This article has been accepted for publication in BJO following peer review.

The definitive copyedited, typeset version is available online at 10.1136/bjo-2023-323921

Title: Prediction of spectacle refraction uncertainties with discrete IOL power steps and manufacturing tolerances according to ISO using a Monte-Carlo model

Short title: Refraction uncertainties with IOL power steps and manufacturing tolerances

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Article Category: Clinical Science

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Synopsis/Precis

(35 words, **maximum 35 words**)

We consider the effects of both discrete power steps in implantable lens ranges, which limit surgeons' options, and of lens power labelling tolerances which can introduce stochastic variations in the achieved refraction following refractive surgery.

Abstract

(250 words, **maximum 250 words**)

Purpose: The purpose of this study was to develop a concept for predicting the effects of both discrete intraocular lens (IOL) power steps (PS) and power labelling tolerances (LT) on the uncertainty of the refractive outcome REFU.

Design: Retrospective non-randomised cross sectional Monte-Carlo simulation study

Methods: We evaluated a dataset containing 16,669 IOLMaster 700 preoperative biometric measurements. The PS and the delivery range of 2 modern IOLs (Bausch and Lomb enVista and Alcon SA60AT) were considered for this Monte-Carlo simulation. The uncertainties from PS or LT were assumed to be normally distributed according to ± ½ the IOL power step or the ISO 11979 labelling tolerance. REFU was recorded and analysed for all simulations.

Results: With both lenses the REFU from discrete PS ranged from 0.11 to 0.12 dpt. Due to the larger PS for low / high power lenses with the enVista / SA60AT, REFU is more dominant in initially myopic / hyperopic eyes. REFU from LT ranged from 0.18 to 0.19 dpt for both lenses. Since LT increases stepwise with IOL power, REFU is more prevalent in initially hyperopic eyes requiring high IOL power values, and for lenses with a wide delivery range towards higher powers.

Conclusions: Since surgeons and patients are typically aware of the effect of discrete power steps on REFU, these might be tolerated in cataract surgery. However, REFU resulting from labelling tolerances is inevitable while the true measured IOL power is not reported on the package, leading to background noise in postoperative achieved refraction.

Key words: Discrete IOL power steps, IOL labelling tolerances, ISO 11979, Monte-Carlo simulation, refractive performance, IOL power formulae

Key messages

What is already known on this topic?

Discrete power steps and the delivery range of an IOL limit the flexibility of the surgeon in planning and achieving the desired target refractive outcome for the patient following cataract surgery, while power labelling tolerances as specified in ISO 11979 mean that IOLs are typically labelled with only nominal power values.

The actual measured power values are typically not disclosed by IOL manufacturers and may distort the refractive outcome after cataract surgery independently of the IOL power calculation scheme.

What this study adds?

Larger power steps for low or high power lenses can limit the ability of the surgeon to customise the target refraction for initially myopic or hyperopic eyes.

Variations in IOL power within the labelling tolerances are typically not disclosed to the surgeon or patient and can induce stochastic variations (background noise) in the refraction after cataract surgery, making interpretation of study results in terms of comparisons of biometers, calculation concepts, or different lens types difficult.

How this study might affect research practice or policy?

A straightforward measure that could easily be implemented would be for manufacturers to report the exact IOLP as measured during final quality checks by printing it on the IOL package, enabling the actual value to be factored into future scientific studies, eliminating this source of error.

Introduction

The reliability of ocular biometry before cataract surgery and of intraocular lens (IOL) power calculation has improved significantly in the last decade.[1-3] Using optical biometry clinicians can achieve highly repeatable and mostly user independent results. Modern intraocular lens power (IOLP) concepts are trained to deal with these high performance measures. The IOLP formulae currently in use are remarkably consistent, with little difference between the spectacle refraction predictions of different formulae. This means that, in studies, very large sample sizes are required to distinguish systematically between these differences.[4,5]

However, there is still a gap between the search for perfection on the one hand and the classical standards of IOL power tolerances according to the ISO standard (Ophthalmic implants; EN ISO 11979-2:2014) [6] and the discrete power steps of modern IOLs on the market on the other hand. According to this ISO standard the equivalent power of an IOL could deviate from the labelled IOLP (deviation/uncertainty: ISOU in dpt) by ISOU = -0.3 dpt to 0.3 dpt for low power IOLs (IOLP ≤ 15 dpt) up to ISOU = -1.0 to 1.0 dpt for high power IOLs (IOLP > 30 dpt). Some IOL manufacturers provide their IOLs with fixed IOLP steps (e.g. ½ dpt) for the entire power range, whereas others provide low (and / or high) powered IOLs with larger power steps (e.g. 1 dpt), with smaller power steps (e.g. ½ dpt) being used only for the most commonly used lens powers (Ophthalmic implants; EN ISO 11979-2:2014).[6]

This discretisation of manufacturing power steps (instead of using the 'perfect' lens power) limits the ability to achieve a specific target refraction, requiring the surgeon to discuss with the patient the options for the postoperative refraction. Using the nearest available power step leads to a choice of whether to target the final refraction more to plus (with the next lower power) or more to minus (with the next larger power). This means that we always have a variation between the 'perfect' lens power and the next available power step (uncertainty STEPU in dpt). In general this might not be a disadvantage given that both the surgeon and the patient are aware of the discrete power steps of the IOL and the consequent possible deviation of the achieved refraction from the target refraction. In contrast, the ISO tolerances for manufacturers are a different task: if during cataract surgery an IOL with any labelled power is implanted, the surgeon could be surprised on the refractive outcome if the 'real' equivalent IOLP somehow deviates from the power label. This can especially impact initially hyperopic eyes where surgery might in general be more challenging anyway due to limited space in the anterior chamber and where predictability of the refractive outcome is lower in any case. In this situation the larger IOLP tolerances of the high power IOL may add some uncertainty to the refractive outcome.[5,7,8]

In the literature we could find only limited studies addressing the effect of IOL power steps or labelling tolerances on the prediction of the refractive outcome or providing benchmarks for REFU.[9,10] However, as other error sources related to ocular biometry and IOLP calculation are reduced, IOLP steps and labelling errors gain more and more relevance and will be subject to discussions in the near future.[7,8]

The **purpose of this paper** is to investigate the effect of IOL power steps and ISO labelling tolerances on the IOLP, as well as combinations of both on the formula predicted refraction after cataract surgery. The calculation is performed on a large dataset containing measurements from a modern optical biometer from a cataractous population, and a Monte-Carlo simulation is used to propagate the IOLP deviation due to power steps or manufacturing/labelling tolerances to a refraction uncertainty at the spectacle plane.

Methods

Dataset for the prediction model

A large dataset containing 21,108 biometric measurements was considered in this study. All measurements were performed at the Augen- und Laserklinik, Castrop-Rauxel, Germany and Department of Ophthalmology and Optometry, Johannes-Kepler-University Linz, Austria with the IOLMaster 700 (Carl-Zeiss Meditec, Jena, Germany).

The data were anonymised by the source and transferred to a .csv data table using the software module for batch data export. Data tables were reduced to the relevant parameters required for our data analysis, consisting of the following measurements: from the measurement before cataract surgery we extracted the patient's age (Age) in years, the laterality (left or right eye), sex (female or male), flat ($R1_a$) and steep ($R2_a$) corneal front surface radii of curvature both in mm, axial length (AL) in mm, central corneal thickness (CCT) in mm, anterior chamber depth (ACD) in mm (measured from corneal epithelium to lens), central thickness of the crystalline lens (LT) in mm, and horizontal corneal diameter (CD) in mm. Only one eye from each subject was included in this study. Where measurements of both eyes were available, one eye was randomly selected. Subjects with missing data or data with a 'Failed' or 'Warning' in the internal quality check of the IOLMaster 700 for $R1_a$, $R2_a$, AL, CCT, ACD, LT, CD were excluded. The data were transferred to Matlab (Matlab 2022b, MathWorks, Natick, USA) for further processing.

Data pre-processing in Matlab

The mean corneal curvature R_a in mm was derived from the corneal curvature in the flat and steep meridians as $R_a = 0.5 \cdot (R1_a + R2_a)$. For the IOLP calculation we implemented the Haigis formula [11] as an example of a fully disclosed 4^{th} generation lens power calculation formula, as well as the Castrop formula [3,12,13] as a modern lens power calculation formula dealing with a thick lens model for the cornea and an effective lens position prediction which resamples the anatomically correct axial position of the IOL in the pseudophakic eye.[14-16] To simplify the data interpretation, instead of the measured corneal back surface data we used a corneal back surface derived from a fixed front to back surface ratio (7.77 mm / 6.4 mm) and a fixed central corneal thickness CCT = 0.5 mm according to the schematic model eye of Liou & Brennan.[17] As examples we considered for our calculations 2 commonly used IOL models: enVista (MX60, Bausch & Lomb, Rochester, USA) and SA60AT (Alcon Laboratories, Fort Worth, USA). The respective formula constants for the Haigis formula (a0 / a1 / a2 = 0.1835 / 0.3153 / 0.1725 and -1.501 / 0.285 / 0.235 for the MX60 and SA60AT, respectively) and for the Castrop formula (C / H / R = 0.3669 / 0.156 / -0.1252 and 0.2907 / 0.1128 / 0.0138) were

extracted from the IOLCon WEB platform (https://IOLCon.org, accessed on 30.04.2023). The 'perfect' or 'exact' lens power (IOLPE) was calculated for each eye with both lens power calculation formulae.[3,11-13] In addition to the IOLCon optimised formula constants we also extracted the manufacturer step sizes together with the delivery range for both lenses from the IOLCon WEB platform (https://IOLCon.org, accessed on 30.04.2023; MX60: 0 to 9 dpt in 1 dpt steps and 10 to 30 dpt in 0.5 dpt steps, SA60AT: 6 to 30 dpt in 0.5 dpt steps and 31 to 40 dpt in 1 dpt steps).

Monte-Carlo simulation in Matlab

First we selected for the best fit lens for all eyes and both formulae. According to the practice of most surgeons, instead of searching for the closest power step within the delivery range, we added a tolerance value of TOL = 0.15 dpt to IOLPE (to prevent postoperative hyperopia) and then searched for the closest available IOL power step (quantised power IOLPQ). For both tails of the delivery range we decided to select the respective IOLPQ if IOLPE + TOL did not deviate more than half the power step size at the respective tail. This means, that e.g. for the MX60 IOLPE was considered in a range between -0.65 dpt and 30.10 dpt and for the SA60AT of IOLPE was considered in a range between 5.60 dpt and 40.35 dpt. The uncertainty in IOLP due to discrete power steps STEPU was defined as the range from the lower boundary ($STEP_{lo}$: IOLPQ -½ the step to the next lower lens power) to the upper boundary ($STEP_{hi}$: IOLPQ + ½ the next higher power step).

Both the uncertainty in IOLP due to the discrete IOL power steps STEPU (as provided from the manufacturers) and the variation due to the labelling tolerances ISOU according to the ISO standard (EN ISO 11979-2:2014) were assumed to be uniformly distributed and uncorrelated to each other. For the manufacturer provided power steps the lower and upper boundaries of the ranges for the uniform distributions was derived from the step sizes (the IOLPQ neighbours of IOLPE). For the ISO labelling tolerance the lower (ISO_{lo}) and upper (ISO_{up}) boundaries of the ranges for the uniform distributions was derived symmetrically from IOLPQ according to ISO 11979, with values depending on the lens power of: ISO_{lo} = IOLPQ – 0.3 dpt to ISO_{hi} = IOLPQ + 0.3 dpt for IOLPQ ≤ 15 dpt, ISO_{lo} = IOLPQ – 0.4 dpt to ISO_{hi} = IOLPQ + 0.4 dpt for 15 dpt < IOLPQ ≤ 25 dpt, ISO_{lo} = IOLPQ – 0.5 dpt to ISO_{hi} = IOLPQ + 0.5 dpt for 25 dpt < IOLPQ ≤ 30 dpt, and ISO_{lo} = IOLPQ – 1.0 dpt to ISO_{hi} = IOLPQ + 1.0 dpt for IOLPQ > 30 dpt (EN ISO 11979-2:2014).[6]

In the next step, a Monte Carlo simulation [18] was set up using the biometric data from the dataset and the quantised IOLPQ together with the lower and upper boundaries ($STEP_{lo}$ to $STEP_{up}$ and ISO_{lo} to ISO_{up}) to calculate the effect of IOLP quantisation and labelling tolerances on the refractive outcome at the spectacle plane. For each eye and for both formulae, NMC = 100,000 uniformly distributed samples in a range $STEP_{lo}$ to $STEP_{up}$ and NMC = 100,000 uniformly distributed samples in a range ISO_{lo} and ISO_{hi} were calculated. Additionally we considered an overlay of both deviations (discrete power

steps and labelling tolerance) to investigate the combined effect. For the combined effect, the variation in IOLP follows a trapezoidal probability density distribution derived from a convolution of the 2 uniform (rectangular) probability density distributions for the power steps and the labelling tolerances. In total, for each eye 100,000·2 (lens types)·2 (formulae)·3 (power steps, labelling tolerances and combinations) = 1,200,000 calculations were performed.

Statistical evaluation

From the NMC = 100,000 samples we extracted the 68% confidence intervals (CI) by individually searching for the shortest interval in the data containing 68% of the entire refraction data at the spectacle plane. (The 68% CI is typically used in the literature (Lumme et al. 2015) for error propagation strategies since, in the simple case of a normal distribution, it corresponds to the standard deviation (SD)). Half of this 68%CI interval is quoted as the 'target parameter' refraction uncertainty at the spectacle plane REFU. Explorative data analysis in tables was performed with the arithmetic mean, the SD, the median, and the lower and upper boundary of the 95% confidence interval (which refers to the 2.5% and 97.5% quantiles).

Results

From the N = 21,108 data transferred to us, and after considering the selection criteria, a dataset with N = 16,669 eyes of 16,669 patients was selected for our analysis (N = 9285 eyes from the Augen- und Laserklinik Castrop-Rauxel, N = 7384 eyes from the Department of Ophthalmology, Johannes-Kepler-University Linz). In total, 8407 left and 8262 right eyes from 7107 male and 9562 female patients were included. In **Table 1** the descriptive data for the ocular biometry before cataract surgery is listed including age, AL, ACD, LT, CD, $R1_a$ and $R2_a$, and R_a. Since, for simplicity, we used a fixed central corneal thickness and a fixed corneal front to back surface curvature ratio for calculating the IOLP with the Castrop formula, the CCT and corneal back surface radius data are not listed.

From the initial dataset of N = 16,669 eyes, a total of 16,501 (99.00%) / 16,477 (98.85%) eyes had calculated IOLP values within the delivery range of power steps for the enVista, and 16,523 (99.12%) / 16,515 (98.08%) eyes had calculated IOLP values within the delivery range of power steps for the SA60AT, for IOLP calculations performed with the Castrop / Haigis formula respectively.

Figure 1 displays the refraction uncertainty at the spectacle plane REFU resulting from the discrete power steps of the IOL provided by the IOL manufacturer STEPU. The plots on the left / right graphs display REFU for the enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the upper graphs, REFU is shown as a function of the IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. In addition to the different delivery ranges of both IOLs (0 to 30 dpt for the enVista and 6 to 40 dpt for the SA60AT), the REFU shows larger values for the enVista in the lower power range (power steps 1.0 dpt instead of 0.5 dpt) and larger values for the SA60AT in the higher power range (power steps 1.0 dpt instead of 0.5 dpt).

In **Figure 2**, the REFU resulting from power labelling tolerances ISOU is shown. The plots on the left / right graphs display REFU for the enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the upper graphs, REFU is shown as a function of the 'perfect' lens power IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. In addition to the different delivery ranges of both lenses which results in a different scaling on the x axes, the labelling tolerances increase stepwise from 0.3 to 1.0 dpt for increasing IOLP values.

Figure 3 gives an impression of the variation in spectacle refraction REFU when both effects (discrete power steps of the IOL and labelling tolerances) are superimposed. The plots on the left / right graphs display REFU for the enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the

upper graphs REFU is shown as a function of the IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. The enVista (delivery range 0 to 30 dpt) shows larger power steps for low power lenses and a larger labelling tolerance for high power lenses, whereas the SA60AT shows larger power steps and larger labelling tolerances for high power lenses in both cases.

The average effects of discrete power steps of the IOL STEPU and labelling tolerances ISOU on the uncertainty of spectacle refraction REFU are listed in **Table 2** for both lens types and both IOLP calculation formulae. This REFU data include all clinical cases in the dataset where the lens type offers an appropriate power step. The results for the superposition of IOL power steps and labelling tolerances are not shown in the table. We see from **Table 2** that REFU is quite similar for both IOL power calculation formulae and for both lens types under test. In general, the effect of labelling tolerances ISOU on REFU seems to be larger as compared to the effect of the manufacturing power steps STEPU.

Discussion

In recent decades optical biometry has become the gold standard in ocular biometry (Scholtz et al. 2021) and many new intraocular lens power calculation concepts have been proposed to improve the prediction of the refractive outcome after cataract surgery.[1,3,5] These improvements in biometry and IOLP calculation can be seen as cornerstones for modern lens categories such as multifocal, enhanced depth of focus, monofocal plus or toric lenses. However, even for modern IOL types, the power steps have not changed too much compared to previous lenses on the market. Furthermore, the ISO tolerances for the labelled power have not been upgraded with modern optical measurement techniques in the optics labs of IOL manufacturers.

However, the situation with discrete power steps is completely different to the situation with labelling tolerances.[8,19,20] Knowing that IOLs are available in discrete power steps, the surgeon can discuss target refraction with the patient and decide for the next higher or lower power step depending on the requirements of the patient. Therefore the refraction uncertainty resulting discrete power steps can be managed within the patient's expectations, and does not impact the quality metrics of biometry and IOLP calculation or formula performance when evaluating the postoperative results.[1,4] Power labelling tolerances are a completely different task, as the 'real' equivalent power value of the implanted IOL is not known. Both the surgeon and the patient have to rely on the validity of the labelled power, and especially in high power lenses where the labelling tolerances are quite large a clinically relevant 'stochastic' refraction error could occur which cannot be traced back. In other words, the clinical results after cataract surgery using any biometer, IOLP calculation concept, or any lens type is always biased by the uncertainty caused by the labelling tolerances.[1,7]

In the present paper we have addressed the effect of discrete IOLP steps and labelling tolerances and translated these lens power uncertainties into a corresponding uncertainty in spectacle refraction after cataract surgery. In a Monte-Carlo simulation based on a large clinical dataset with biometric measurements from a cataractous population [18] we used the power step data, the delivery range (both provided by the manufacturer) and the labelling tolerances according to the ISO standard to predict the effect of STEPU and ISOU on REFU. Since with an exact lens power IOLPE for any target refraction we could select either the next higher or lower lens power IOLPQ, the distribution of STEPU is clearly uniformly distributed with a variation of half the power step size to the next higher and lower IOLPQ. In contrast, the real labelling tolerances of an IOL are unknown, and therefore we assumed a uniformly distributed IOLP error within the ISO tolerances. This might be the worst case scenario, and in real life the labelling tolerances may not be fully exploited by the manufacturers.

Therefore the 'real' labelling tolerances might also be represented by a truncated normal distribution; however, such data are not disclosed by the IOL manufacturers.[8]

What can be seen from our results is that for the power step uncertainty STEPU the overall mean or median REFU is in a range of 0.11 to 0.12 dpt for both lens power calculation formulae and both lenses under test. If any lens type were provided in ½ dpt steps over the entire delivery range this value might be slightly smaller. The more eyes we have in our dataset which are treated with a lens power having 1 dpt manufacturing steps the larger the REFU value. This means that we expect the smallest REFU values in lenses with a reduced delivery range and / or ½ dpt steps over the entire range. In addition we see from our results that for the labelling tolerance uncertainty ISOU the overall mean or median REFU is in a range of 0.18 to 0.19 dpt for both lenses. As the SA60AT is available up to an equivalent power of 40 dpt, the labelling tolerance adds more REFU on average as compared to the enVista, which is available only up to power values of 30 dpt. This means that the ISO labelling tolerances of up to ± 1 dpt do not contribute to the overall REFU mean as this lens is not available with power values of more than 30 dpt. However, as the number of eyes requiring a lens power of more than 30 dpt is rather small, the effect on the overall mean is also small (mean REFU 0.1936 / 0.1913 dpt for the SA60AT with the Castrop / Haigis formula compared to 0.1866 / 0.1865 dpt with the enVista). However, what we learn from our data is that if the IOL manufacturer fully exploits the labelling tolerances according to the ISO standard then we could expect a stochastic error in the postoperative spectacle refraction of nearly 0.2 dpt for a normal cataract population, which seems to be the 'background noise' for the refraction predictability after cataract surgery irrespective of the biometer or IOLP calculation scheme used.

Given that we are dealing with uncertainty distributions other than normal distributions, classical strategies such as Gaussian error propagation using the gradients of the transfer function do not work properly.[21] Therefore, we used a Monte-Carlo simulation model, where we can easily deal with any probability density function of the lens power uncertainty. Even superposition effects as shown in **Figure 3**, where the uncertainty due to discrete power steps and due to labelling tolerances are combined, can be simulated without restrictions. We restricted our Monte-Carlo simulation model to NMC = 100,000 iterations, which is expected to be a good trade-off between simulation time and accuracy of the result. For the entire simulation where 1,200,000 Monte-Carlo iterations where performed for each of 16,669 data points the process time on a standard office PC was around 8 min.

However, our study has some limitations: Even though the delivery ranges and power steps are fully known for all IOLs on the market, there are data on repeatability or reliability of IOLP measurements on optics labs but no reliable data on the 'real IOLP' or 'real' labelling tolerances of IOL on the

market.[7,19,20] Even if we try to measure the true lens power in a large set of lenses over the entire power range, the power label according to the ISO standard reflects the paraxial equivalent power (within a 3 mm central zone), but without the exact design data the image side principal plane is unknown as a reference for the measurement. Therefore we decided to simulate the 'worst case scenario' assuming a uniformly distributed error within the labelling tolerances according to EN ISO 11979-2:2014.[6] Further we assumed that the IOLP uncertainty due to discrete power steps is also uniformly distributed, which is not a systematic drawback as clinicians have to make a decision for the next higher or lower power step, and with any tolerance value added to IOLPE such a decision will be made for IOLPE + TOL to the closest available power step. Using a different value for the tolerance TOL will simply shift the IOLPE range and is not expected to affect the REFU result significantly.

In conclusion, our data show that the discrete power steps and the delivery range of an IOL could individually affect the predictability of the refractive outcome after cataract surgery. Larger power steps for low power or high power lenses reduce the options of the surgeon to customise the target refraction for initially myopic or hyperopic eyes. However, and even worse, labelling tolerances as not disclosed to the surgeon or patient induce stochastic variations in the refraction after cataract surgery and will lead to a background noise in all studies focussing on the refractive outcome after cataract surgery with comparisons of biometers, calculation concepts, or different lens types. If the 'real' IOLP measured during final quality check of a lens were reported on the package, this error source could be easily eliminated from scientific evaluations in the future.

Acknowledgement

Funding/Support: The authors confirm that the study was not granted or supported by any governmental or non-governmental organisation.

Financial disclosures:

Dr. Langenbucher reports speaker fees from Hoya Surgical and Johnson & Johnson Vision outside the submitted work.

Dr. Szentmáry and Dr. Cayless do not report any financial interests.

Dr. Bolz reports speaker fees from Carl Zeiss Meditec AG outside the submitted work.

Dr. Hoffmann reports speaker fees from Heidelberg engineering, Hoya Surgical and Johnson & Johnson outside the submitted work.

Dr. Wendelstein reports speaker fees from Carl Zeiss Meditec AG, Alcon and Johnson & Johnson Vision outside of the submitted work.

Ethics statement

The local Institutional Review Board provided a waiver for this retrospective study (Ethikkommission der Ärztekammer des Saarlandes, registration number 157/21), and informed consent from the patient was not required.

References:

1. Preußner PR, Olsen T, Hoffmann PC, Findl O. Intraocular lens calculation accuracy limits in normal eyes. J Cataract Refract Surg 2008; 34(5):802–8.
2. Scholtz S, Cayless A, Langenbucher A. Calculating the Human Eye—Basics on Biometry. In: Liu, C., Shalaby Bardan, A. (eds) Cataract Surgery. Springer Cham, 2021. doi.org/10.1007/978-3-030-38234-6_7
3. Wendelstein J, Hoffmann P, Hirnschall N, Fischinger IR, Mariacher S, Wingert T, Langenbucher A, Bolz M. Project hyperopic power prediction: accuracy of 13 different concepts for intraocular lens calculation in short eyes. Br J Ophthalmol 2022; 106(6):795-801. doi: 10.1136/bjophthalmol-2020-318272.
4. Hirnschall N, Findl O, Bayer N, Leisser C, Norrby S, Zimper E, Hoffmann P. Sources of error in toric Intraocular lens power calculation. J Refract Surg 2020; 36(10):646-652. doi: 10.3928/1081597X-20200729-03.
5. Olsen T. Calculation of intraocular lens power: a review. Acta Ophthalmol Scand 2007; 85(5):472-485. doi: 10.1111/j.1600-0420.2007.00879.x.
6. Ophthalmic implants - Intraocular lenses - Part 2: Optical properties and test methods (ISO 11979-2:2014); EN ISO 11979-2:2014
7. Janknecht P. [Can the scattering of differences from the target refraction be avoided?]. Klin Monbl Augenheilkd 2008; 225(10):868-73. doi: 10.1055/s-2008-1027630.
8. Kim M, Eom Y, Song JS, Kim HM. Comparative evaluation of refractive outcomes after implantation of two types of intraocular lenses with different dioptre intervals (0.25 diopter versus 0.50 diopter). BMC Ophthalmol 2018; 18(1):176. doi: 10.1186/s12886-018-0840-0.
9. Norrby S. Sources of error in intraocular lens power calculation. J Cataract Refract Surg 2008; 34(3):368-76. doi: 10.1016/j.jcrs.2007.10.031.
10. Norrby NE, Grossman LW, Geraghty EP, Kreiner CF, Mihori M, Patel AS, Portney V, Silberman DM. Accuracy in determining intraocular lens dioptric power assessed by interlaboratory tests. J Cataract Refract Surg 1996; 22(7):983-93. doi: 10.1016/s0886-3350(96)80204-5.
11. Haigis W, Lege B, Miller N, Schneider B. Comparison of immersion ultrasound biometry and partial coherence interferometry for intraocular lens calculation according to Haigis. Graefes Arch Clin Exp Ophthalmol 2000;238(9):765-73. doi: 10.1007/s004170000188.
12. Langenbucher A, Szentmáry N, Cayless A, Weisensee J, Fabian E, Wendelstein J, Hoffmann P. Considerations on the Castrop formula for calculation of intraocular lens power. PLoS One 2021; 16(6):e0252102. doi: 10.1371/journal.pone.0252102.

13. Langenbucher A, Szentmáry N, Cayless A, Weisensee J, Wendelstein J, Hoffmann P. The Castrop formula for calculation of toric intraocular lenses. Graefes Arch Clin Exp Ophthalmol 2021; 259(11):3321-3331. doi: 10.1007/s00417-021-05287-w.
14. Langenbucher A, Szentmáry N, Cayless A, Wendelstein J, Hoffmann P. Prediction of the axial lens position after cataract surgery using deep learning algorithms and multilinear regression. Acta Ophthalmol 2022; 100(7):e1378-e1384. doi: 10.1111/aos.15108.
15. Norrby NE, Koranyi. Prediction of intraocular lens power using the lens haptic plane concept. J Cataract Refract Surg 1997; 23(2):254-259. doi: 10.1016/s0886-3350(97)80350-1.
16. Olsen T, Hoffmann P. C constant: new concept for ray tracing-assisted intraocular lens power calculation. J Cataract Refract Surg 2014; 40(5):764-773. doi: 10.1016/j.jcrs.2013.10.037.
17. Liou HL, Brennan NA. Anatomically accurate, finite model eye for optical modeling. J Opt Soc Am A Opt Image Sci Vis 1997; 14(8):1684-95. doi: 10.1364/josaa.14.001684.
18. Hill W, Potvin R. Monte Carlo simulation of expected outcomes with the AcrySof toric intraocular lens. BMC Ophthalmol 2008; Oct 27; 8:22. doi: 10.1186/1471-2415-8-22.
19. Romero Valero D, Escolano Serrano J, Monera Lucas CE, Castilla Martínez G, Martínez Toldos JJ. Limits of the precision in refractive results after cataract surgery. Arch Soc Esp Oftalmol (Engl Ed) 2022; 97(7):370-375. doi: 10.1016/j.oftale.2021.11.002.
20. Zudans JV, Desai NR, Trattler WB. Comparison of prediction error: labelled versus unlabelled intraocular lens manufacturing tolerance. J Cataract Refract Surg 2012; 38(3):394-402. doi: 10.1016/j.jcrs.2011.08.044.
21. Lumme S, Sund R, Leyland AH, Keskimäki I. A Monte Carlo method to estimate the confidence intervals for the concentration index using aggregated population register data. Health Serv Outcomes Res Methodol 2015; 15(2):82-98. doi: 10.1007/s10742-015-0137-1.

Tables and Table Legends

N = 16,669	Age in years	AL in mm	ACD in mm	LT in mm	CD in mm	$R1_a$ in mm	$R2_a$ in mm	R_a in mm
Mean	70.4927	23.7899	3.2253	4.4514	11.9906	7.7985	7.6337	7.7161
Standard deviation	9.5482	1.4129	0.3768	0.3956	0.4106	0.2821	0.2813	0.2725
Median	72.0000	23.5887	3.2155	0.5248	11.9873	7.7876	7.6314	7.7099
2.5% quantile	49.0000	21.5962	2.5058	3.3858	11.1955	7.2863	7.1016	7.2050
97.5% quantile	86.0000	27.1777	3.9791	4.9697	12.7984	8.3887	8.1887	8.2750

Table 1: Explorative data of the input parameters used for lens power calculation in terms of mean value, standard deviation, median, and 95% confidence interval. Age refers to the patient age at the time point of the biometric measurement before cataract surgery, AL to the axial length of the eye, ACD to the phakic anterior chamber depth as the distance between the front corneal apex and the front lens apex, LT to the central thickness of the crystalline lens, CD to the horizontal corneal diameter, $R1_a$ and $R2_a$ to the corneal radii of curvature in the flat and steep meridians, and R_a to the mean corneal radius.

REFU in dpt; N = 16,669	Bausch and Lomb enVista				Alcon SA60AT			
	IOL power steps STEPU		Labelling tolerances ISOU		IOL power steps STEPU		Labelling tolerances ISOU	
	Castrop	Haigis	Castrop	Haigis	Castrop	Haigis	Castrop	Haigis
Mean	0.1201	0.1193	0.1866	0.1865	0.1224	0.1206	0.1936	0.1913
Standard deviation	0.0162	0.0146	0.0217	0.0230	0.0103	0.0107	0.0308	0.0318
Median	0.1177	0.1174	0.1879	0.1874	0.1216	0.1201	0.1944	0.1921
2.5% quantile	0.1123	0.1117	0.1355	0.1324	0.1161	0.1123	0.1404	0.1347
97.5% quantile	0.1259	0.1237	0.2420	0.2427	0.1272	0.1255	0.2505	0.2505

Table 2: Explorative data of the predicted 'overall' refraction uncertainty at the spectacle plane REFU resulting from discretised IOL power steps STEPU and labelling tolerances ISOU according to EN ISO 11979-2:2014. The REFU values are derived using a Monte-Carlo simulation based on N = 16,669 datapoints in the dataset. Data where (according to the Castrop or Haigis formula) no appropriate lens power steps were available were excluded. The table lists the mean, standard deviation, median, and the lower and upper boundary of the 95% confidence interval (2.5% and 97.5% quantiles).

Figure Legends

Figure 1: Refraction uncertainty at the spectacle plane REFU resulting from discrete power steps of the IOL as provided by the IOL manufacturer. For this Monte-Carlo simulation the difference between the 'perfect' lens power IOLPE and the discretised lens power IOLPQ was assumed to be uniformly distributed. The plots on the left / right graphs display REFU for the enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the upper graphs REFU is shown as a function of the IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. In addition to the different delivery ranges of both IOLs (0 to 30 dpt for the enVista and 6 to 40 dpt for the SA60AT), the REFU shows larger values for the enVista in the lower power range (power steps 1.0 dpt instead of 0.5 dpt) and larger values for the SA60AT in the higher power range (power steps 1.0 dpt instead of 0.5 dpt).

Figure 2: Refraction uncertainty at the spectacle plane REFU resulting from labelling tolerances according to EN ISO 11979-2:2014. For this Monte-Carlo simulation the labelling error was assumed to be uniformly distributed within the limits. The plots on the left / right graphs display REFU for the enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the upper graphs REFU is shown as a function of the 'perfect' lens power IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. Both lenses are available with different delivery ranges (0 to 30 dpt for the enVista and 6 to 40 dpt for the SA60AT); the labelling tolerances increase stepwise from 0.3 to 1.0 dpt for increasing IOLP values.

Figure 3: Refraction uncertainty at the spectacle plane REFU due to superposition of the effect of discrete power steps of the IOL provided by the IOL manufacturer and labelling tolerances according to EN ISO 11979-2:2014. For this Monte-Carlo simulation the difference between the 'perfect' lens power IOLPE and the discretised lens power IOLPQ as well as the labelling error was assumed to be uniformly distributed, resulting in a trapezoidal distribution of the superposition. The plots on the left / right graphs display REFU for the

enVista IOL (Bausch and Lomb) / SA60AT (Alcon) respectively. In the upper graphs REFU is shown as a function of the IOLPE without discretisation (calculated with either the Castrop or the Haigis formula) and in the lower graphs REFU is shown as a function of axial length AL. In addition to the different delivery ranges of both IOLs (0 to 30 dpt for the enVista and 6 to 40 dpt for the SA60AT) REFU shows larger values for the enVista in the lower power range (power steps 1.0 dpt instead of 0.5 dpt) and larger values for the SA60AT in the higher power range (power steps 1.0 dpt instead of 0.5 dpt), whereas the power labelling tolerances according to ISO are identical.