (*P* < .001) and offset *t* = −0.128 (*P* = .017); correlation coefficient = 0.81. (Rx calc = predicted refraction; Rx true = postoperative manifest refraction).

surgery and measurement was 5 days, 3 times it was 7 days, and once it was 9 days. All other times were 13 days or more. The best corrected distance visual acuity after IOL implantation was available for 117 eyes as follow: 4/20, 2 eyes; 6/20 to 20/15, 115 eyes; and 20/30 or better 85 eyes (73%).

The mean SE before laser surgery for myopia (n = 105) was −7.60 ± 3.90 D (range −20.00 to −1.25 D).

Figure 2 shows a comparison between the SE of the actually achieved refractions (Rx true) and the calculated values (Rx calc) resulting from the Haigis-L formula. A high correlation coefficient (0.81) was found.

The mean arithmetic prediction error ME was calculated as the mean value of the individual differences (Rx true − Rx calc) and the mean absolute prediction error MA, as the mean of the absolute values of the individual differences (Rx true − Rx calc). The results obtained were ME −0.04 ± 0.70 D (range −2.30 to +2.40 D), MA 0.51 ± 0.48 D (range 0.00 to 2.40 D), median of absolute prediction error, 0.37 D (Table 2). The ME was not significantly different from 0 (*P* = .398).

Figure 3 shows the distribution of the arithmetic prediction errors and a graph of the normal distribution. The Kolmogorov-Smirnov test confirmed the normal distribution of the arithmetic prediction errors (*P* = .100). Three (1.6%) of 187 cases were outside ±2.00 D (Figure 3).

The percentages of correct refraction predictions within ±2.0, ±1.0, and ±0.5 D were 98.4%, 84.0%, and 61.0%. Table 2 shows these results are compared with respective data from a normal cataract group (n = 771).

Table 2 also gives the corresponding results for the application of the regular Haigis formula instead of the Haigis-L. Figure 4 shows the box plots of the arithmetic prediction error (Rx true − Rx calc) in these 2 cases.

DISCUSSION

The primary aim of this paper is not to compare different methods of IOL calculation after refractive surgery with a new method. Rather, it is intended to describe the Haigis-L algorithm, which has been in clinical use for approximately $2^1/_2$ years, has been published in part in German,[1,2] and is included in the current IOLMaster software (version 4.0 and later). Nevertheless, the procedure can be directly compared with the no-history method of Shammas and Shammas,[3] whose basic IOL power formula is also not subject to the formula error (which in other formulas must be corrected by the Aramberri double-K method[11]).

One problem in the literature on IOL calculation after corneal refractive surgery is the comparatively small number of patients for which the refractive outcomes after cataract surgery are available. Masket and Masket[6] report 30 eyes, Latkany et al.[8] 21 eyes, Rosa et al.[9] 19 cases, Einighammer et al.[21] 12 eyes, Walter et al.[7] 9 eyes, Shammas and Shammas[3] 15 eyes, and Rabsilber et al.[23] 10 eyes. It seems as though the

Table 2. Correct refraction predictions within ± 2.0 D, ± 1.0 D, and ± 0.5 D, ME, MA, and medians in eyes after refractive laser surgery for myopia (present work) and normal cataract eyes calculated with different formulas (from Haigis[21]).

	Cataract After Refractive Surgery		Normal Cataract*
Parameter	Haigis-L Formula	Haigis Formula	Haigis Formula
Within ±2.0 D (%)	98.4	84.0	99.1
Within ±1.0 D (%)	84.0	36.9	93.0
Within ±0.5 D (%)	61.0	13.4	73.4
Mean ME (D) ± SD	−0.04 ± 0.70	1.28 ± 0.83	0.00 ± 0.59
Median ME (D)	−0.02	1.20	—
Mean MA (D) ± SD	0.51 ± 0.48	1.31 ± 0.76	0.42 ± 0.42
Median MA (D)	0.37	1.20	—

IOL = intraocular lens; MA = mean absolute prediction error; ME = mean arithmetic prediction error
*Eyes without previous refractive surgery and with an SI-40 IOL (n = 771); data provided by J. Brändle, Füssen, Germany

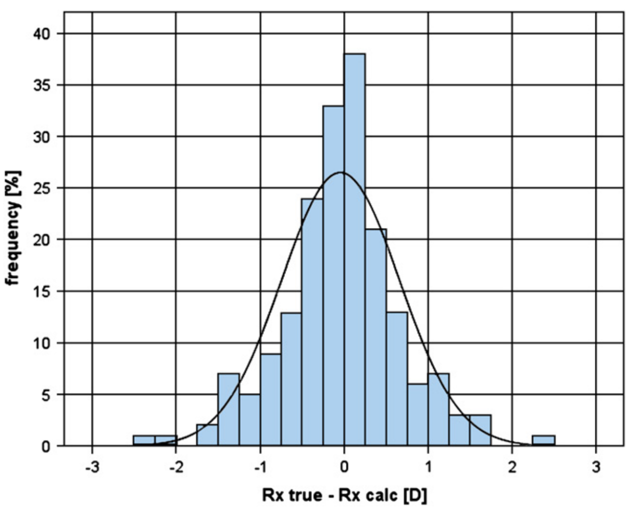

Figure 3. Distribution of the arithmetic prediction errors (Rx true − Rx calc). The solid curve is the Gaussian distribution (Rx calc = predicted refraction; Rx true = postoperative manifest refraction).

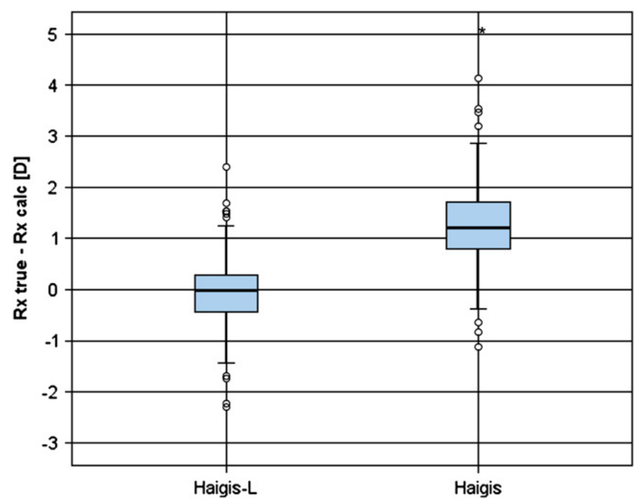

Figure 4. Arithmetic prediction error (Rx true − Rx calc) obtained with the Haigis-L and the regular Haigis formula. Each box is given by the 75% percentile (*top*) and 25% percentile (*bottom*) and its length (interquartile range) by the difference between the 2 percentiles. The horizontal line inside the box represents the median (50% percentile). Open circles represent outliers (between 1.5 and 3.0 box lengths above the upper or below lower quartile); stars are extreme values (more than 3.0 box lengths above the upper or below lower quartile). The horizontal lines that end with a whisker denote the smallest and largest values that are not yet outliers (Rx calc = predicted refraction; Rx true = postoperative manifest refraction).

present study, with 187 eyes, comprises the largest series to date of cataractous eyes after refractive surgery with post-cataract follow-up.

The present mean ME (−0.04 ± 0.70 D) and MA (0.51 ± 0.48 D) prediction errors compare most favorably with results in the literature; for example, eg, ME 0.31 ± 0.84 D and MA 0.74 ± 0.46 D,[22] ME 0.08 ± 0.62,[4] ME 0.14 D,[23] and ME −0.15 ± 0.29 D.[6] Shammas and Shammas'[3] results (ME 0.003 ± 0.63 D, MA 0.55 ± 0.31 D) are given for the IOL prediction error; converted to refraction prediction errors, these numbers are even smaller.

The results for normal cataracts (ie, eyes without previous refractive surgery) compared with those in eyes after refractive surgery are better by nature: 73.4% versus 61.0% correctly predicted within ±0.50 D, 93.0% versus 84.0% within ±1.00 D, and 99.1% versus 98.4% within ±2.00 D. With the current results, however, even eyes after refractive surgery would virtually comply with a recent benchmark standard of 85% of patients achieving a final refraction (SE) within ±1.00 D and 55% within ±0.50 D of the predicted figure.[24]

Ignoring a preceding refractive surgery and treating a patient like a normal cataract case (ie, applying the regular Haigis formula) produced a mean postoperative hyperopia of 1.28 ± 0.83 D (Figure 4). This number illustrates the contribution of the radius measurement and keratometer index errors because no additional error is created by the Haigis formula as the formula does not use the corneal radius as a predictor of IOL position.

An advantage of this study—the large number of post-cataract post-refractive surgery eyes—is also responsible for its limitations. Although refractive results were obtained and processed for all eyes with IOL powers determined prospectively, it cannot be ruled out that patient selection in the retrospective cases may have been biased; for example, by sending only cases with better results (although this is doubtful). Furthermore, it was not possible to obtain additional data (eg, patient age, best corrected distance acuity, time between surgery, and refraction measurement) in every case, as would have been desirable, even though all core data necessary for the calculations were obtained for all 187 eyes from all 57 different centers. I am aware of the weakness caused by missing data but decided to accept it in favor of the high number of eyes for which an IOL calculation after laser surgery for myopia could be performed.

Another possible limitation is that the follow-up time covers a wide range, from 1 to 434 days. However, there are no essential changes in overall results if only eyes from a limited follow-up period are considered, as a separate analysis of 34 cases with a follow-up between 4 weeks and 12 weeks (median 42 days) showed. This analysis found a mean ME of −0.12 ± 0.58 D, a mean MA of 0.43 ± 0.41 D, and a respective median of 0.28 D, which compare favorably with the results from all 187 eyes.

In conclusion, the new algorithm allows precisely predictable outcomes in eyes after corneal refractive laser surgery for myopia solely on the basis of current measurements. Previous patient data are not required. In the largest series of post-refractive and post-cataract outcomes published to date, quality criteria relating to refractive predictability that are presently demanded for normal eyes are fulfilled.

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APPENDIX

Surgeons Who Provided Patient Data for the Study

Australia: M. Goggin. *Austria*: P. Jirak. *Belgium*: F. Goes. *Canada*: M. McCarthy. *Germany*: M.K. Amberger, M. Armbrust, G. Auffarth, A.J. Augustin, W. Bachmann, A. Bacskulin, S. Behrendt, D. Bergner, P. Busch, O. Dollinger, K. Ellendorf, B. Flohr, E. Frieling, P. Hiss, P. Hoffmann, C. Karakoulakis, T. Kauffmann, A. Kreuzmann, K. Krüger, P. Kühnrich, C. Lackerbauer, P. Meier, S. Schmickler, G.-M. Schröder, W. Sekundo, K. Selde, J. Sold, H. Strobl, E. Ungerechts, D. Uthoff, J.R. Vilada, J. Weindler, R. Wertheimer, I. Wiswe, T.M. Wohlrab. *Switzerland*: M. Kynigopoulos. *United States*: G. Berdy, H. Fine, S. Grosser, W. Hill [also provided data of 10 other U.S. surgeons, M. Meyer, M. Packer, F.R. Reid.

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