Artificial Neural Networks Application in Intraocular Lens Power Calculation

Martin Sramka[1] Alzbeta Vlachynska[2]

[1]Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, Czech Republic, sramkma2@fel.cvut.cz

[2]Faculty of Applied Informatics, Tomas Bata University in Zlin, Zlin, Czech Repubic, vlachynska@fai.utb.cz

Abstract

This article deals with intra-ocular lens (IOL) power calculations during the cataract surgery. At present, IOL power calculated by formulas is usually able to provide acceptable results for the majority of the patients. The problem appears when any of input parameters have the value which is not normal in population distribution. Then the patient post-operative refraction result can inconsiderable deviate from intended target. This work describes approach how to preoperatively indicate which samples of a patient could be problematic in accurate IOL calculations by classification of Artificial Neural Networks (ANN). Small and long eyes are used to test the ability of ANN to classify input samples which are taken from pre-operative measurements to several groups which represent probable post-operative result. In our experiment, ANN classifies samples into two groups. The first group is for data samples with a probable result in positive ranges of diopter and second group is for negative ranges. The accuracy of ANN, in this case, is 94.1 %.

Keywords: intra-ocular lens (IOL) power calculation, artificial neural networks (ANN), cataract surgery, refraction result

1 Introduction

A cataract is present when the transparency of the eye lens is reduced to the point that the patient's vision is impaired. According to the latest assessment of World Health Organization, cataract is responsible for 51 % of world blindness which represents about 20 million people (2010). Fortunately, it can be surgically removed. Natural lens of the eye that has developed an opacification is replaced with an artificial IOL. Choosing the appropriate IOL power is a major determinant of patient satisfaction with cataract surgery. There are 3 main factors: accurate measurements (biometry), selecting appropriate calculations (formulas), and assessing the patient's needs and expectations to determine the postoperative refractive target (clinical considerations) (Henderson et al., 2014).

When the human lens is replaced with an intra-ocular lens, the optical status becomes a two-lens system (cornea and intra-ocular lens) projecting an image onto the fovea. The distance (X) between the two lenses affects the refraction as does the distance (Y) between the two-lens system and the fovea. X is defined as the distance from the anterior surface (vertex) of the cornea, which curvature is described by keratometry (K), to the effective principle plane of the intra-ocular lens in the visual axis. Y is defined as the distance from the principal plane of the intra-ocular lens to the photoreceptors of the fovea in the visual axis. It is easy to see in Figure 1 that X + Y is equal to the visual axis, the axial length of the eye (AL). Therefore, knowing X and A will allow the calculation of Y (Y = AL - X). Also to calculate the intra-ocular lens power (P), we must know the vergence of the light rays entering the cornea (refractive error (R)). For emmetropia, R is zero. The relationship of these factors (X, Y (AL-X), P, K, R) is such that a formula can be written to describe it. Knowing the values of any four of these variables will allow for the calculation of the fifth (Roger and David, 2010).

1.1 Calculation formulas

For appropriate intra-ocular lens power selection, the mathematical computing formulas are used. These formulas have been developed approximately from the sixties of the last century (Kuchynka, 2007). Over time, some trends have emerged regarding which formulas to use in general categories of patients:

- <22 mm: Hoffer Q
- 22-23 mm: Hoffer Q or Holladay 1
- 24-26 mm: Holladay 1
- >26 mm: SRK/T or Holladay 2

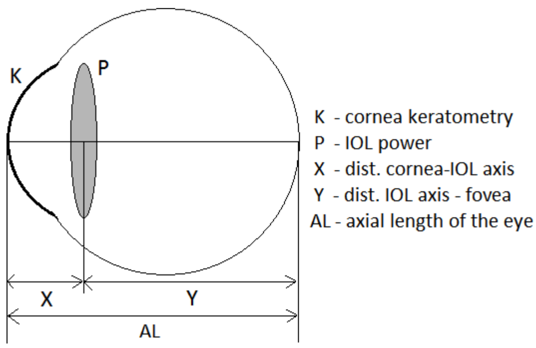

Figure 1. Ocular dimesions.

It is essential to use the appropriate power calculation constant (A constant, ACD-constant, surgeon factor) specified by the intra-ocular lens manufacturer for the specific formula, chosen intra-ocular lens style, and personalized as warranted by the surgeon (Henderson et al., 2014). These formulas usually work very well for the majority of the patients, but the problem may appear if any of input parameter has a value which is not normal in population distribution.

1.2 Calculation of Intra-Ocular Lens for Non-Normal Eyes

Many results and ways how to solve the problem of intra-ocular lens power calculation can be found in the present literature. The problem of accurate calculation is quite complex and depending on many pre and post-operative factors. Therefore needs to be divided into many parts.

One of many ways how to calculate intra-ocular lens power can be seen in (Abulafia et al., 2015). The accuracy of Holladay 1, SRK/T, Hoffer Q, Haigis, Barrett Universal II, Holladay 2, and Olsen formulas for eyes axial length longer than 26.0 mm is provided. SRK/T, Hoffer Q, Haigis, Barrett Universal II, Holladay 2, and Olsen methods are having a prediction error of $\pm$0.5 D in at least 71 % of eyes and $\pm$1.0 D in 93 % of eyes.

A calculation for 53 eyes of 36 patients with axial length more than 27.0 mm by the IOL Master is evaluated in (Bang et al., 2011) for the Holladay 1, Holladay 2, SRK/T, Hoffer Q and Haigis formulas. For eyes longer than 27.0 mm the Haigis formula is found to be most accurate followed by SRK/T, Holladay 2, Holladay 1 and in the last place Hoffer Q. All formulas predicted more myopic outcome than was the real result of the surgery.

Refractive outcomes for small eyes and calculation with Hoffer Q, Holladay 1, Holladay 2, Haigis, SRK-T, and SRK-II are observed in (Carifi et al., 2015). The Hoffer Q formula provides best refractive outcomes of which 39 %, 61 %, and 89 % of the eyes had a final refraction within $\pm$0.5 D, $\pm$1.0 D, and $\pm$2.0 D of the target, respectively.

The accuracy of Hoffer Q and Haigis formula according to anterior chamber depth in small eyes is evaluated in (Eom et al., 2014). 75 eyes of 75 patients with axial length less than 22.0 mm is included in the study. The difference between the predicted refractive errors of the Hoffer Q and Haigis formula increased as ACD decreased in short eyes. No significant difference is found when anterior chamber depth is longer than 2.4 mm.

Predictability of intra-ocular lens power calculation using Carl-Zeiss IOL Master and applanation ultrasound using SRK/T, SRK II, Holladay 1 and Haigis with an axial length longer than 25.0 mm is evaluated in (Wang et al., 2008). The mean axial length was significantly longer than in case of applanation ultrasound. The mean average errors calculated by the SRK/T, SRK II, and Holladay 1 formulas were comparable between both methods of measurement. The best results were provided by the IOL Master data in combination with the Haigis formula.

Refractive prediction of Holladay 1, Hoffer Q, Haigis and SRK/T intraocular lens power calculation formulas for eyes longer than 25.0 mm is evaluated and method for axial length optimization is proposed in (Wang et al., 2011). Refractive prediction errors with the Holladay 1, Haigis, SRK/T, and Hoffer Q formulas were evaluated in consecutive cases. Eyes were randomized to a group used to develop the method of optimizing AL by back-calculation or a group used for validation. Further validation was performed in two additional datasets. The proposed method of optimizing AL significantly reduced the percentage of long eyes with a hyperopic outcome. Updated optimizing AL formulas by combining all eyes from the two study centers are proposed.

Refractive outcomes of Haigis–L formula for calculation intraocular lens power in Asian eyes with axial lengths longer than 25.0 mm that had a previous myopic laser in situ keratomileusis or photorefractive keratectomy are evaluated in (Wong et al., 2015). The predictability of being within $\pm$0.5 D and $\pm$1.0 D of the target was 35.7 % and 63.1 %, respectively. 31.6 % and 60.5 %, respectively, in eyes with an AL less than 27.0 mm; and 39.1 % and 65.2 %, respectively, in eyes with an AL of 27.0 mm or longer.

Next interesting way how to calculate an intra-ocular lens power is provided by (Clarke and Burmeister, 1997). The accuracy of trained artificial neural network and Holladay 1 formula is compared. In 72.5 % of cases for artificial neural network and in 50.0 % of cases for Holladay 1 formula an error of less than $\pm$0.75 D is achieved.

2 Back ground of studies

As was described; many ways how to calculate intra-ocular lens power is being used at present. Many algorithms and calculation formulas have its own accuracy limits for example in the calculation for the unusual cases of eyes - eyes with long or short axial length or keratometry.

In the field of cataract surgery as well as in all health-care related fields patients demands and expectations to provided care are continuously increasing. Together with increasing prevalence of cataract surgery, this could be one of the main motivating factors to provide best possible postoperative refraction results to if possible the greatest amount of patients. Another factor which is no less important could be the economic side of re-operation or following refractive correction of the patient which has implanted bad calculated intra-ocular lens.

As was written in the previous section of this article. Our algorithm for intra-ocular lens power estimation is based on Artificial Neural Networks which are used as a classifier.

3 Artificial Neural Network

Artificial Neural Networks dominate by ability in immediate pattern recognition of input/output relations. This differs ANN from expert systems which achieve excellent results in the sequence of logical operations and fuzzy logic methods and are characterized by the ability represent knowledge (Tuckova, 2009).

Artificial Neural Networks are inspired by biological neural networks. This property in some way determines that the Artificial Neural Network should be capable to behave well or at least like their biological patterns. Knowledge of Artificial Neural Network is stored in relations between neurons. These relations are strengthened during the learning process or penalized when the learning does not lead to better results. More about Artifical Neural Networks can be found in (Tuckova, 2009).

Our algorithm for intraocular lens power estimation is based on Artificial Neural Network which is used as a classifier. The base principal of our access is following:

1. Multi-layer Artificial Neural Network classifies input matrix compound from pre-operatively measured K, ACD and AL into several groups.
2. Each group has its own estimated post-operative refraction outcome.
3. Intra-ocular lens power is calculated using standard SRK/T formula.
4. Intra-ocular lens power calculated by SRK/T formula can be corrected by surgeonâĂŹs decision based on refractive outcome estimated by classification of Artificial Neural Network.

3.1 Real data

For the research purposes, specific patientâĂŹs data had to be collected from clinic database, then cleaned up and preprocessed.

3.1.1 Collected Data

- Implanted IOL manufacturer and type
- Pre operative ïňĆat meridian of the cornea - K1 [D]
- Pre operative steep meridian of the cornea - K2 [D]
- Pre operative anterior chamber depth - ACD [mm]
- Pre operative axial length of the eye - AL [mm]
- Implanted IOL power - P [D]
- Implanted IOL A constant - A
- Subjective post operative sphere - SfS [D]
- Subjective post operative cylinder - CyS [D]
- Subjective post operative spherical equivalent - SfES [D]
- Objective post operative sphere - SfO [D]
- Objective post operative cylinder - CyO [D]
- Objective post operative spherical equivalent - SfEO [D]
- Eye

3.1.2 Specification of Patients Data Selected for Collection

- Patient undergoing cataract surgery
- Indicated for monofocal intra-ocular lens
- Data from beginning of January 2012 till end of July 2015
- Both eyes
- Calculated for emetropia
- Pre operative ïňĆat meridian of the cornea between 30 and 55 diopters
- Pre operative steep meridian of the cornea between 30 and 55 diopters
- Pre operative anterior chamber depth between 1 and 5 millimeters
- Axial length of the eye between 15 and 21 or between 25 to 35 millimeters
- Post operative sphere between -10 and 10 diopters
- Post operative cylinder between -10 and 10 diopters
- No cases with previous corneal refractive surgery

3.1.3 Specification of Preprocessing Parameters

- SfCalc: post operative sphere calculated by SRK/T from K1, K2, AL, P and A constant.
- RDS: difference between SfCalc and SfS.

$$RDS = SfCalc - SfS \tag{1}$$

- RDO: difference between SfCalc and SfO.

$$RDO = SfCalc - SfO \tag{2}$$

- K: mean keratometry calculated from K1 and K2.

$$K = \frac{K1 + K2}{2} \tag{3}$$

- InputVector: matrix which is used as input for Artificial Neural Networks and is composed from AL, ACD and K vectors, which are normalized between 0 and 1.

$$ALn = \frac{AL - min(AL)}{max(AL) - min(AL)} \tag{4}$$

$$ACDn = \frac{ACD - min(ACD)}{max(ACD) - min(ACD)} \quad (5)$$

$$Kn = \frac{K - min(K)}{max(K) - min(K)} \quad (6)$$

- TargetVector: this variable separates InputVector into several groups and is used for Artificial Neural Network training and testing. Ranges of these groups are described in results section.

On the Figures 2, 3, 4 there can be seen dependence of RDS between AL, Kmean and ACD of tested data. Most significant dependency can be seen on Figure 2 where RDS grows with decreasing AL and conversely. Some other trends can be also find in Figure 3 or Figure 4.

These multifactorial dependencies are the main reason why we chose the Artificial Neural Networks as our main decision algorithm for intra-ocular lens power estimation improvement.

4 Results

We use the Feedforward-Pattern net with one hidden layer. Input vector (a compound from ACDn, ALn, Kn) contains 114 data samples from biometry measurements. Patients with three different monofocal intra-ocular lenses - BAUSCH & LOMB MI 60 (43 samples), CROMA ACR6D SE (55 samples), EYEOL UK LW 5752R (16 samples) were chosen.

4.1 Objective

To estimate whether the post-operative refraction based on ACD, AL and K values from preoperative biometry measurements will be larger or smaller than 0 diopters.

4.2 ANN training

Data were randomly divided into the three subsets (training set, validation set, testing set). ANN was trained on 80 samples, validated on 17 samples and tested on 17 samples causally chosen from InputVector with 114 samples.

ANN performance was calculated by cross-entropy which lot penalizes extremely inaccurate outputs and leads to good classifiers (Møller, 1993). Cross-entropy chart can be seen on Figure 5.

As a learning algorithm scaled conjugate gradient backpropagation was chosen. The data vector is fed to the input of ANN. After passing through the network the output of each neuron is calculated and the result is compared with the desired value. Mean squared error is calculated and previous layers and synaptic weights representing memory are corrected. This process repeats till minimum error between the real value and the desired value is reached. Scaled conjugate gradient backpropagation algorithm ensures rapid convergence of learning and using standard numerical optimization methods. More about this ANN learning algorithm can be found in (Tuckova, 2009; Pelusi, 2012).

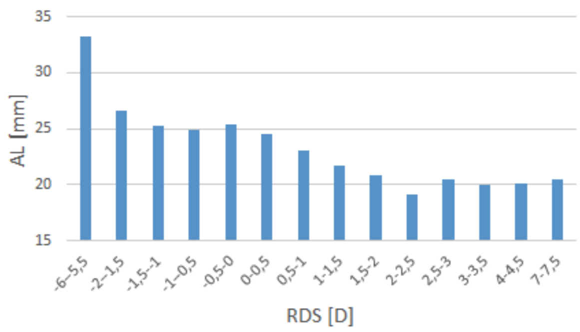

Figure 2. Relation of AL between RDS (Sramka, 2015).

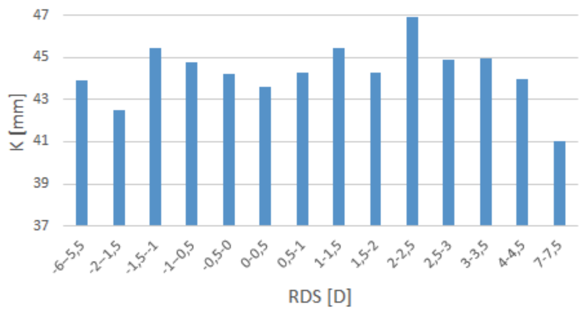

Figure 3. Relation of K between RDS (Sramka, 2015).

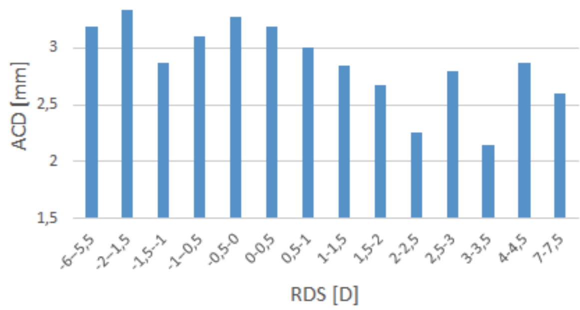

Figure 4. Relation of ACD between RDS (Sramka, 2015).

Algorithm for the best count of the hidden layer neurons was constructed and the ANN was tested for 1 to 50 neurons in the hidden layer. As can be seen in Figure 6 best performance was reached with 37 hidden layer neurons.

4.3 ANN settings

Following ANN settings which can also be seen in Figure 7 were used:

- Input neurons: 3
- Hidden layer neurons: 37
- Hidden layer transfer function: Hyperbolic tangent sigmoid
- Output layer neurons: 2
- Output layer transfer function: Soft max
- Number of training epochs: 16

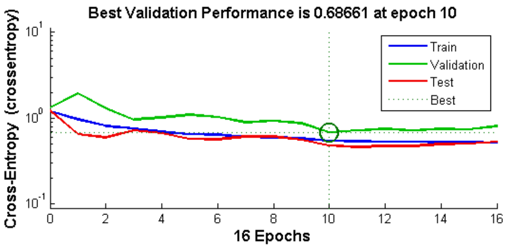

Figure 5. Relation between ANN performance and number of hidden layer neurons

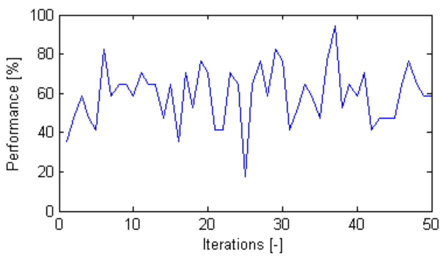

Figure 6. Relation between ANN performance and number of hidden layer neurons

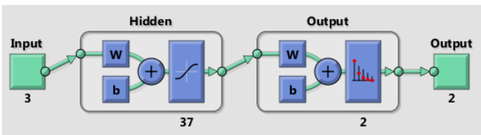

Figure 7. Scheme of Artificial Neural Network used in experiment

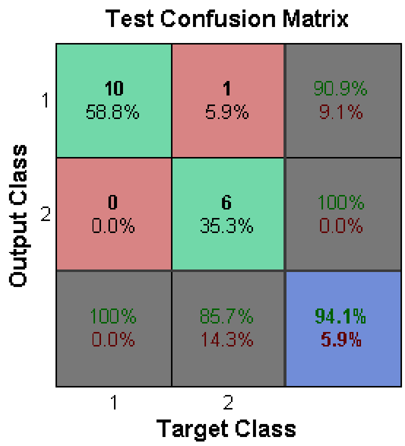

Figure 8. Test Confusion matrix. Green squares - samples correctly classified. Red squares - samples misclassified. Grey squares - Accuracy of each group. Blue square - overall accuracy (Sramka, 2015).

4.4 Results

On the Figure 8 there can be found that the overall accuracy of the testing is 94.1 %. Ten samples which represent 58.8 % of the testing set were correctly classified into Group 1 (Table 1). Six samples which represent 35.3 % of the testing set were correctly classified into Group 2 (Table 1). One sample which represents 5.9 % from Group 2 was incorrectly classified into Group 1.

5 Conclusions

This work deals with IOL power calculations during the cataract surgery. At present, intra-ocular lenses power is mostly being calculated by calculation formulas SRK/T, Holladay 1, Holladay 2, Haigis, Hoffer Q and others. All of these formulas using data measured by ultrasound or more often optical biometry and are able to provide acceptable results for the majority of the patients. This is based on fact that these formulas using constants which was derived by regression analysis. In the moment when any of input parameters has a value which is significantly unusual a problem can appear. In such a cases patient post-operative refraction can significantly deviate from intended target.

Table 1. Group 1: Samples with Subjective Post-operative Refraction Larger than 0; Group 2: Samples with Subjective Post-operative Refraction Smaller than 0

Group 1	Group 2
SfS > 0	SfS < 0

This work describes approach how to preoperatively compensate or indicate which samples of patients could be problematic in accurate intraocular lens calculations by classification of Artificial Neural Networks. Small and long eyes are used to test the ability of Artificial Neural Networks to classify input samples which are taken from pre-operative measurements to several groups which represent the probable post-operative result. In our experiment, Artificial Neural Network classifies samples into two groups. The first group is for data samples with a probable result in positive ranges of diopters and second group is for negative ranges. The accuracy of Artificial Neural Network, in this case, is 94.1 % and Artificial Neural Network seems like the instrument which has potential to improve an intra-ocular lens power calculation accuracy.

Based on the experiment Artificial Neural Networks seems to be the good solution for intra-ocular lens power compensation for non-standard eyes.

6 Future work

We will focus how to reach better accuracy in compensation inaccurate calculations by classification to more groups. Target is that each classification group would have an increment by 0.5 diopters, what is also a dioptric increment of IOL power usually given by manufacturers. Then could be inaccurate calculation compensate very exactly. Artificial Neural Network training could be tested for each IOL type and surgeon. Artificial Neural Network formula selection could also be tested for the special cases. The special algorithm for compensation calculations for the patient with previous corneal refractive surgery could be designed.

Acknowledgment

The work was done in cooperation with Gemini Eye Clinic in Zlin. This article was supported by the Internal Grant Agency at TBU in Zlin, project No. IGA/CebiaTech/2016/007.

References

A. Abulafia, G. D. Barrett, M. Rotenberg, G. Kleinmann, A. Levy, O. Reitblat, D. D. Koch, L. Wang, and E. I. Assia. Intraocular lens power calculation for eyes with an axial length greater than 26.0 mm: Comparison of formulas and methods. *Journal of Cataract and Refractive Surgery*, 41(3):548 – 556, 2015. ISSN 0886-3350. doi:http://dx.doi.org/10.1016/j.jcrs.2014.06.033.

S. Bang, E. Edell, Q. Yu, K. Pratzer, and W. Stark. Accuracy of intraocular lens calculations using the {IOLMaster} in eyes with long axial length and a comparison of various formulas. *Ophthalmology*, 118(3):503 – 506, 2011. ISSN 0161-6420. doi:http://dx.doi.org/10.1016/j.ophtha.2010.07.008.

G. Carifi, F. Aiello, V Zygoura, N Kopsachilis, and M. Maurino. Accuracy of the refractive prediction determined by multiple currently available intraocular lens power calculation formulas in small eyes. *American Journal of Ophthalmology*, 159(3):577 – 583, 2015. ISSN 0002-9394. doi:http://dx.doi.org/10.1016/j.ajo.2014.11.036.

G.P. Clarke and J. Burmeister. Comparison of intraocular lens computations using a neural network versus the Holladay formula. *Journal of Cataract and Refractive Surgery*, 23(10): 1585–1589, 1997. cited By 6.

Y. Eom, S. Kang, J. S. Song, Y. Y. Kim, and H. M. Kim. Comparison of Hoffer Q and Haigis formulae for intraocular lens power calculation according to the anterior chamber depth in short eyes. *American Journal of Ophthalmology*, 157(4):818 – 824.e2, 2014. ISSN 0002-9394. doi:http://dx.doi.org/10.1016/j.ajo.2013.12.017.

B. N. Henderson, Pineda R., and S. H. Chen. *Essentials of cataract surgery*. SLACK Incorporated, Thorofare, New Jersey, second edition. edition, 2014. ISBN 978-1-63091-006-8.

P. Kuchynka. Oční lékařství. Grada, Praha, 1.vyd. edition, 2007. ISBN 80-247-1163-X.

M. F. Møller. Original contribution: A scaled conjugate gradient algorithm for fast supervised learning. *Neural Netw.*, 6(4):525 – 533, 1993.

Tivegna M. Pelusi, D. Optimal trading rules at hourly frequency in the foreign exchange markets. *Mathematical and Statistical Methods for Actuarial Sciences and Finance*, pages 341 – 348, 2012.

Roger Steinert. *Cataract surgery*. Saunders, Philadelphia, 3rd ed. edition, 2010. ISBN 978-141-6032-250.

M. Sramka. Artificial neural networks application in ophthalmology, intraocular lens power calculation improvement for patient undergoing cataract surgery. *Dissertation thesis statement*, 2015.

J. Tuckova. *Selected applications of the artificial neural networks at the signal processing.* Nakladatelství ČVUT, Praha, 2009. ISBN 978-80-01-04229-8.

J. Wang, Ch. Hu, and S. Chang. Intraocular lens power calculation using the {IOLMaster} and various formulas in eyes with long axial length. *Journal of Cataract and Refractive Surgery*, 34(2):262 – 267, 2008. ISSN 0886-3350. doi:http://dx.doi.org/10.1016/j.jcrs.2007.10.017.

L. Wang, M. Shirayama, X. J. Ma, T. Kohnen, and D. D. Koch. Optimizing intraocular lens power calculations in eyes with axial lengths above 25.0 mm. *Journal of Cataract and Refractive Surgery*, 37(11):2018 – 2027, 2011. ISSN 0886-3350. doi:http://dx.doi.org/10.1016/j.jcrs.2011.05.042.

Ch. Wong, L. Yuen, P. Tseng, and D. C. Y. Han. Outcomes of the Haigis-l formula for calculating intraocular lens power in Asian eyes after refractive surgery. *Journal of Cataract and Refractive Surgery*, 41(3):607 – 612, 2015. ISSN 0886-3350. doi:http://dx.doi.org/10.1016/j.jcrs.2014.06.034.