POSTERIOR CORNEAL ASTIGMATISM

THESIS BY

BENJAMIN RICHARD LAHOOD (MBCHB, PGDIPOPHTH)

BACHELOR OF MEDICINE AND BACHELOR OF SURGERY (OTAGO)

POSTGRADUATE DIPLOMA IN OPHTHALMIC BASIC SCIENCE (OTAGO)

THE UNIVERSITY OF ADELAIDE

SCHOOL OF MEDICINE

FACULTY OF OPHTHALMOLOGY AND VISUAL SCIENCES

THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS OF THE

DEGREE OF

DOCTOR OF PHILOSOPHY

DECEMBER 2021

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 3

Scholarly Activity

3.1 LIST OF PEER REVIEWED PUBLICATIONS

1) Assessing the Likely Effect of Posterior Corneal Curvature on Toric Intraocular Lens Calculation for IOLs of 2.5 Dioptres cylinder power or more.
   LaHood B, Goggin M, Esterman A
   Journal of Refractive Surgery*: 2017 Nov 8;33(11):730-4

2) Measurement of Posterior Corneal Astigmatism by the IOLMaster 700.
   LaHood B, Goggin M
   Journal of Refractive Surgery*: 2018 May 9;34(5):331-6

3) Comparing Total Keratometry Measurement on the IOLMaster 700 with Goggin Nomogram Adjusted Anterior Keratometry.
   LaHood B, Goggin M, Beheregaray S, Andrew N, Esterman A
   Journal of Refractive Surgery*: 2018 Aug 9;34(8):521-6

*Journal of Refractive Surgery is the peer reviewed monthly official journal of the International Society of Refractive Surgery with an impact factor of 3.573 (2020).

3.2 LIST OF RELATED INTERNATIONAL PRESENTATIONS

- **American Society of Cataract and Refractive Surgeons (ASCRS) Annual Conference 2017 Los Angeles, USA**
  Presentation: Total Corneal Astigmatism Measurement without Lenticular Astigmatism.

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2017 Lisbon, Portugal**
  Presentation: Toric IOLs: planning for success and dealing with failure

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2017 Lisbon, Portugal**
  Presentation: Calculated Posterior Corneal Astigmatism

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2017 Lisbon, Portugal**
  Presentation: Toric IOL Alignment in the Absence of Preoperative Marking.

- **Save Sight Society 2018 Nelson, New Zealand**
  Presentation: Posterior Corneal Astigmatism Update Lecture

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2018 Vienna, Austria**
  Presentation: Moderation of presentation session on keratometry

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2018 Vienna, Austria**
  Presentation: Toric IOLs: planning for success and dealing with failure

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2018 Vienna, Austria**
  Presentation: Posterior Corneal Astigmatism Measured on the IOLMaster 700

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2018 Vienna, Austria**
  Presentation: New Method of Toric IOL Calculation post Laser Vision Correction.

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2018 Vienna, Austria**
  Presentation: Demystifying the Optical Properties of Posterior Corneal Astigmatism (Video symposium).

- **Cornea and Contact Lens Society Meeting 2019 Rotorua, New Zealand**
  Presentation: Invited presentation on the latest in intraocular lens (IOL) calculation in relation to posterior corneal astigmatism.

- **SynergEyes 2019 Melbourne, Australia**
  Presentation: The role of posterior corneal astigmatism in toric IOL calculation.

- **Australasian Society of Cataract and Refractive Surgeons (AUSCRS) Annual Conference 2019 Queenstown, New Zealand**

Presentation: Toric IOL calculation methods

- **Australasian Society of Cataract and Refractive Surgeons (AUSCRS) Annual Conference 2019 Queenstown, New Zealand**
  Presentation: Invited panel discussion on optimal IOL calculation methods.

- **European Society of Cataract and Refractive Surgeons (ESCRS) Annual Conference 2019 Paris, France**
  Presentation: Toric IOLs: planning for success and dealing with failure

- **Zeiss Advanced Biometry Webinar June 2020 (Online)**
  Presentation: Invited presentation about posterior corneal astigmatism in IOL calculation.

- **Zeiss Global Webinar November 2020 (Online)**
  Presentation: Invited presentation as part of a trilogy series on getting started with toric IOLs.

- **Global Education and Research Society of Ophthalmology (GERSO) Global Webinar January 2021 (Online)**
  Presentation: Invited presentation about pre-operative assessment of astigmatism and surgical planning.

- **Emirates Society of Ophthalmology (ESO) November 2021 (Online)**
  Presentation: Invited workshop about toric IOL calculation formulae updates.

Chapter 4

Abstract

4. ABSTRACT

In order to calculate an appropriate intraocular lens (IOL) power for an eye undergoing cataract surgery, the most important measurements are the axial length of the eye and corneal shape. The cornea is a three dimensional structure and so, although it has commonly been considered as a single refractive surface, we must take into account that the anterior and posterior surfaces of the cornea have different astigmatic magnitudes and axes. Total astigmatism of the cornea is determined by the combination of both anterior corneal astigmatism and posterior corneal astigmatism. In order to treat astigmatism of the eye during cataract surgery precisely, total corneal astigmatism needs to be neutralised, and not just the measured anterior corneal astigmatism. Otherwise residual astigmatism will be present and visual quality will be impacted.

Although the contribution of posterior corneal astigmatism has been postulated for many decades, our ability to measure it accurately, and incorporate it into a practical surgical plan, has only become possible much more recently. While measuring anterior corneal astigmatism accurately has been relatively straight forward, posterior corneal astigmatism has been less simple to measure due to relative similarity in refractive indices of cornea and the adjacent aqueous humor as well as having a very low magnitude to detect. Our measurement of anterior corneal astigmatism is far from perfect. Measuring a fluid surface accurately and consistently is not easy. When the magnitude of anterior corneal astigmatism is very low, the accuracy and consistency of measures of both magnitude and axis of astigmatism decrease. Measurements of posterior corneal astigmatism are therefore faced with the difficult combination of trying to measure a very low magnitude of astigmatism, and doing so in extremely difficult optical conditions.

Modern cataract surgery has seen a shift in IOL calculation methods from using measured anterior corneal astigmatism alone, to incorporating a population statistics based estimation of posterior corneal astigmatism. The research published as part of this thesis has been at the forefront of the logical next step, which is the incorporation of individual measurement of posterior corneal astigmatism into IOL calculation. Despite having been aware of the presence of an optical contribution of posterior corneal astigmatism for a long time, our knowledge about the magnitude

and variation of this contribution as well as our ability to measure it has been relatively poorly defined.

The main objectives of this thesis are:

1) To assess whether the contribution of posterior corneal astigmatism to total corneal astigmatism in eyes with high magnitude anterior corneal astigmatism becomes so minor that it can be ignored.

2) To assess how measurement of posterior corneal astigmatism using optical coherence tomography (OCT) of the IOLMaster 700 compares to previous estimates.

3) To assess whether IOLMaster 700 measurement of total corneal astigmatism, “total keratometry” (TK) is as accurate as Goggin nomogram adjusted keratometry (GNAK) values.

Chapter 5

Thesis Declaration

5. THESIS DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

The author acknowledges that copyright of published works contained within the thesis resides with the copyright holder(s) of those works. I give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Signed ___ ____ on 30 December 2021

Benjamin R LaHood

Chapter 6

Acknowledgements and Dedications

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors; Associate Professor Michael Goggin, Professor Bob Casson, and Dr Tiffany Gill for their advice, support and motivation throughout my PhD study.

I am extremely thankful for the encouragement, expertise and kindness of Associate Professor Michael Goggin. Without him, I would not have been introduced to this field of work and would never have considered attaining further academic degrees. Being able to discuss ideas and hypotheses with someone so knowledgeable, yet humble has been incredibly rewarding and enjoyable. As my own academic career has grown, I never forget that I am standing on the shoulders of giants.

Completing my academic requirements during a pandemic has not always been easy and I am grateful to both Professor Bob Casson and Dr Tiffany Gill for helping to make the process as smooth as possible.

All of my published research for this thesis has involved the people of South Australia and I will be forever thankful to the participants of my new adopted home.

I am also thankful to The University of Adelaide for creating an environment where I was able to complete my work, was encouraged to upgrade from a Masters degree to a Doctorate, and will continue to participate as a lecturer. I really feel as though I have learnt a lot during this academic process and have found my niche.

Finally, I would like to thank my co-authors, Michael Goggin, Adrian Esterman, Simone Behegaray, and Nick Andrew. So much work goes into getting a project from concept to final publication and I could not have done it alone.

Ben LaHood 2021

DEDICATION

This thesis is dedicated to my wonderful partner, Eve, who has supported, motivated and encouraged me.

Chapter 5

List of Abbreviations

7. LIST OF ABBREVIATIONS

ACA Anterior Corneal Astigmatism

ATR Against The Rule

GNAK Goggin Nomogram Adjusted Keratometry

IOL Intraocular Lens

LVC Laser Vision Correction

OCT Optical Coherence Tomography

PCA Posterior Corneal Astigmatism

TCA Total Corneal Astigmatism

TK Total Keratometry

WTR With the rule

Chapter 8

Introduction

CHAPTER 8: INTRODUCTION

8.1 BACKGROUND

8.1.1 Measurement of posterior corneal astigmatism

Modern cataract surgery initially had a modest goal of removing an opacified crystalline lens to clear the visual axis. Subsequently, implantation of an artificial intraocular lens (IOL) became routine practice. This process evolved from giving every eye the same power of IOL, to a more personalised approach where IOL power was determined by taking into account various biometric measurements. The most important of these were the axial length of the eye and the overall curvature and refractive power of the cornea. This process likely still required the patient to fine tune their post-operative visual outcome with glasses as surgical outcomes were less predictable. This was due to a combination of larger surgical incisions, less reliable IOL production techniques and relatively basic IOL calculation methods.

As the cataract surgery process became more refined, we saw advances in micro-incisional surgery, improved IOL manufacturing and greatly improved methods of IOL calculation. The introduction of toric IOLs meant that corneal astigmatism could be neutralised also. These improvements transformed cataract surgery from simply removing opacity, to aiming to provide a precise refractive outcome. This cycle of incremental surgical and manufacturing improvements along with increased patient expectations continued to drive development of improved methods of calculating an appropriate IOL power for an individual eye. The area which saw the most major changes and appreciation of its complexity was in the measurement of corneal shape or keratometry. Surgeons now had the IOLs and surgical capabilities to neutralise corneal astigmatism as well as aim for an excellent refractive outcome. They needed precise measurements of the magnitude and axis of corneal astigmatism to plan their treatments and deliver the desired results.

Measurement of anterior corneal curvature was first made possible with the development of the ophthalmometer of Helmholtz in 1853. Further modification of this instrument by Javal and Schiotz in 1881 allowed it to be more readily used in clinical practice.[1] The presence of clinically important posterior corneal astigmatism was postulated in 1890 when Javal described the relationship between refractive astigmatism and keratometric astigmatism.[2] In other words, the astigmatism measured in the physical shape of the cornea did not account for all of the astigmatism present when the vision of the same eye was completely treated with glasses. It was assumed that this residual amount of astigmatism was due to the shape of the posterior cornea. Initial published attempts at measuring the curvature of the posterior cornea were performed using Purkinje images.[3] Central posterior corneal second Purkinje image analysis proved troublesome due to interference from the far brighter first Purkinje images and so early estimates of posterior corneal radius of curvature came from the peripheral cornea in a small number of eyes.[4]

More accurate measurements of posterior corneal curvature began to be published in the 1970s and 1980s, initially with estimates of the radius of curvature of the posterior cornea in the vertical meridian using slit-lamp photographic analysis, and later, Scheimpflug photography.[5, 6] A return to Purkinje image analysis similar to that used by Tscherning[3] occurred in the 1990s.[7] This led Royston and colleagues to publish that the radius of curvature of the posterior cornea was steeper than previous estimates.[8] It was in this same period that Royston, Dunne and colleagues published the first analyses of posterior corneal surface toricity.[9-11] These were the first practical estimates of posterior corneal astigmatism.

The next step in attempting to characterise posterior corneal astigmatism incorporated a combination of videokeratoscopy and pachymetry.[12-14] This method was hampered by alignment errors and so with yet another adaptation of previous methods, Dubbelmann used corrected Scheimpflug imaging to describe the shape of the posterior corneal surface in a healthy population.[15]

Up until this time, measurement of posterior corneal astigmatism was completely research oriented. The first commercially available device capable of measuring posterior corneal astigmatism was the Orbscan (Bausch & Lomb, Rochester, USA) which processed slit-beam images of corneal cross-sections to produce a complete corneal map. This was quickly followed by the Orbscan II (Orbtek, USA) that incorporates Placido technology.[16, 17] Two commonly used tomography devices, the Pentacam (Oculus Optikgeräte GmbH, Wetzlar, Germany) and the Galilei (Zeimer Group, Port, Switzerland) directly measure posterior corneal astigmatism using

Scheimpflug imaging.[18, 19] The Cassini, a novel topographer that uses multicolor point-to-point ray tracing, combined with second Purkinje imaging technology is capable of measuring posterior corneal astigmatism as part of its total corneal analysis.[20]

The latest revolution in imaging posterior corneal astigmatism has become possible by using OCT. This technology enables high speed and high resolution imaging of the cornea and has been reported as having better reproducibility of corneal thickness measurement than scanning-slit topography.[21] The IOLMaster 700 was the first swept-source OCT biometry device. It has been positively compared to its predecessor, the IOLMaster 500 which used partial coherence interferometry.[22]

8.1.2 Incorporation of posterior corneal astigmatism into IOL calculation

It was not until 2012, when Koch et al published a large series of eyes where posterior corneal astigmatism had been measured with modern equipment and enough consistency was found that population based statistical averages could be used to enhance astigmatic outcomes.[19] At the time, IOL formulae were treating the cornea as though both the anterior and posterior corneal surfaces had a very fixed relationship, without an independent contribution from the shape of the posterior cornea. There was not currently a widely used device which could be easily used to measure the posterior corneal astigmatism accurately, and a formula which could incorporate this information.

The findings by Koch et al, of an average magnitude of posterior corneal astigmatism and a very high rate of being steep vertically, led the way for a systematic adjustment to calculations where the effect of posterior corneal astigmatism could be added to an existing calculation. Koch's Baylor nomogram made adjustment to the toric IOL cylinder power at the end of the calculation.[23] This involved increasing the cylinder value of the implanted toric IOL in eyes with against the rule (ATR) anterior corneal astigmatism and decreasing the cylinder power in eyes with with the rule (WTR) anterior corneal astigmatism. This was a simple systematic adjustment. The Baylor nomogram also had a preference for leaving eyes with some WTR refractive astigmatism due to our understanding that with age, at a population level, we know many eyes develop ATR corneal astigmatism over time.[24]

Michael Goggin took a different approach by adjusting the keratometry values prior to toric IOL calculation. His Goggin nomogram used his own set of post-surgery eyes to assess residual astigmatism and came to a similar conclusion that eyes with ATR anterior corneal astigmatism were being undercorrected while astigmatism in eyes with anterior corneal WTR astigmatism was being overcorrected.[25] His nomogram, which has continued to be refined, reduces the magnitude of keratometric astigmatism in WTR eyes and enlarges keratometric astigmatism in ATR eyes prior to being used as input into online toric calculators.[26]

Alongside these nomogram adjustments to outputs and inputs to IOL calculation respectively, IOL formulae developed which also took into account the presence of a standard, typical magnitude and direction of posterior corneal astigmatism. One of the first, most successful, and popular of these is the Barrett Universal formula.

It has been shown in multiple studies that incorporation of posterior corneal astigmatism into IOL calculation through nomogram or formulae choice is superior to using anterior corneal astigmatism alone.[26-28]

8.2 RATIONALE AND OBJECTIVES FOR THIS THESIS

8.2.1 Need to define posterior corneal astigmatism limit of clinical relevance.

When measuring a refractive outcome for a post-operative patient after cataract surgery, it is common to refine their astigmatism in increments of 0.25 dioptres (D). This is generally considered a level which a healthy eye may be able to discern the difference in vision quality and so it becomes a clinically significant level to observe. Often, patients have difficulty discerning a difference of 0.25D and refraction can only be tested in 0.50D steps. Previously published averages of magnitude of posterior corneal astigmatism are around 0.3D.[19,29,30] This is a level of astigmatic power which becomes clinically relevant.

When planning to treat the astigmatism of an eye, it is the total corneal astigmatism which needs to be treated completely. That is the vector addition of the anterior corneal astigmatism and posterior corneal astigmatism. As anterior corneal astigmatism increases in magnitude, posterior corneal astigmatism may increase at a much slower rate and so at some point, it is plausible that as a component of total corneal astigmatism, the posterior component becomes irrelevant.
Finding a cut-off value where posterior corneal astigmatism is no longer relevant or needs to be considered is important in order to provide patients with the most accurate plan for toric IOL implantation to minimise residual refractive astigmatism. Previous research has shown a trend towards nomogram adjustment being required for eyes receiving toric IOLs with cylinder power 2.50D or greater but this trend did not reach statistical significance, indicating that this may be a threshold above which posterior corneal astigmatism could be ignored.[26] The aim of this first study of this thesis is to define whether this is a limit where nomogram adjustment is no longer needed.

8.2.2 Assessment of IOLMaster 700 ability to measure posterior corneal astigmatism

Optical biometry is considered a necessity when performing modern cataract surgery. One of the most common, popular and easy to use biometers has been the IOLMaster range from Zeiss (Carl Zeiss Meditec, Jena, Germany). At the outset of this thesis, the ability of their latest release, the IOLMaster700, to measure posterior corneal astigmatism was not made public. This feature, along with others to come, including central corneal topography, were released to consumers later under licence. The IOLMaster700 was the first widely used biometry device to use OCT imaging and this technique was incorporated into measurement of posterior corneal astigmatism.

Posterior corneal astigmatism is difficult to measure accurately and reliably. We do not have a gold standard device to compare measurements against to assess a new technique. With the IOLMaster700 being a widely used device and being aware of its ability to measure posterior corneal astigmatism, it was important to assess whether measurement in a very large set of eyes would produce statistics similar to previous large scale studies. This was important to know prior to this measuring ability becoming available to the public. The aim of this second study of this thesis was to consider how measurement of posterior corneal astigmatism with the IOLMaster700 compares to our historical knowledge and see whether it raises any new information to refine current IOL calculation techniques.

8.2.3 Comparing individual measurement to estimation of posterior corneal astigmatism

The IOLMaster700 allows individual measurement of anterior and posterior corneal astigmatism. It also performs vector addition to provide a measure of total corneal astigmatism or “total keratometry” (TK). This means that an individual eye is measured and the individual refractive power of their cornea can be used to calculate a toric IOL suitable for that eye. This is a very different scenario to any of the population statistic based methods of nomogram or formulae prior to TK where a population estimate of the impact of posterior corneal astigmatism was in some way added into the calculation along with actual individual biometry of the anterior cornea. It would therefore make sense that this individual TK measurement technique would provide superior results in every case. The potential benefits include reduction in outliers where the posterior cornea is very different to the population average, as well as providing more refined individual results even in those which are closer to the average.

It is important to perform a comparison of TK individual measurement method vs an estimation method to assess for this expected improvement. The Goggin nomogram was chosen as the estimation method comparison as it is one of the only toric IOL calculation methods with consistent, published, prospective results. It was therefore chosen as a gold standard to compare against. The aim of this third study of this thesis was to compare whether total keratometry using individual measurement of posterior corneal astigmatism differed from the gold standard of Goggin nomogram adjusted anterior keratometry (GNAK) values.

8.3 FORMAT AND OUTLINE OF THIS THESIS

I have structured this thesis to provide insight into the thought process while planning each related study and to discuss the impact of each of the three published articles.

The next three chapters each centre around one of the published articles I have authored. Each publication is preceded by a brief summary and followed by a discussion of the impact each article had in the research space. Each summary will only be brief as I have already introduced the rationale for each work and the article itself already contains a succinct discussion.

Chapter 12 summarises the research findings and discusses future directions that these publications are taking my own research as well as others research in this field.

Chapter 9

Assessing the Likely Effect of Posterior Corneal Curvature on Toric Intraocular Lens Calculation for IOLs of 2.5 Dioptres Cylinder Power or More

CHAPTER 9: Assessing the Likely Effect of Posterior Corneal Curvature on Toric Intraocular Lens Calculation for IOLs of 2.5 Dioptres cylinder power or more.

9.1 SUMMARY

This study aimed to assess whether posterior corneal astigmatism could be treated as being relatively insignificant as anterior corneal astigmatism increased in magnitude. Eyes were chosen for this study if they required a toric IOL with cylinder value 2.50D or greater as previous studies had indicated a statistically insignificant trend for nomogram adjustment requirement at this level. Refractive assessment of these eyes, showed that nomogram adjustment indeed was not required and so, the Goggin nomogram officially had a refined cut-off value where if an unadjusted IOL calculation indicated a toric IOL cylinder power of 2.50D or greater, no adjustment was recommended.

This differs from other methods where the posterior corneal astigmatism contribution continues to have a recommended impact despite magnitude of any biometric measurements. The Baylor nomogram where IOL cylinder power is adjusted, makes no cut-off value above which adjustment is not recommended, and the Barrett Universal formula continues to make adjustments to recommended toric IOL cylinder power and axis of implantation regardless of anterior corneal astigmatism magnitude.

This article has been cited 15 times since publication.

9.2 STATEMENT OF AUTHORSHIP

Statement of Authorship

Title of Paper	Assessing the Likely Effect of Posterior Corneal Curvature on Toric Intraocular Lens Calculation for IOLs of 2.5 Dioptres Cylinder Power or More
Publication Status	[X] Published [ ] Accepted for Publication [ ] Submitted for Publication [ ] Unpublished and Unsubmitted work written in manuscript style
Publication Details	LaHood BR, Goggin M, Esterman A. Assessing the likely effect of posterior corneal curvature on toric IOL calculation for IOLs of 2.50 D or greater cylinder power. Journal of Refractive Surgery. 2017 Nov 1;33(11):730-4.

Principal Author

Name of Principal Author (Candidate)	Ben LaHood		
Contribution to the Paper	Conceptualisation, literature review, data collection, data analysis, writing of drafts and final submission, addressing reviewers' comments leading to the final publication		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	30 December 2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Michael Goggin		
Contribution to the Paper	15% Study design, data analysis, editing of drafts, statistical analysis		
Signature		Date	30 December 2021

Name of Co-Author	Adrian Esterman		
Contribution to the Paper	5% Statistical Analysis		
Signature		Date	30 December 2021

Please cut and paste additional co-author panels here as required.

ORIGINAL ARTICLE

Assessing the Likely Effect of Posterior Corneal Curvature on Toric IOL Calculation for IOLs of 2.50 D or Greater Cylinder Power

Benjamin R. LaHood, MBChB, PGDipOphth, FRANZCO; Michael Goggin, FRCSI(Ophth), FRANZCO, MS; Adrian Esterman, PhD, AStat

ABSTRACT

PURPOSE: To establish whether average refractive overcorrection or undercorrection of corneal astigmatism based on the orientation (rule) of the astigmatism occurs if toric intraocular lenses (IOLs) are calculated on the basis of anterior corneal measurements in eyes requiring toric IOL cylinder power of 2.50 diopters (D) or greater.

METHODS: One hundred thirteen consecutive eyes with anterior corneal keratometric astigmatism requiring IOL cylinder power of 2.50 D or greater underwent phacoemulsification with IOL powers calculated using anterior corneal curvature data alone. Eyes were grouped as either "with-the-rule" (WTR) or "against-the-rule" (ATR) on the basis of the steep anterior corneal meridian. Targeted and achieved astigmatic outcomes were compared. The main outcome measure was the postoperative refractive astigmatic prediction error.

RESULTS: A mean overcorrection occurred in anterior WTR eyes of 0.16 ± 0.57 D and a mean undercorrection of ATR eyes of -0.14 ± 0.53 D. These were significantly different from the ideal value of zero (WTR: $P = .04$, ATR: $P = .05$). Although statistically significant, the effect sizes of these prediction errors were 0.40 for WTR and 0.36 for ATR and the error values fell below a clinically significant value of 0.25 D.

CONCLUSIONS: In eyes requiring toric IOLs of cylinder power 2.50 D or greater, an overcorrection occurs in anterior WTR eyes and an undercorrection in ATR eyes. This probable posterior corneal astigmatism effect is not clinically significant. IOL cylinder powers are sufficiently accurately calculated using unadjusted anterior keratometry values in these eyes.

[*J Refract Surg*. 2017;33(11):730-734.]

Until recently, IOL power was routinely calculated using methods that only incorporated anterior keratometric curvature data. Posterior corneal astigmatism and its effect on total corneal astigmatism has long been described.[1,2] The assumption that anterior keratometric curvature data were adequate to describe total corneal refractive power has been shown to be a source of system error in astigmatism correction with toric IOLs. This error can be improved by incorporating information about the posterior corneal astigmatism into IOL calculations.[3-5] Variations in correlation between anterior and posterior corneal astigmatism show that such adjustments will not always be correct or appropriate but do overall yield better astigmatic corrections than using unadjusted values.[3] Some online calculators and IOL calculating formulas currently incorporate an estimated adjustment for the posterior corneal astigmatism based on measurements of the anterior corneal surface. While we await an accurate method of measurement of posterior corneal astigmatism, methods have been described to estimate its effect and adjust toric IOL cylinder power calculation appropriately. However, further improvement in this area is warranted to optimize visual outcomes in cataract surgery.[4-8]

There is a documented population tendency for the steep meridian of the posterior cornea to be aligned vertically.[2,3,9] This induces a negative effect on total corneal power of the vertical meridian predicted by anterior corneal measurements alone. Failure to take this posterior corneal effect into account leads to overestimation of vertical meridian power. Conversely, the horizontal meridian power will be underestimated. Predicted overestimation and underestimation when correcting corne-

From The Queen Elizabeth Hospital, Adelaide, Australia (BRL, MG); South Australian Institute of Ophthalmology, Adelaide, Australia (BRL, MG); University of Adelaide, Adelaide, Australia (BRL, MG); Sansom Institute of Health Service Research, University of South Australia, Adelaide, Australia (AE); and the Australian Institute for Health and Medical Research, James Cook University, Smithfield, Australia (AE).

Submitted: May 27, 2017; Accepted: August 25, 2017

The authors have no financial or proprietary interest in the materials presented herein.

Correspondence: Benjamin R. LaHood, MBChB, PGDipOphth, FRANZCO, The Queen Elizabeth Hospital, 28 Woodville Road, Adelaide, South Australia 5011, Australia. E-mail: benlahood@gmail.com

doi:10.3928/1081597X-20170829-03

al astigmatism with toric IOL choices based purely on anterior corneal curvature has been reported.[10] Statistically significant overcorrection and undercorrection was seen in subgroup analysis of eyes requiring IOL cylinder power of 2.00 diopters (D) or less. Subsequent application of a coefficient of adjustment to anteriorly measured keratometric cylinder values based on the "rule" of the eye led to improved astigmatic outcomes.[5] Eyes requiring IOL cylinder of 2.50 D or greater trended toward similar overcorrection and undercorrection, but this trend did not reach statistical significance.[10]

The purpose of this study was to establish whether there was an average overcorrection or undercorrection of corneal astigmatism based on the "rule" of anterior corneal astigmatism in patients with toric IOLs of cylindrical power of 2.50 D or greater calculated on the basis of anterior corneal measurements alone, and, if appropriate, to calculate a coefficient of adjustment to avoid systematic error for toric IOLs in this cylinder power range subsequently implanted.

PATIENTS AND METHODS

Approval for this study was obtained from the Central Adelaide Local Health Network Human Research Ethics Committee.

Retrospective data were collected for 113 consecutive eyes of 101 patients with anterior corneal surface astigmatism requiring implantation of a toric IOL with cylinder power of 2.50 D or greater. They all underwent cataract surgery between November 2009 and November 2016, receiving AT TORBI 709M or 709MP toric IOLs (Carl Zeiss Meditec, Jena, Germany). Eyes with oblique keratometric astigmatism were excluded because the number of patients was too small for analysis. Demographic data for patients with with-the-rule (WTR) and against-the-rule (ATR) astigmatism were similar (**Table 1**), except the average age of patients with ATR astigmatism was 16 years older than those with WTR astigmatism. This is consistent with population data showing a shift from WTR to ATR anterior keratometry with age.[11-13]

Preoperative IOL calculations were performed using the IOLMaster 500 (Carl Zeiss Meditec) prior to November 2016 and the IOLMaster 700 from December 2016 onward for keratometry and biometry. IOL powers (sphere and cylinder) were calculated using the Carl Zeiss Meditec online calculator (https://zcalc.meditec.zeiss.com/zcalc/), which provides predicted postoperative refraction values. This calculator incorporates anterior chamber depth and axial length to minimize prediction error but does not make any adjustment for posterior corneal curvature.

All eyes underwent micro-incision phacoemulsification using a 1.9-mm temporal clear corneal incision on the horizontal meridian performed by four surgeons using identical techniques. This incision technique is astigmatically neutral, allowing the use of preoperatively measured keratometric values in the IOL calculations and obviating the necessity to predict postoperative keratometric astigmatism using previously established surgically induced corneal astigmatism.[14] For all eyes studied, the surgically induced astigmatism summated vector mean (or centroid) of the corneal incisions was 0.16 D. The mean surgically induced corneal astigmatism axis was 96° ± 44° (range: 7° to 179°).

TABLE 1
Demographic Data

Demographic Data	Total	WTR	ATR
Patients	113	53	60
Male	51	23	28
Female	62	30	32
Mean age (y)	68	60	76
Left eye	55	28	27
Right eye	58	25	33

WTR = with-the-rule astigmatism; ATR = against-the-rule astigmatism

To exclude further the possibility of corneal shape change due to our cataract incision, we compared astigmatic prediction error on the same eyes using preoperative keratometric astigmatism versus postoperative keratometric astigmatism as the targeted error for correction with the toric implant. Using preoperative astigmatism as the error to be corrected, the mean signed astigmatism prediction error was -0.003 D (95% confidence interval: -0.11 to 0.10 D). Using the postoperative astigmatism as the error to be corrected (avoiding the effect of any inadvertent corneal astigmatic change), the mean signed astigmatism prediction error was -0.037 D (95% confidence interval: -0.15 to 0.08 D). The 95% confidence interval of the difference between these means (-0.013 to 0.082 D) falls within a range of ±0.25 D and can consequently be considered not only not significantly different but statistically equivalent.[15] This equivalence of values strongly supports our assertion that overall corneal astigmatism was unchanged by the incision (ie, that our technique is astigmatically neutral). As a consequence, keratometric surgically induced corneal astigmatism was not included in our calculation of prediction error.

The inferior end of the vertical corneal meridian was marked preoperatively using a previously described technique.[16] The incision and IOL toric meridians were planned from this mark using a Mendez ring. Postoperative review was performed at 6 weeks by one of four surgeons and included subjective refraction, keratometry, and anterior chamber depth on the

TABLE 2

Magnitude of Error: Two Sample *t* Tests With Equal Variances

Rule	N	Mean ± SD (Range)	*P*	Effect Size	95% CI Effect Size
ATR	60	-0.14 ± 0.53 D (-1.72 to 0.96 D)	.005	0.54	0.16 to 0.92
WTR	53	0.16 ± 0.57 D (-2.94 to 1.26 D)			

rule = designated using anterior keratometric astigmatism; SD = standard deviation; CI = confidence interval; ATR = against-the-rule; D = diopters; WTR = with-the-rule
Magnitude of error is presented as a negative value for undercorrection and a positive value for overcorrection (surgically induced astigmatism minus target induced astigmatism).

TABLE 3

Magnitude of Error: One-Sample *t* Test Comparing Means to Zero

Rule	N	Mean ± SD (D)	95% CI Mean	*P*	Effect Size	95% CI Effect Size
ATR	60	-0.14 ± 0.53	-0.27 to 0.00	.05	0.36	0.00 to 0.72
WTR	53	0.16 ± 0.57	0.01 to 0.32	.04	0.40	0.01 to 0.78

rule = designated using anterior keratometric astigmatism; SD = standard deviation; D = diopters; CI = confidence interval; ATR = against-the-rule; WTR = with-the-rule

IOLMaster (Carl Zeiss Meditec) and observation of the toric axis of the IOL.

Eyes were grouped according to the "rule" of anterior corneal astigmatism (WTR: anterior keratometric astigmatism with steep meridian between 60° and 120°; ATR: anterior keratometric astigmatism with steep meridian between either 0° and 30° or 150° and 180°). Eyes with steep meridians outside of these classifications were considered "oblique" and excluded. The small number of oblique eyes would not allow adequate analysis. Vector analysis was used to compare preoperative anterior keratometric astigmatism with postoperative targeted refractive astigmatism provided by the online toric IOL calculator and the achieved postoperative refractive astigmatism, the latter two values being corrected to the corneal plane.[17] Target induced astigmatism and surgically induced astigmatism vector values for IOL insertion were thus derived for each eye. The arithmetic difference of vector powers (magnitude of error), subtracting the target induced astigmatism power from the surgically induced astigmatism power, established whether overcorrection (positive value) or undercorrection (negative value) had occurred for each eye.

The ratio of surgically induced astigmatism power to target induced astigmatism power expresses the proportion of astigmatism corrected. The inverse of this ratio can be used as a coefficient of adjustment for subsequent calculations. A coefficient of adjustment was derived for each eye and geometric means of these coefficients were calculated. WTR eyes were compared with ATR eyes. To establish whether the magnitude of error for WTR and ATR eyes represented real prediction error, one-sample *t* tests were used to demonstrate whether the values differed significantly from zero. Two-sample *t* tests with equal variances were used to compare means between the groups. A probability of less than 5% or a *P* value of less than .05 was considered statistically significant. Analysis of statistical equivalence conforms to the extension of the Consort 2010 statement.[15]

RESULTS

One hundred thirteen eyes with anterior keratometric astigmatism indicating the use of a toric IOL with cylinder power of 2.50 D or greater were analyzed (**Table A**, available in the online version of this article).

Postoperative refractive astigmatism and targeted refractive astigmatism were both corrected to the corneal plane for analysis (**Table B**, available in the online version of this article).

Table 2 shows the comparison of the magnitude of error between WTR and ATR eyes to assess whether there is a difference in refractive outcome between these two groups. As expected, there was a significant difference between the two groups and the effect size was medium.[18]

Table 3 shows the magnitude of error in WTR and ATR eyes analyzed using a one-sample *t* test to examine whether the values differed significantly from zero (ie, if there were significant errors in outcome prediction). Both comparisons reach statistical significance but have small to medium effect sizes.

Estimations of astigmatism correction index and coefficient of adjustment for WTR and ATR eyes are presented in **Table 4** as geometric means.

Figure 1 illustrates the low trend to overcorrection in WTR eyes and undercorrection in ATR eyes suggested by the mean values we report. Limited data in eyes with high anterior corneal astigmatism make comment on trends in such eyes problematic.

DISCUSSION

Clinically and statistically significant refractive overcorrection and undercorrection of corneal astigmatism

TABLE 4

Astigmatism Correction Index and Coefficient of Adjustment for Eyes With IOL Cylinder of 2.50 Diopters or Greater

Rule	Astigmatism Correction Index	Coefficient of Adjustment
ATR	0.94	1.06
WTR	1.07	0.93

IOL = intraocular lens; rule = designated using anterior keratometric astigmatism; ATR = against-the-rule; WTR = with-the-rule

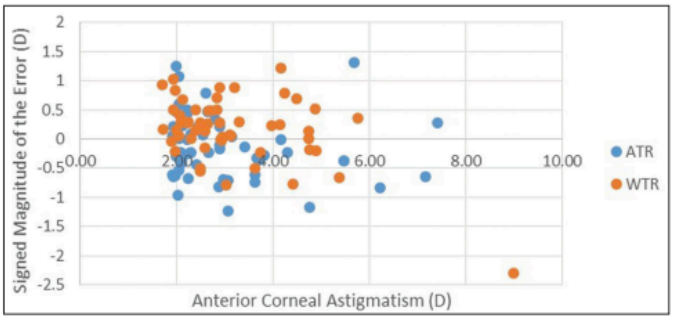

Figure 1. Magnitude of the error compared to anterior corneal astigmatism. D = diopters; ATR = against-the-rule; WTR = with-the-rule

based on the orientation or rule of the astigmatism has previously been shown to occur if toric IOLs are calculated on the basis of anterior corneal measurements alone in eyes requiring an IOL cylinder power of 2.00 D or less.[10] Subsequent adjustment of the toric IOL cylinder power by the application of a coefficient of adjustment (0.75 for WTR and 1.41 for ATR anterior keratometric astigmatism) to anteriorly measured keratometric cylinder values led to a significant improvement in refractive astigmatic outcome in eyes requiring a toric IOL cylinder power of 2.00 D or less.[5] Whereas eyes requiring an IOL cylinder power of 2.50 D or greater trended toward similar overcorrection and undercorrection, previous analysis in this IOL power range did not reach statistical significance.

By comparison, the current study analyzed a larger number of eyes requiring an IOL cylinder power of 2.50 D or greater. The data presented show that average refractive astigmatism overcorrection and undercorrection also occurs, although on a smaller scale, in eyes requiring an IOL cylinder power of 2.50 D or greater when the IOL cylinder power is calculated on the basis of anterior corneal astigmatism alone.

This overcorrection and undercorrection of astigmatism by IOLs related to "rule" is likely to be due to the finding that the steep meridian of the posterior cornea is vertically oriented in most eyes.[3] Because the steepest meridian of the posterior cornea is not vertically oriented in all eyes, the universal use of a coefficient of adjustment may not lead to an optimal outcome. A more appropriate solution would be to measure the posterior cornea reliably in every eye with the assistance of a corneal tomographer. We have shown that one of these devices (Pentacam; Oculus Optikgeräte, Wetzlar, Germany) at least has demonstrable test-to-test variability that may make it unreliable for this purpose, meaning an adjustment of the keratometry on the basis of observed refractive results in a population of eyes is currently legitimate and likely to improve toric IOL refractive outcome in most eyes.[19]

In eyes requiring an IOL cylinder power of 2.50 D or greater, we report a mean ± standard deviation prediction error analyzed by "rule" of -0.14 ± 0.53 (an undercorrection) for ATR eyes and +0.16 ± 0.57 (an overcorrection) for WTR eyes. These values are small in clinical terms and any adjustment based on these values to attempt to decrease the overcorrection and undercorrection would be small (coefficients of adjustment of 1.06 for ATR and 0.93 for WTR). Given the small magnitude of adjustment to anterior corneal data indicated by these coefficients of adjustment for this level of astigmatism (IOLs of 2.50 D cylinder power or greater), as well as the small effect size, our recommendation is that, despite being statistically significant, the clinical significance is too small to warrant use in practice. Current standard available steps in toric IOL cylinder power mean that the effect of application of such small adjustments would more likely manifest as small adjustments in the astigmatic refractive target rather than a change in recommended IOL cylinder power for a given eye.

Also, this study confirms that eyes requiring a toric IOL cylinder power of 2.50 D or greater require different coefficients of adjustment. It would seem anatomically unlikely that there is a precise cut-off value above which posterior corneal astigmatism ceases to affect total corneal astigmatism. It would be more plausible that, in common with most biological variables, there would be a gradation of effect that might be demonstrable with more data. The published Baylor nomogram suggests slightly less than 1.00 D of reduction in the implanted IOL cylinder powers versus the power calculated using anterior corneal power data alone in the cylinder power range of 1.00 to 4.00 D for WTR eyes and an augmentation of slightly more than 0.45 D for ATR eyes of the same range.[4] In principle, this will lead to greater proportional adjustment of lower powered cylinders.[10] However, it adjusts IOL cylinder power for eyes in which we would suggest the IOL cylinder power based on unadjusted keratometric data is currently adequate to achieve close to full astigmatism correction (with IOL cylinder powers of 2.50 D or greater).

Vector analysis allowed calculation of the effect of the toric IOL cylinder power (regardless of orientation) at the corneal plane accurately in each eye using the known postoperative anterior chamber depth. The larger remaining prediction errors could conceivably be accounted for by the posterior cornea or the inherent failure of prediction with any IOL power calculation up to values of 1.50 or 1.75 D.

Ongoing refinement in precision and repeatability of measurement of the posterior cornea will undoubtedly eventually mean that anatomical analysis will replace mathematical adjustments. Early studies of new methods for measuring total corneal power, taking into account the posterior corneal surface, are showing promise but are not yet ideal.[20] To optimize outcome prediction in cataract surgery requiring toric IOLs, we recommend that eyes be divided into two groups: those requiring a toric IOL with cylinder power of 2.00 D or less (lower power toricity) and those eyes requiring an IOL cylinder power of 2.50 D or greater (higher power toricity). For lower power toric IOLs, a coefficient of adjustment can be applied to the anterior keratometry values via an online calculator (www.goggintoric.com) and the new, adjusted keratometry values can be used in any IOL calculator that does not already make an allowance for the posterior cornea. For higher power toric IOLs, we recommend not adjusting anterior keratometry values in the knowledge that the anticipated adjustment for these eyes would not be clinically significant.

Our study indicates that the effect of posterior corneal astigmatism on total corneal astigmatism is proportionally lower as anterior corneal astigmatism increases. It is not possible from our analysis to deduce whether posterior corneal astigmatism stays at a consistent low value or whether it increases in magnitude as anterior corneal astigmatism increases but to a lesser extent. It would seem implausible that there exists a defined astigmatic cut-off value below which posterior corneal astigmatism is significant and above which it is not. It is far more likely that there is a gradual decrease in relevance from low to high anterior corneal astigmatism. Further studies with a greater number of eyes requiring higher power toric IOLs will allow for a more precise breakdown of what coefficient of adjustment would be most suitable for each step of IOL cylinder power.

AUTHOR CONTRIBUTIONS

Study concept and design (BRL, MG, AE); data collection (BRL, MG); analysis and interpretation of data (BRL, MG, AE); writing the manuscript (BRL); critical revision of the manuscript (BRL, MG, AE); statistical expertise (MG, AE); administrative, technical, or material support (MG, AE); supervision (MG)

REFERENCES

1. Royston JM, Dunne MC, Barnes DA. Measurement of posterior corneal surface toricity. *Optom Vis Sci.* 1990;67:757-763.
2. Dunne MC, Royston JM, Barnes DA. Posterior corneal surface toricity and total corneal astigmatism. *Optom Vis Sci.* 1991;68:708-710.
3. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38:2080-2087.
4. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. *J Cataract Refract Surg.* 2013;39:1803-1809.
5. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of adjustment for posterior corneal curvature in toric intraocular lens calculation and selection. *J Cataract Refract Surg.* 2016;42:1441-1448.
6. Abulafia A, Barrett GD, Kleinmann G, et al. Prediction of refractive outcomes with toric intraocular lens implantation. *J Cataract Refract Surg.* 2015;41:936-944.
7. Abulafia A, Hill WE, Franchina M, Barrett GD. Comparison of methods to predict residual astigmatism after intraocular lens implantation. *J Refract Surg.* 2015;31:699-707.
8. Klijn S, Reus NJ, Sicam VA. Evaluation of keratometry with a novel Color-LED corneal topographer. *J Refract Surg.* 2015;31:249-256.
9. Hirji NK, Larke JR. Thickness of human cornea measured by topographic pachometry. *Am J Optom Physiol Sci.* 1978;55:97-100.
10. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg.* 2015;31:98-102.
11. Gudmundsdottir E, Jonasson F, Jonsson V, Stefánsson E, Sasaki H, Sasaki K. "With the rule" astigmatism is not the rule in the elderly. Reykjavik eye study: a population based study of refraction and visual acuity in citizens of Reykjavik 50 years and older: Iceland-Japan co-working study groups. *Acta Ophthalmol Scand.* 2000;78:642-646.
12. Gudmundsdottir E, Arnarsson A, Jonasson F. Five-year refractive changes in an adult population: Reykjavik Eye Study. *Ophthalmology.* 2005;112:672-677.
13. Ho JD, Liou SW, Tsai RJ, Tsai CY. Effects of aging on anterior and posterior corneal astigmatism. *Cornea.* 2010;29:632-637.
14. Goggin M, Moore S, Zamora-Alejo K, Esterman A. Astigmatic neutrality in 1.9-mm coaxial microincision phacoemulsification. *J Refract Surg.* 2012;28:451-452.
15. Piaggio G, Elbourne DR, Pocock SJ, Evans SJ, Altman DG; CONSORT Group. Reporting of noninferiority and equivalence randomized trials: extension of the CONSORT 2010 statement. *JAMA.* 2012;308:2594-2604.
16. Durkin SR, Goggin M. A one-point technique for per-operative corneal meridian identification. *Graefes Arch Clin Exp Ophthalmol.* 2013;251:2481-2482.
17. Alpins NA. A new method of analyzing vectors for changes in astigmatism. J Cataract Refract Surg. 1993;19:524-533.
18. Coe R. It's the effect size, stupid: what "effect size" is and why it is important. Paper presented at: Annual Conference of the British Educational Research Association; September 2002; Exeter, United Kingdom.
19. Goggin M, Patel I, Billing K, Esterman A. Variation in surgically induced astigmatism estimation due to test-to-test variations in keratometry. *J Cataract Refract Surg.* 2010;36:1792-1793.
20. Ferreira TB, Ribeiro FJ. A novel color-LED corneal topographer to assess astigmatism in pseudophakic eyes. *Clin Ophthalmol.* 2016;10:1521-1529.

9.4 DISCUSSION OF INFLUENCE OF PUBLICATION

This article provided clinical evidence of a theorised limit to clinical significance for posterior corneal astigmatism as a portion of total corneal astigmatism. This solidified the refinement of the Goggin nomogram. It also provided published, prospective data for outcomes in eyes requiring high cylinder power toric IOLs. Prospective data publication of astigmatic outcomes in cataract surgery are relatively rare with most studies comparing hypothetical, calculated outcomes rather than actual visual and refractive findings. I would hope that in the future, more research teams also publish their own prospective data, as this is the best evidence we have to evaluate a method.

The main finding of this research that there is a point where posterior corneal astigmatism stops being clinically relevant has influenced the direction of my collaborators research in this area. It would seem unlikely or biologically implausible that there is simply a hard cut-off value above and below which nomogram adjustment is ignored or applied in a black or white fashion. Theoretically it would be much more likely that there is some reduction in nomogram adjustment magnitude before this adjustment being reduced to zero. Our aim is to collect enough surgical cases with a range of anterior corneal astigmatism magnitudes so that we can assess whether this theorised gradation in nomogram adjustment should be applied.

Chapter 10

Measurement of Posterior Corneal Astigmatism by the IOLMaster 700

CHAPTER 10: Measurement of Posterior Corneal Astigmatism by the IOLMaster 700.

10.1 SUMMARY

The IOLMaster700 biometry device was released with the main advertised benefits being much faster measurement acquisition, the ability to acquire axial length measurements even through very densely opaque cataracts and OCT imaging of the whole eye allowing the user to visualise the fovea to make sure alignment was correct. There was no mention from the manufacturer that this device would have the ability to measure posterior corneal astigmatism and incorporate this into a total corneal astigmatism measurement. My co-author and I were offered the opportunity to be provided with early access to measurements of posterior corneal astigmatism due to our previous publications in astigmatism analysis.

The most interesting findings from this analysis, which was the first published review of the IOLMaster700's ability to measure posterior corneal astigmatism, were that the percentage of eyes where the posterior corneal steep axis was oriented vertically was lower than previous studies using other devices, and that in eyes with ATR anterior corneal astigmatism, the likelihood of vertical orientation of the posterior corneal steep axis was even lower. The magnitude of average posterior corneal astigmatism appeared similar to previous studies using a multitude of devices which was reassuring to indicate that the IOLMaster700 OCT measurements were likely to be accurate.

This article has been cited 28 times since publication.

10.2 Statement of Authorship

Statement of Authorship

Title of Paper	Measurement of Posterior Corneal Astigmatism by the IOLMaster 700.
Publication Status	[X] Published; [ ] Accepted for Publication; [ ] Submitted for Publication; [ ] Unpublished and Unsubmitted w ork w ritten in manuscript style
Publication Details	LaHood BR, Goggin M. Measurement of posterior corneal astigmatism by the IOLMaster 700. Journal of Refractive Surgery. 2018 May 1;34(5):331-6.

Principal Author

Name of Principal Author (Candidate)	Ben LaHood		
Contribution to the Paper	Conceptualisation, literature review, data collection, data analysis, writing of drafts and final submission, addressing reviewers' comments leading to the final publication		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	30 December 2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Michael Goggin		
Contribution to the Paper	15% Data analysis, statistical analysis, editing of drafts, replies to reviewer queries.		
Signature		Date	30 December 2021

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Please cut and paste additional co-author panels here as required.

ORIGINAL ARTICLE

Measurement of Posterior Corneal Astigmatism by the IOLMaster 700

Benjamin R. LaHood, MBChB, PGDipOphthBS, FRANZCO; Michael Goggin, FRCSI(Ophth), FRANZCO, MS

ABSTRACT

PURPOSE: To provide the first description of posterior corneal astigmatism as measured by the IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany) and assess how its characteristics compare to previous measurements from other devices.

METHODS: A total of 1,098 routine IOLMaster 700 biometric measurements were analyzed to provide magnitudes and orientation of steep and flat axes of anterior and posterior corneal astigmatism. Subgroup analysis was conducted to assess correlation of posterior corneal astigmatism characteristics to anterior corneal astigmatism and describe the distribution of posterior corneal astigmatism with age.

RESULTS: Mean posterior corneal astigmatism was 0.24 ± 0.15 diopters (D). The steep axis of posterior corneal astigmatism was vertically oriented in 73.32% of measurements. Correlation between the magnitude of anterior and posterior corneal astigmatism was greatest when the steep axis of the anterior corneal astigmatism was oriented vertically ($r = 0.68$, $P < .0001$). Vertical orientation of the steep axis of anterior corneal astigmatism became less common as age increased, whereas for posterior corneal astigmatism it remained by far the most common orientation.

CONCLUSIONS: This first description of posterior corneal astigmatism measurement by the IOLMaster 700 found the average magnitude of posterior corneal astigmatism and proportion of vertical orientation of steep axis was lower than previous estimates. The IOLMaster 700 appears capable of providing enhanced biometric measurement for individualized surgical planning.

[*J Refract Surg.* 2018;34(5):331-336.]

Both anterior and posterior corneal astigmatism contribute to total corneal astigmatism. However, "total" corneal astigmatism traditionally has been calculated based on anterior corneal measurements alone using a fixed ratio describing the relationship between the anterior and posterior corneal surfaces. Precise and reliable measurement of total corneal astigmatism and its simple incorporation into lens formulas is the holy grail of biometry. Calculating intraocular lens (IOL) powers by incorporating additional knowledge of the precise shape of the posterior corneal surface would potentially enhance surgical outcome accuracy. Currently, most ophthalmologists rely on various formulas or nomograms to calculate estimates of total corneal astigmatism when attempting to correct refractive errors completely during cataract surgery.

A growing number of devices claim to be able to measure posterior corneal astigmatism and provide total corneal astigmatism values. Many such devices are impractical because they do not provide other biometric measures such as axial length or are not capable of using their output to provide calculated IOL recommendations. The IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany) is a widely used biometry device that uses swept-source optical coherence tomography (OCT) to produce measurements of anterior corneal curvature and other required biometric measurements to provide immediate lens calculations. Its capability to measure posterior corneal astigmatism has just recently been released and we present the first description of these data.

The IOLMaster 700 is the first swept-source OCT biometry device. It has been positively compared to its predecessor, the IOLMaster 500, which used partial coherence interferometry.[1] OCT technology enables high-speed and high-resolution imag-

From The Queen Elizabeth Hospital, Adelaide, Australia; South Australian Institute of Ophthalmology, Adelaide, Australia; and University of Adelaide, Adelaide, Australia.

Submitted: August 6, 2017; Accepted: February 2, 2018

The authors have no financial or proprietary interest in the materials presented herein.

Correspondence: Benjamin R. LaHood, MBChB, PGDipOphthBS, FRANZCO, The Queen Elizabeth Hospital, 5011 Adelaide, Australia. E-mail: benlahood@gmail.com

doi:10.3928/1081597X-20180214-02

ing of the cornea and has been reported as having better reproducibility of corneal thickness measurement than scanning-slit topography.[2] The IOLMaster 700 has not yet incorporated posterior corneal astigmatism into its output or interface options, but it is capable of taking such measurements. The purpose of this study was to examine posterior corneal astigmatism as measured by the IOLMaster 700 and assess how its characteristics compare to previous measurements from other devices.

PATIENTS AND METHODS

Biometric measurements included in the study comprised those from eyes scheduled for cataract surgery and eyes after cataract surgery because these data are routinely gathered at our institution. This study followed the tenets of the Declaration of Helsinki and local ethics approval for the study protocol was given. All measurements on the IOLMaster 700 at two sites (private ophthalmology clinic and public hospital ophthalmology department) in South Australia were included in the initial data analysis. Measurements were taken prospectively between October 2016 and March 2017 and de-identified data were analyzed by Zeiss in Germany using proprietary methods.

Inclusion criteria were IOLMaster 700 measurements with good-quality data from both the anterior and posterior corneal surfaces. Because all measurements underwent analysis, our study population represented a standard, urban population including measurements taken from eyes with no previous ocular surgery, those that had undergone surgery, eyes that may have had undiagnosed forme fruste keratoconus, and a small number of patients with keratoconus. In total, 1,186 measurements were taken on the IOLMaster 700, of which 76 were excluded due to failed anterior or posterior corneal surface measurement acquisition and a further 12 were excluded due to previous laser keratorefractive surgery because these surgically altered measurements would be inappropriate to include in a study assessing the relationship between anterior and posterior corneal astigmatism.

Routine IOLMaster 700 measurements were taken from each eye, including axial length, anterior chamber depth, anterior corneal power and anterior corneal astigmatism, lens thickness, and white-to-white distance. From these measurements, Zeiss provided measurements of magnitudes and orientation of steep and flat axes of anterior and posterior corneal astigmatism in radii of curvature and calculated total corneal power and astigmatism in diopters (D). We chose to present our results in diopters rather than radii of curvature for readers' ease of understanding and comparison to previous publications. The traditionally and most commonly used keratometric refractive index of 1.3375 was chosen only for convenience, rather than for optical significance. It is used for calculating anterior corneal refractive power. The refractive indices used for calculating the refractive power of the posterior cornea were 1.376 and 1.336 for cornea and aqueous humor, respectively.

The mean posterior corneal astigmatism magnitude and distribution of orientation of steep axis was calculated and correlation with basic demographics recorded. The correlation of magnitude and alignment of astigmatism of the anterior and posterior corneal surfaces was evaluated with categorization of steep axes into "vertical" (60° to 120°), "oblique" (31° to 59° or 121° to 149°), and "horizontal" (0° to 30° or 150° to 180°). Note that we did not use the traditional astigmatic descriptive terms "with-the-rule" and "against-the-rule" because the negative dioptric power of the posterior cornea can cause confusion in nomenclature. Subgroup analysis was conducted to assess correlation of posterior corneal astigmatism to age at the time of measurement and changes in orientation of the steep axis of the posterior cornea over time. Statistical analysis was done using SPSS software for Windows (version 20; SPSS, Inc., Chicago, IL). A P value of less than .05 was considered statistically significant.

RESULTS

A total of 1,098 measurements were included in the study, of which 893 were phakic, 202 were pseudophakic, and 3 were aphakic. Right eyes were measured 547 times and left eyes were measured 551 times. The average age was 73.4 ± 10.7 years (range: 24 to 95 years) at the time of measurement in the 1,092 eligible measurements where age was recorded accurately.

Mean posterior corneal astigmatism was 0.24 ± 0.15 D (range: 0 to 1.21 D). Posterior corneal astigmatism was 0.25 D or less in 59.7% of measurements, 0.50 D or less in 94.8% of measurements, 0.75 D or less in 98.9% of measurements, and 1.00 D or less in 99.6% of measurements.

The steep axis of posterior corneal astigmatism was vertically oriented in 73.32% of measurements (**Table 1**). The steep anterior corneal astigmatism axis was horizontally oriented most commonly (43.65%). Mean anterior corneal astigmatism was 1.19 ± 0.96 D (range: 0.00 to 8.37 D).

The steep axis of posterior corneal astigmatism was most commonly oriented vertically in eyes with a vertically oriented axis of anterior corneal astigmatism (**Figure 1**). There was a similar trend in orientation but a lower proportion of vertical posterior steep axes when the anterior cornea was steepest obliquely, and an even lower proportion when the anterior steep axis was oriented horizontally (**Table 2**).

Subgroup analysis of average astigmatic power by age (**Table 3**) shows that the highest proportion of measurements were taken in the age range of 70 to 79

TABLE 1
Distribution of Orientation of Steep Axis of Astigmatism on the Anterior and Posterior Corneal Surfaces

Surface	Orientation of Steep Axis	No. of Measurements	%
Posterior cornea	Vertical	808	73.32%
	Horizontal	105	9.89%
	Oblique	185	16.79%
Anterior cornea	Vertical	412	37.39%
	Horizontal	477	43.65%
	Oblique	209	18.97%

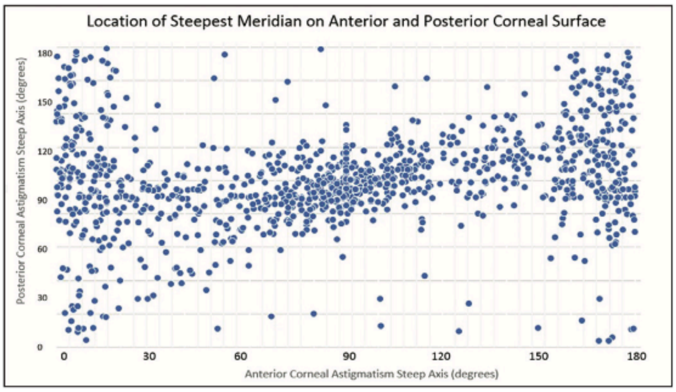

Figure 1. Distribution of orientation of the steep axis of astigmatism on the anterior and posterior corneal surfaces.

TABLE 2
Orientation of Steep Axis of Anterior and Posterior Corneal Astigmatism

Anterior Corneal Orientation	Posterior Corneal Orientation	No. of Measurements	%[a]
Vertical	Vertical	378	91.75%
Vertical	Horizontal	8	1.94%
Vertical	Oblique	26	6.31%
Horizontal	Vertical	275	57.65%
Horizontal	Horizontal	89	18.66%
Horizontal	Oblique	113	23.69%
Oblique	Vertical	155	74.16%
Oblique	Horizontal	8	3.83%
Oblique	Oblique	46	22.01%

[a]*Percentages of measurements are in relation to groupings by anterior corneal astigmatism orientation.*

TABLE 3
Average Astigmatic Power of the Anterior and Posterior Corneal Surface by Age Group

Age Group (y)	No.	Average Anterior Astigmatic Power (D)	Average Posterior Astigmatic Power (D)
20 to 29	10	2.80747	0.536744
30 to 39	5	2.504532	0.345089
40 to 49	19	1.337004	0.265237
50 to 59	74	1.222665	0.260095
60 to 69	223	1.0927	0.265038
70 to 79	408	1.15257	0.240181
80 to 89	328	1.204335	0.213983
90 to 99	25	1.369004	0.176217

D = diopters

years, which is consistent with the average age of patients undergoing cataract surgery in our study region.

Correlation between the magnitude of anterior and posterior corneal astigmatism (**Figure A**, available in the online version of this article) was moderate when all measurements were combined ($r = 0.46$, $P < .0001$) and statistically significant. The correlation was greater (**Figure B**, available in the online version of this article) when the steep axis of the anterior corneal astigmatism was oriented vertically ($r = 0.68$, $P < .0001$). The correlation was extremely weak (**Figure B**) when the steep axis of the anterior corneal astigmatism was oriented horizontally ($r = 0.05$, $P < .0001$).

Trends in astigmatic axis orientation with age differed between anterior and posterior corneal astigmatism. As age increased, the steep axis of anterior corneal astigmatism oriented vertically became a smaller percentage, whereas the horizontal orientation greatly increased (**Figure 2**). On the posterior corneal surface, the orientation of the steep axis of astigmatism was more consistent, with vertical orientation remaining by far the most common throughout all age groups (**Figure 2**).

DISCUSSION

The importance of posterior corneal astigmatism in attaining accurate surgical outcomes is gaining recognition. This is emphasized by both a new revolution of IOL calculators and nomograms incorporating posterior cornea estimates and a growing number of devices aimed at accurately assessing total corneal power. The IOLMaster 700 is one such device that has recently revealed that it is able to measure posterior corneal astigmatism and provide a value for total corneal power and astigmatism. To our knowledge, this is the first description of measurements of posterior corneal astigmatism from the IOLMaster 700 and the first comparison to previous assessments of posterior corneal astigmatism by other devices.

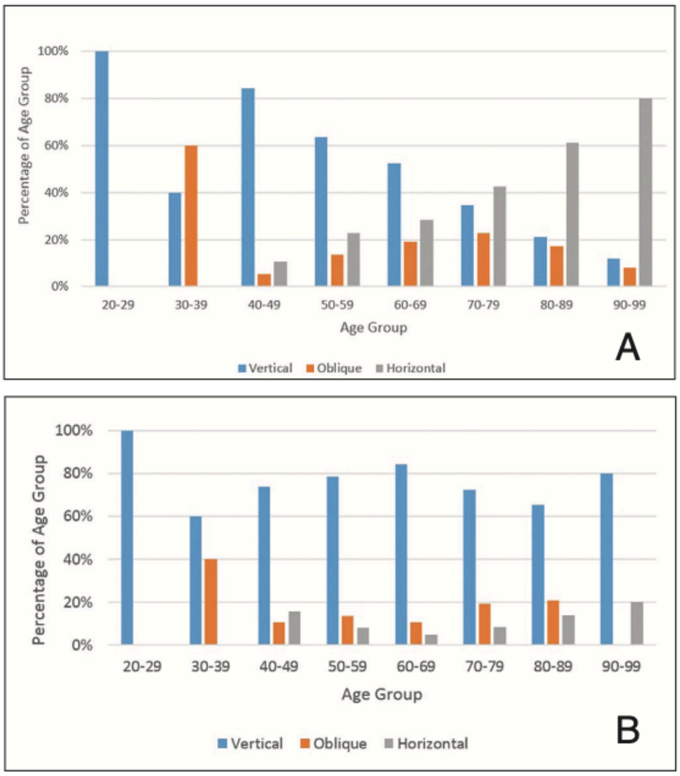

Figure 2. Distribution of orientation of steep axis of (A) anterior and (B) posterior corneal astigmatism by age group.

Posterior corneal astigmatism was analyzed in the first modern case series in 1990 when 5 eyes had their corneas measured in three meridians using Purkinje images.[3] The average magnitude of posterior corneal astigmatism was 0.38 D (range: 0.17 to 0.78 D). It was found that relatively steep or flat anterior keratometry gave rise to similarly relatively steep or flat posterior corneal meridians in this series (ie, there was correlation between the magnitude of anterior and posterior corneal astigmatism, as we found in our study). Using similar methods, Dunne et al.[4] studied 60 eyes of young patients and found that the posterior cornea was steepest in the vertical meridian in 81.7% of cases and the average magnitude of posterior corneal astigmatism of 0.26 D contributed an average of 0.15 D to total corneal astigmatism.[4] Similar analysis in a wider demographic cross-section was performed on 80 eyes the following year. This found that average posterior corneal astigmatism was greater than that of the anterior surface and that males displayed greater posterior corneal astigmatism than females. The shape of the posterior corneal surface was found to be greatly influenced by the anterior surface and the steep meridian of the posterior cornea was on average vertically oriented.[5]

Using Scheimpflug imaging, Dubbelman et al.[6] found posterior corneal astigmatism to average 0.62 D, which is similar to results obtained with an indirect measurement technique using a combination of videokeratoscopy and pachymetry by Patel et al.[7] (0.64 D) and Edmund[8] (0.65 D). They found a significant relationship between magnitude of anterior and posterior corneal astigmatism, as well as between posterior corneal astigmatism and age of the eye. A later study by Dubbelman et al.[9] aimed to assess this relationship between posterior corneal astigmatism and age in more detail. They found the average posterior corneal astigmatism in a wide age range of eyes to be 0.31 D, steepest at 97°. Posterior astigmatism appeared to increase with age and this occurred to a greater degree in the vertical meridian compared to the horizontal meridian. Although this study found a similar magnitude and axis of posterior corneal astigmatism, our study found the opposite pattern in that posterior astigmatism appeared to decrease in average magnitude with increasing age.

The first analysis of posterior corneal astigmatism that used a large number (9,000) of data points from each cornea used Orbscan scanning-slit topography. Forty eyes were measured to find a mean posterior corneal astigmatism value of 0.66 D (range: 0.32 to 1.38 D).[10] A similar assessment of 88 healthy corneas using the Orbscan found central posterior corneal cylinder values between 0.75 and 0.78 D, values far higher than our current findings.[11] In 2009, Ho et al.[12] analyzed posterior corneal measurements from 493 eyes using the Pentacam device. This rotating Scheimpflug imaging method collects data from 25,000 data points across the cornea and has been shown to be repeatable in measuring the posterior cornea.[13] Ho et al.[12] found the anterior cornea to be steepest vertically in 71.8% of eyes and the posterior surface to be steepest vertically in 96.1% of eyes. The relationship of posterior to anterior corneal astigmatism magnitude had an r value similar to the current study (0.481). Taking average posterior corneal astigmatism of 0.33 D into account, on average total corneal astigmatism was reduced by 0.21 D.

In 2012, interest in posterior corneal astigmatism was refreshed with the publishing of a study by Koch et al.,[14] where 715 corneas had their posterior corneal astigmatism analyzed using the dual Scheimpflug and Placido disc combined technology of the Galilei device. They found that average posterior corneal astigmatism was 0.30 D. The anterior cornea was steepest vertically in 51.9% of eyes and the posterior cornea was steepest vertically in 86.6% of eyes. They found that although the anterior cornea steep meridian tended to change from vertical to horizontal with age, the steep posterior corneal meridian did not move. Unlike previous studies, they found that anterior and posterior corneal astigmatism magnitude only correlated when the anterior corneal astigmatism was "with-the-rule." These findings are similar to those presented in this study. Although we found that a slightly lower percentage of eyes had a steep posterior surface axis oriented vertically, there was a consistent posterior astigmatic axis with increasing age and similar correlation between anterior and posterior astigmatic magnitude depending on orientation of anterior astigmatism steep axis.

The Pentacam HR high-resolution version of the Pentacam was used to measure the corneal astigmatism of 608 eyes in 2015.[15] The mean magnitudes of anterior and posterior corneal astigmatism were 1.14 and 0.37 D, respectively, and average orientation of the steepest axis was vertical in 68% and 91% of anterior and posterior surfaces, respectively. There was a significant ($P < .001$) correlation between the magnitudes of anterior and posterior corneal astigmatism ($r = 0.4739$) overall, but in eyes with horizontally oriented anterior corneal astigmatism there was no significant correlation between the magnitudes of anterior and posterior corneal astigmatism. The steep axis of the posterior cornea was vertically oriented in 96.6% of eyes where the anterior corneal steep axis was vertically oriented and in 73.9% of eyes where the anterior cornea steep axis was oriented horizontally. This study also confirmed a tendency for anterior corneal astigmatism to have its steep axis swing from vertical to horizontal predominance with aging, whereas the orientation of the posterior cornea did not change. The rotation of the anterior corneal steep axis with age has previously been described.[16] Minimal change in magnitude was noted in the posterior corneal astigmatism with aging, again indicating that it is stable throughout life.

The Pentacam HR was also used to analyze posterior corneal astigmatism in a study comparing astigmatism in 256 healthy eyes to keratoconic eyes.[17] Regarding the healthy eyes only, the average posterior corneal astigmatism was 0.30 D and the magnitude of corneal astigmatism of the anterior and posterior corneal surfaces correlated. The anterior corneal astigmatism steep axis was vertically oriented in 85.7% of healthy eyes and, of this group, 97.2% had posterior corneal astigmatism with the steep axis also oriented vertically.

Another device capable of measuring posterior corneal astigmatism, the Cassini, uses the reflections of 679 colored light-emitting diodes (LEDs) to describe the anterior corneal surface, and the reflections of seven additional infrared LEDs to measure the curvature of the posterior corneal surface. In a study of 91 eyes, the median posterior corneal astigmatism magnitude was 0.35 D.[18]

Overall, measurements of posterior corneal astigmatism by the IOLMaster 700 appear consistent with studies using other devices. We found that the average magnitude of posterior corneal astigmatism was 0.24 D, which is a mildly lower value than that found by other large studies (**Table A**, available in the online version of this article). Our finding of 73.32% of measurements showing the posterior corneal steep axis to be vertical was also mildly lower than previous estimates (**Table B**, available in the online version of this article). However, although these values are both slightly lower than anticipated, they are relatively close and remain plausible values.

Currently, no agreed upon gold standard exists to compare measurements of posterior corneal astigmatism against, making it difficult to validate the accuracy of any new device. The best that can be achieved at the current stage is to compare values and correlations between studies and the IOLMaster 700 appears to perform well in this regard. Our study is one of the largest analyses of measurements of posterior corneal astigmatism and our consistency with other large groups of data from other devices is reassuring that its measuring capabilities are highly likely to be accurate. Our correlation statistics assessing the relationship between anterior and posterior corneal astigmatism magnitude were similar to previous studies using other devices and the pattern of distribution of posterior and anterior astigmatism axis with age matches well with those of Koch et al.[14]

In addition to being directly measured, posterior corneal astigmatism has been calculated and this may be considered the closest we currently have to a gold standard. The presence of undercorrection and overcorrection in the treatment of astigmatism with toric IOL implantation without taking into account posterior corneal astigmatism has been proven.[19,20] Many theoretical studies employing back-calculation of potential outcomes have been published that consider methods of adjusting toric IOL cylinder power to allow for the effect of the posterior cornea.[21,22] Prospective data have also been published, proving that such adjustments are effective.[23] Validation of the IOLMaster 700 in measuring posterior corneal astigmatism will likely come from this type of calculation in the near future.

In terms of the general population, our findings must be interpreted in the knowledge that our age distribution was heavily skewed toward older age groups. Our study population reflects the typical patients undergoing cataract surgery who require precise measurement of their posterior corneal astigmatism for optimal outcomes. So, although our measurements of posterior corneal astigmatism magnitude and axis may not precisely represent the general population, they remain a good representation of the typical population undergoing routine cataract surgery.

The implications of our study are two-fold. First, because we have shown that the IOLMaster 700 appears to be able to measure posterior corneal astigmatism consistent with other estimates, we are likely witnessing the next evolution in biometry and lens calculation. With other tomography devices having been shown to have significant variability, there has been an understandable reluctance by many ophthalmologists to stray from using a single biometry device in their surgical planning to create individualized treatment plans. For example, the Orbscan has been shown to be less reliable than the Pentacam HR or Galilei devices, and there is significant variability between measurements of the posterior cornea for all of them.[24,25] The IOLMaster 700 is widely used and trusted, so if it is able to measure posterior corneal astigmatism accurately and calculate total corneal power, there would be no need to use either a secondary tomography device or lens calculation formulas that merely estimate the impact of posterior corneal astigmatism. Second, and perhaps most important, our study found a lower overall proportion of eyes with a vertically oriented posterior corneal steep axis of astigmatism compared to previous studies. Formulas, nomograms, and calculators that estimate the impact of posterior corneal astigmatism in planning cataract surgery apply population generalizations to individual patients. If that generalization that the posterior cornea is always treated as being steepest vertically is correct for fewer individuals than originally thought, then a higher proportion of patients may receive inaccurate plans for their cataract surgery. Truly individualized, precise biometric measurement and planning are surely the future for cataract surgery and the IOLMaster 700 appears capable of achieving this goal.

AUTHOR CONTRIBUTIONS

Study concept and design (BRL, MG); data collection (BRL); analysis and interpretation of data (BRL); writing the manuscript (BRL); critical revision of the manuscript (MG); statistical expertise (BRL, MG)

REFERENCES

1. Akman A, Asena L, Güngör SG. Evaluation and comparison of the new swept source OCT-based IOLMaster 700 with the IOLMaster 500. *Br J Ophthalmol.* 2016;100:1201-1205.
2. Jhanji V, Yang B, Yu M, Ye C, Leung CK. Corneal thickness and elevation measurements using swept-source optical coherence tomography and slit scanning topography in normal and keratoconic eyes. *Clin Exp Ophthalmol.* 2013;41:735-745.
3. Royston J, Dunne M, Barnes D. Measurement of posterior corneal surface toricity. *Optom Vis Sci.* 1990;67:757-763.
4. Dunne MC, Royston JM, Barnes DA. Posterior corneal surface toricity and total corneal astigmatism. *Optom Vis Sci.* 1991;68:708-710.
5. Dunne M, Royston JM, Barnes DA. Normal variations of the posterior corneal surface. *Acta Ophthalmol (Copenh).* 1992;70:255-261.
6. Dubbelman M, Weeber HA, Van Der Heijde RG, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. *Acta Ophthalmol Scand.* 2002;80:379-383.
7. Patel S, Marshall J, Fitzke F. Shape and radius of posterior corneal surface. *J Refract Surg.* 1993;9:173-181.
8. Edmund C. Posterior corneal curvature and its influence on corneal dioptric power. *Acta Ophthalmol.* 1994;72:715-720.
9. Dubbelman M, Sicam V, Van der Heijde G. The shape of the anterior and posterior surface of the aging human cornea. *Vis Res.* 2006;46:993-1001.
10. Prisant O, Hoang-Xuan T, Proano C, Hernandez E, Awad S, Azar DT. Vector summation of anterior and posterior corneal topographical astigmatism. *J Cataract Refract Surg.* 2002;28:1636-1643.
11. Módis L Jr, Langenbucher A, Seitz B. Evaluation of normal corneas using the scanning-slit topography/pachymetry system. *Cornea.* 2004;23:689-694.
12. Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement. *Am J Ophthalmol.* 2009;147:788-795.
13. Chen D, Lam AK. Intrasession and intersession repeatability of the Pentacam system on posterior corneal assessment in the normal human eye. *J Cataract Refract Surg.* 2007;33:448-454.
14. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38:2080-2087.
15. Miyake T, Shimizu K, Kamiya K. Distribution of posterior corneal astigmatism according to axis orientation of anterior corneal astigmatism. *PLoS One.* 2015;10:e0117194.
16. Gudmundsdottir E, Jonasson F, Jonsson V, Stefánsson E, Sasaki H, Sasaki K. "With the rule" astigmatism is not the rule in the elderly. *Acta Ophthalmol.* 2000;78:642-646.
17. Shajari M, Friderich S, Sadeghian MP, Schmack I, Kohnen T. Characteristics of corneal astigmatism of anterior and posterior surface in a normal control group and patients with keratoconus. *Cornea.* 2017;36:457-462.
18. Klijn S, Reus NJ, van der Sommen CM, Sicam VAD. Accuracy of total corneal astigmatism measurements with a Scheimpflug imager and a color light-emitting diode corneal topographer. *Am J Ophthalmol.* 2016;167:72-78.
19. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg.* 2015;31:98-102.
20. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. *J Cataract Refract Surg.* 2013;39:1803-1809.
21. Abulafia A, Koch DD, Wang L, et al. New regression formula for toric intraocular lens calculations. *J Cataract Refract Surg.* 2016;42:663-671.
22. Ferreira TB, Ribeiro P, Ribeiro FJ, O'Neill JG. Comparison of astigmatic prediction errors associated with new calculation methods for toric intraocular lenses. *J Cataract Refract Surg.* 2017;43:340-347.
23. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of adjustment for posterior corneal curvature in toric intraocular lens calculation and selection. *J Cataract Refract Surg.* 2016;42:1441-1448.
24. de Jong T, Sheehan MT, Koopmans SA, Jansonius NM. Posterior corneal shape: comparison of height data from 3 corneal topographers. *J Cataract Refract Surg.* 2017;43:518-524.
25. An Y, Kim H, Joo C-K. Comparison of anterior segment measurements between dual and single Scheimpflug camera. *Journal of the Korean Ophthalmological Society.* 2016;57:1056-1062.

10.4 DISCUSSION OF INFLUENCE OF PUBLICATION

This publication created a lot of interest in the practical incorporation of individual measurement of posterior corneal astigmatism into toric IOL calculation. The published graphs were presented in multiple international talks and introduced the concept that we now had an easy to use, widely owned device capable of providing a potentially improved level of accuracy in surgical planning.

Finding that the average magnitude of posterior corneal astigmatism matched historical methods was reassuring and soon, the feature became available to IOLMaster700 owners worldwide, although methods to incorporate individual measurement of posterior corneal astigmatism into IOL calculation was still not available. At this stage, measurement of posterior corneal astigmatism was mainly useful to check that an eye did fall into the typical population based statistical average range rather than actually using this data for an individual surgical plan.

The most important outcome of this study being published was that it appeared to indicate the end of an era for toric IOL calculation methods which used population based estimates of posterior corneal astigmatism. Fewer eyes than expected had a vertical steep axis to their posterior corneal astigmatism than had been expected from previous studies and it was mainly in eyes with WTR anterior corneal astigmatism where the vertical posterior steep axis predominated. This appeared to indicate that there must be a large number of eyes where individual measurement should do better in terms of refractive outcome prediction.

Chapter 11

Comparing Total Keratometry Measurement on the IOLMaster 700 with Goggin Nomogram Adjusted Anterior Keratometry

CHAPTER 11: Comparing Total Keratometry Measurement on the IOLMaster 700 with Goggin Nomogram Adjusted Anterior Keratometry.

11.1 SUMMARY

After the newly released IOLMaster 700 unveiled its ability to measure posterior corneal astigmatism, the next available feature was that it could provide a measure of total corneal astigmatism or “total keratometry” (TK). This was a vector addition taking into account the anterior corneal curvature, corneal thickness and posterior corneal curvature. In order to assess whether these TK values were accurate, a comparison needed to be made to an existing standard for total corneal astigmatism. The Goggin nomogram derived total corneal astigmatism values were chosen as a gold standard given their excellent published, prospective results. This comparison showed that both TK values and Goggin nomogram adjusted anterior keratometry values (GNAK) were found to be suitably similar that TK values could be used safely.

This article has been cited 9 times since publication.

11.2 Statement of Authorship

Statement of Authorship

Title of Paper	Comparing Total Keratometry Measurement on the IOLMaster 700 with Goggin Nomogram Adjusted Anterior Keratometry.		
Publication Status	X Published ☐ Submitted for Publication	☐ Accepted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style	
Publication Details	LaHood BR, Goggin M, Beheregaray S, Andrew NH, Esterman A. Comparing total keratometry measurement on the IOLMaster 700 with Goggin nomogram adjusted anterior keratometry. Journal of Refractive Surgery. 2018 Aug 1;34(8):521-6.		

Principal Author

Name of Principal Author (Candidate)	Ben LaHood		
Contribution to the Paper	Conceptualisation, literature review, data collection, data analysis, writing of drafts and final submission, addressing reviewers' comments leading to the final publication		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	30 December 2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Michael Goggin		
Contribution to the Paper	15% Conceptualisation, data analysis, statistical analysis, editing of drafts, replies to reviewer queries.		
Signature		Date	30 December 2021

Name of Co-Author	Adrian Esterman		
Contribution to the Paper	5% Statistical Analysis		
Signature		Date	30 December 2021

Please cut and paste additional co-author panels here as required.

Statement of Authorship

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Simone Beheregaray		
Contribution to the Paper	5% Data collection, draft manuscript editing		
Signature		Date	30 December 2021

Name of Co-Author	Nick Andrew		
Contribution to the Paper	5% Data collection, draft manuscript editing		
Signature		Date	30 December 2021

Please cut and paste additional co-author panels here as required.

ORIGINAL ARTICLE

Comparing Total Keratometry Measurement on the IOLMaster 700 With Goggin Nomogram Adjusted Anterior Keratometry

Benjamin R. LaHood, MBChB, PGDipOphth, FRANZCO; Michael Goggin, FRCSI(Ophth), FRCOphth, FRANZCO; Simone Beheregaray, MD, PhD; Nicholas H. Andrew, MBBS; Adrian Esterman, PhD, AStat

ABSTRACT

PURPOSE: To compare "total keratometry" measurements with Goggin nomogram adjusted anterior keratometry (GNAK) for toric intraocular lens calculation.

METHODS: Routine biometry provided measured total keratometry values from which astigmatism was derived. The Goggin nomogram was applied to anterior keratometry values on the same eyes to provide nomogram-adjusted anterior keratometry values (GNAK) that estimate total corneal astigmatism. The agreement between total keratometry and GNAK was analyzed.

RESULTS: Overall, in 46 eyes there was no statistically significant difference between median GNAK and total keratometry power values (P = .746). No statistically significant difference remained in against-the-rule and oblique subgroup analyses. Absolute and signed steep axis of astigmatism was statistically significantly different for GNAK and total keratometry in the overall analysis (P < .001 and = .029, respectively) and for against-the-rule and oblique subgroup analyses. The with-the-rule subgroup showed a statistically significant difference in astigmatic power and no significant signed steep axis difference between GNAK and total keratometry.

CONCLUSIONS: Total keratometry appears able to measure total corneal astigmatism to match closely (clinically and statistically) GNAK estimation of that parameter. This indicates that it would be safe and reasonable to use total keratometry data for planning of cataract surgery with toric IOLs.

[*J Refract Surg*. 2018;34(8):521-526.]

The IOLMaster700 (Carl Zeiss Meditec, Jena, Germany) uses swept-source optical coherence tomography to provide a detailed analysis of corneal curvature and power. The significant contribution of posterior corneal astigmatism to total corneal astigmatism is well recognized[1] and the ability of this device to measure both anterior and posterior corneal surfaces could potentially simplify surgical planning and improve visual outcomes from cataract surgery. Recently, the manufacturer has incorporated these new measurements of posterior corneal astigmatism and total corneal power or "total keratometry" into the IOLMaster 700 user interface.

Given that this device has produced posterior corneal astigmatism measurements consistent with previous studies,[2] one could expect it to measure total corneal astigmatism more accurately than current estimations based on population average statistics. If total keratometry is found to be accurate, it would allow individualized measurement of total corneal power, negating the need for external calculation, adjustment, and potential transcription errors. Total keratometry would be expected to be of most benefit to patients who fall outside the population average in terms of posterior corneal astigmatic power and axis orientation that are not considered in current formulas, calculators, and nomograms that apply population average statistics to individual patients.

Goggin nomogram adjusted anterior keratometry (GNAK) is a population average-based keratometry adjustment algorithm.[3] It was chosen as the gold-standard comparison method for total corneal astigmatism estimation in this study for

From The Queen Elizabeth Hospital, Adelaide, Australia (BRL, MG, SB, NHA); South Australian Institute of Ophthalmology, Adelaide, Australia (BRL, MG, SB, NHA); University of Adelaide, Adelaide, Australia (BRL, MG, SB, NHA); Sansom Institute of Health Service Research, University of South Australia, Adelaide, Australia (AE); and Australian Institute for Health and Medical Research, James Cook University, Smithfield, Australia (AE).

Submitted: April 12, 2018; Accepted: July 3, 2018

The authors have no financial or proprietary interest in the materials presented herein.

Correspondence: Benjamin R. LaHood, MBChB, PGDipOphth, FRANZCO, The Queen Elizabeth Hospital, 28 Woodville Road, Adelaide, South Australia, 5011, Australia. E-mail: benlahood@gmail.com

doi:10.3928/1081597X-20180706-01

four reasons. First, it is the only method of adjusting keratometry to allow for posterior corneal astigmatism with published, prospective validating data.[4] Second, it has recently been confirmed as being accurate in eyes with high levels of astigmatism requiring IOLs of cylinder power greater than 2.50 diopters (D).[5] Third, it allows a more direct comparison of keratometric values rather than comparison to the IOL recommendation output of "black-box" formulas that use population average-based statistics to estimate total corneal power. Fourth, it is our currently used method of cataract surgical planning at our surgical centers.

The Goggin nomogram adjusts the magnitude of anterior keratometric astigmatism to estimate total corneal astigmatism, but makes no adjustment to the axis of astigmatism. This latter strategy may be wrong if the posterior corneal astigmatism is not closely aligned with the anterior astigmatism. Toric calculators that do adjust the axis of anterior corneal astigmatism presumably assume that the steep axis of posterior corneal astigmatism is acting at a vertical meridian and make a vector addition accordingly. Although it is correct that most eyes have a steep axis of posterior corneal astigmatism in the vertical range, this covers an arc from 60° to 120° and is not always precisely at 90°. It is apparent that a biometric technique that can measure total corneal astigmatism power and axis accurately should offer more accurate results.

The aim of this study was to provide the first comparison of the new IOLMaster 700 total keratometry measurement of total corneal astigmatism with validated GNAK estimates of total corneal astigmatism. This would determine whether it was safe and reasonable to use total keratometry measurements prospectively to plan cataract surgery. To the best of our knowledge, this will be the first published assessment of the accuracy of total keratometry values.

PATIENTS AND METHODS

Ethical approval was obtained for this study from the Human Research Ethics Committee of the Central Adelaide Local Health Network, and the study was conducted in accordance with the tenets of the Declaration of Helsinki.

Routine biometric measurements were taken using the IOLMaster 700 on all patients planning to undergo cataract surgery at two sites (The Queen Elizabeth Hospital and Ashford Advanced Eye Care) in Adelaide, Australia. A total of 46 eyes were included in the study. Inclusion criteria consisted of having had biometry measured on the IOLMaster 700 between October 2016 and March 2017 with good quality measurements of all parameters including total keratometry, had cataract surgery with implantation of a toric IOL, and had their final, stable 6-week review. Patients were excluded if there was either a failure to acquire good quality measurement of any biometric parameter, previous laser keratorefractive surgery, previous ocular surgery of any type, or if the patient could not attain an unaided or corrected visual acuity of 20/25 (logMAR 0.1) or better due to any ocular or systemic reason postoperatively.

Each surgery was planned using GNAK derived from the same preoperative biometry measurement on the IOLMaster 700 on the same date as total keratometry acquisition. Adjustments to anterior keratometry measurements were made depending on the steep axis of measured anterior keratometry and the cylinder power of the intended toric IOL to be implanted (see below for a detailed explanation of the principles of the Goggin nomogram). Patients underwent standard microincision phacoemulsification cataract surgery via a 1.9-mm main incision. All eyes were implanted with a Zeiss AT TORBI 709MP monofocal toric IOL (Carl Zeiss Meditec) calculated using the Carl Zeiss Meditec online calculator (https://zcalc.meditec.zeiss.com/zcalc/) aiming for minimal postoperative residual astigmatism regardless of whether the predicted residual astigmatic axis was flipped from the preoperative state.

GNAK and total keratometry astigmatism values were derived and compared to assess whether there was any significant difference in power and steep axis orientation. Eyes were further divided into three subgroups for analysis: "with the-rule" (WTR) if the anterior keratometric steep meridian was oriented between 60° and 120° (n = 15), "against-the-rule" (ATR) if the steep meridian was oriented between 0°and 30° or 150° and 180° (n = 20), and "oblique" if the steep meridian was oriented between 31° and 59° or 121° and 149° (n = 11).

Given that this study has real life implications and we aimed to provide a practical analysis of whether new planning techniques incorporating total keratometry will be safe and accurate to use, we also considered clinical significance in our analysis. We chose an astigmatic value of 0.25 D as a threshold for clinical significance because this is typically the smallest step used in subjective refraction. We chose an axis difference of 10° or greater to signify clinical significance because toric IOL misalignment by 10° or more is considered to cause significant loss of astigmatic correction and is a threshold above which IOL re-rotation is most commonly considered.[6]

TOTAL KERATOMETRY

Measurements taken between October 2016 and March 2017 also included data about the shape and power of the posterior corneal surface, although this additional information was not accessible to the surgeons and did not influence surgical planning. These measurements were de-identified and analyzed by Carl Zeiss Meditec using proprietary methods to provide a value for total corneal power. This value has since been named "total keratometry" and is now available for use on the IOLMaster 700.

Although precise total keratometry values were derived using proprietary methods and undisclosed refractive indices, the basic principles of total keratometry calculation appear to be relatively straightforward. To the best of our knowledge, swept-source optical coherence tomography provides keratometry measurements and pachymetry from points around the clockface of the cornea to describe the shape of the posterior cornea. The combination of anterior and posterior corneal surface shapes along with pachymetry then allows calculation of total corneal power and total corneal astigmatism. The two principal total keratometry axes (flat and steep) can be used to plan surgery and make IOL choices. Total corneal astigmatism values used for analysis were derived from the difference between the steep and flat total keratometry axes. Given that total keratometry is a measured value rather than an estimate, the steep axis of total keratometry may differ from that of anterior keratometry alone.

Goggin Nomogram

All patients undergoing cataract surgery at both research sites had their procedures planned using the Goggin nomogram.[3] This method makes adjustments to anterior keratometry values to allow for the contribution of population average posterior corneal astigmatism, which has been shown consistently to have a steep vertical axis in most eyes.[1,2,7,8] The Goggin nomogram was initially developed by analyzing the refractive outcomes of a large number of patients who had undergone cataract surgery with implantation of a toric IOL.[3] Vector analysis showed a consistent, systematic error where eyes with ATR anterior corneal astigmatism on average had their astigmatism undercorrected and eyes that had WTR anterior corneal astigmatism were overcorrected. Posterior corneal astigmatism with a vertically orientated steep axis in most cases was the cause of this error. The average undercorrection and overcorrection of ATR and WTR eyes, respectively, was used to create a correction coefficient for each group of eyes. To keep this adjustment as simple to use and transparent as possible, adjusted keratometry values rather than changes in IOL cylinder power are provided by the nomogram. The prescribed increase or decrease in astigmatic power provides the surgeon with new steep and flat keratometry values that can be used in any standard toric IOL calculator if required.

The Goggin nomogram originally recommended that such keratometry adjustments be made when a toric IOL cylinder power of 2.00 D or less was required following IOL calculation with unadjusted keratometry values. It was found that there was no significant astigmatic refractive error in outcome based on the rule of the corneal astigmatism in eyes receiving IOLs of 2.50 D cylinder or greater.[3] In view of this finding, a recommendation that such eyes should not undergo adjustment was made. This initial Goggin nomogram was subsequently validated in a prospective study.[4] More recently, using a greater number of patients, a statistically significant result confirmed that eyes requiring a toric IOL cylinder power of 2.50 D or greater should not undergo adjustment of their keratometry.[5] The relatively small effect of posterior corneal astigmatism on these greater magnitudes of anterior astigmatism was found to be neither statistically or clinically significant.

RESULTS

Overall, there was no statistically significant difference between GNAK and total keratometry at assessing magnitude of total corneal astigmatism in all eyes (**Table 1**). This similarity remained in the ATR and oblique subgroups, but there was a statistically significant difference in mean magnitude in the WTR subgroup. All comparisons of mean and median astigmatic values for GNAK and total keratometry were clinically significant within 0.25 D, except for median values in WTR eyes that fell just outside this value at 0.26 D after rounding to two decimal places (**Table 1**).

It is difficult to assess the difference in astigmatic magnitude in the absence of any assessment of directionality. Vector analysis combines both of these factors. Analysis of the vector differences between GNAK and total keratometry values and the summated vector mean (0.10 D at 138°) of this difference provides a clearer overview of individual contributions (**Figure 1**). There does not appear to be any perceptible difference in the tightness of the spread of data or a clear directional bias when all eyes are looked at together. The WTR and ATR eyes appear to have a similar tightness of spread and no particular directional bias. However, the oblique subgroup does appear to be more tightly grouped to one side of the centroid chart, indicating a consistent difference in measurement of these eyes between GNAK and total keratometry in terms of both magnitude and orientation of astigmatism.

The difference in steep axis identification between GNAK and total keratometry is the same as the differ-

TABLE 1

Comparison of GNAK and TK Including Test of Statistical Significance for Difference in Mean Value (D)

Parameter	GNAK	TK
All eyes (N = 46)		
Mean	1.36	1.37
Median	1.10	1.19
95% CI of median	0.89 to 1.32	1.08 to 1.31
Minimum	0.61	0.59
Maximum	3.25	3.40
Mean difference	-0.012	
95% CI of difference	-0.086 to 0.062	
P	.746	
ATR eyes (n = 20)		
Mean	1.75	1.63
Median	1.62	1.49
95% CI of median	1.27 to 1.96	1.18 to 1.81
Minimum	0.82	0.60
Maximum	2.85	3.40
Mean difference	0.122	
95% CI of difference	-0.009 to 0.253	
P	.066	
WTR eyes (n = 15)		
Mean	1.06	1.24
Median	0.84	1.10
95% CI of median	0.68 to 1.00	0.89 to 1.31
Minimum	0.61	0.74
Maximum	3.25	3.11
Mean difference	-0.179	
95% CI of difference	-0.273 to -0.085	
P	.001	
Oblique eyes (n = 11)		
Mean	1.05	1.08
Median	0.95	0.99
95% CI of median	0.85 to 1.05	0.80 to 1.18
Minimum	0.74	0.59
Maximum	1.94	2.00
Mean difference	-0.028	
95% CI of difference	-0.106 to 0.050	
P	.440	

GNAK = Goggin nomogram adjusted anterior keratometry; TK = total keratometry; D = diopters; CI = confidence interval; ATR = against-the-rule astigmatism; WTR = with-the-rule astigmatism; oblique = oblique astigmatism

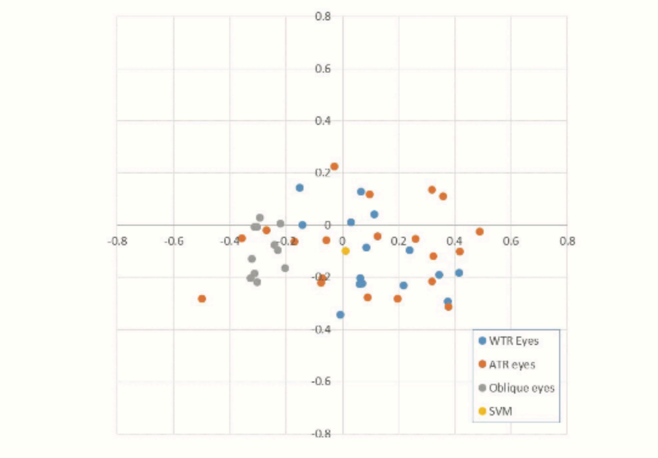

Figure 1. Centroid plot of vector differences between Goggin nomogram adjusted anterior keratometry and total keratometry values for each eye separated into anterior keratometry subgroups. WTR = with-the-rule astigmatism; ATR = against-the-rule astigmatism; SVM = summated vector mean

ence between the anterior keratometric steep axis and total keratometry because GNAK makes no change to the axis. Signed axis difference was analyzed using a one-sample *t* test comparing to the null hypothesis that there was no difference in mean axis measurements. The absolute axis difference data were highly skewed, and a signed rank test was used instead of a *t* test, comparing to the null hypothesis that there was no difference in median absolute axis (**Table 2**).

There was a statistically significant difference in steep axis assessment of GNAK and total keratometry when considering absolute axis differences in all eyes and all subgroups. Results were similar when comparing signed axis difference other than in the WTR subgroup, where the 95% confidence interval just straddled zero difference between the mean axes (**Table 2**).

DISCUSSION

Posterior corneal astigmatism is currently one of the most important factors determining postoperative refractive error following cataract surgery with toric IOL implantation.[9] Nearly half of ophthalmologists responding to the most recent clinical survey by the American Society of Cataract and Refractive Surgeons stated that they did not factor posterior corneal astigmatism into their IOL calculations because they do not think there is a good way to measure it.[6] Clearly, many ophthalmologists find the currently available techniques to estimate or measure posterior corneal astigmatism inadequate in some respect. Physically measuring the posterior cornea has indeed proven difficult and often unreliable in terms of repeatability between devices[10] and sessions.[11]

TABLE 2
Analysis of Axis Difference Between GNAK and TK Measurements in Degrees[a]

Rule	Measure	No.	Mean/Median Difference	95% CI	*P*
Overall	Signed axis difference	46	1.654	0.173 to 3.134	.029
Overall	Absolute axis difference	46	3.611	1.724 to 5.497	< .001
ATR	Signed axis difference	20	1.721	0.615 to 2.827	.004
ATR	Absolute axis difference	20	1.589	0.187 to 2.990	< .001
Oblique	Signed axis difference	11	5.941	1.427 to 10.456	.015
Oblique	Absolute axis difference	11	8.896	6.111 to 11.681	< .001
WTR	Signed axis difference	15	-1.580	-3.680 to 0.519	.129
WTR	Absolute axis difference	15	1.273	0.000 to 4.431	< .001

GNAK = Goggin nomogram adjusted anterior keratometry; TK = total keratometry; CI = confidence interval; ATR = against-the-rule astigmatism; WTR = with-the-rule astigmatism
[a]Mean difference used for signed axis difference and median difference for absolute difference.

Methods that estimate the effects of the posterior cornea using population-derived statistics have always had a limited lifespan while we await accurate measurement of total corneal astigmatism. Population-based methods have performed well and continue to do so for most cases. Many current methods can be used to incorporate posterior corneal astigmatism into IOL calculations. Nomograms allow adjustment of keratometry (GNAK) or IOL choice (Baylor nomogram).[12] Regression formulas based on anterior keratometry have also been developed to estimate the effects of the posterior cornea.[13] Calculators, both online and in device software, have evolved to incorporate such formulas and be able to make similar estimations, although it can be difficult to know exactly how these adjustments are made.[14,15]

Interestingly, these estimation methods have outperformed actual measurement of total corneal power when comparing prediction error for toric IOL implantation in a retrospective study.[16] In our study, total keratometry using actual measurement of the posterior cornea provided measurements of total corneal astigmatism magnitude similar to the validated GNAK estimation method. Overall, there was no statistically or clinically significant difference between the two methods. Subgroup analysis of WTR eyes did show a statistically significant difference in magnitude and the median difference did just breach our threshold for clinical significance. Overall, it is promising that total keratometry provides a good comparative measure to GNAK. The WTR result is surprising because it is generally considered that the steep axis of posterior corneal astigmatism is more consistently aligned with anterior astigmatism in WTR and less correlated in ATR.[1] We would have assumed that this would make estimations of total corneal astigmatism in WTR eyes using GNAK more similar to measured total keratometry results and have perhaps expected this significant difference in the ATR subgroup instead. One interpretation of this result would be that total keratometry is providing a measure of total corneal astigmatism more accurately than GNAK has estimated and that the difference is that the steep axis of the posterior cornea is not aligned vertically as often as previously thought. This theory does have some merit given that exactly this finding was recently reported using the same device in a large number of eyes.[2] However, GNAK has consistently been shown to be accurate, and this result may indicate that the IOLMaster 700 is less accurate at assessing the magnitude of total corneal astigmatism in WTR eyes. This matter will likely be resolved by larger, future studies.

Although it would be somewhat inaccurate to compare total keratometry directly to other predictive methods used in other studies, summated vector mean values for total keratometry versus GNAK difference could be considered similar enough to summated vector mean values for predictive error of residual astigmatism in previous studies. In which case, the overall summated vector mean power of 0.10 D compares favorably with published centroid errors in predicted residual astigmatism where the best method achieved was 0.17 D (Barrett calculator) and the next best was 0.19 D (Alcon calculator).[17]

The accuracy of astigmatism axis identification should be considered as important as magnitude when analyzing a biometry device. Anecdotally, uncertainty about steep axis location, inconsistency between devices, and subsequent fear of managing an astigmatic refractive surprise may inhibit toric IOL uptake by some surgeons. As expected, there was a statistically significant difference in the absolute and signed axis between GNAK and total keratometry in all analyses other than for WTR signed axis difference. This is understandable given that GNAK makes no change to the anterior keratometric steep axis. The more important question is whether this is of clinical significance and would affect visual outcomes for patients. Overall, the difference was small and could be considered insignificant. However, the upper range of the overall 95% confidence interval for median absolute axis difference does reach 5°. Although this difference in itself is not clinically significant, an error of toric IOL alignment on top of this difference of just 5° could reach a clinically significant level. Even with perfect intraoperative alignment, rotation, particularly in the first hour postoperatively, commonly reaches close to 5°.[18] Both signed and absolute axis difference 95% confidence intervals for oblique eyes reached a clinically significant level. These findings combined suggest that the difference between GNAK and total keratometry identification of steep axis of total corneal astigmatism is statistically significantly different and could be considered of clinical significance in certain circumstances.

We are aware that our study is limited by low numbers. However, we believed that it was important for this first comparison to be done to assess whether it would be safe and reasonable to proceed with a prospective comparison. Overall, it appears that total keratometry compares well to the validated GNAK method of assessing total corneal astigmatism. The similarities of magnitude of astigmatism are comforting and the differences in axis seem logical. This combination of findings appears adequate evidence to consider using total keratometry in a prospective trial. Total keratometry analysis on the IOLMaster 700 offers benefits in terms of time efficiency, decreased risk of transcription error, and potentially more precise individual refractive outcomes. It provides an easy-to-use measure of total corneal astigmatism that will add no more complexity than a standard IOL calculation using anterior keratometry. Prospective total keratometry users will, of course, have to use toric IOL calculators that do not already employ another form of posterior corneal astigmatism adjustment. Adoption of this technology should be a step toward reducing residual astigmatism and providing more patients with excellent unaided visual acuity.

AUTHOR CONTRIBUTIONS

Study concept and design (BRL, MG, SB); data collection (BRL, MG, SB, NHA); analysis and interpretation of data (BRL, MG, SB, NHA, AE); writing the manuscript (BRL, MG, SB); critical revision of the manuscript (BRL, MG, NHA, AE); statistical expertise (BRL, MG, AE); administrative, technical, or material support (BRL, MG, SB, NHA, AE); supervision (MG)

REFERENCES

1. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38:2080-2087.
2. LaHood B, Goggin M. Measurement of posterior corneal astigmatism by the IOLMaster 700. *J Refract Surg.* 2018;34:331-336.
3. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg.* 2015;31:98-102.
4. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of adjustment for posterior corneal curvature in toric intraocular lens calculation and selection. *J Cataract Refract Surg.* 2016;42:1441-1448.
5. LaHood BR, Goggin M, Esterman A. Assessing the likely effect of posterior corneal curvature on toric IOL calculation for IOLs of 2.50 D or greater cylinder power. *J Refract Surg.* 2017;33:730-734.
6. American Society of Cataract and Refractive Surgeons. 2017 ASCRS Clinical Survey. Available from: http://supplements.eyeworld.org/h/i/377037466-ascrs-clinical-survey-2017
7. Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement. *Am J Ophthalmol.* 2009;147:788-795.
8. Miyake T, Shimizu K, Kamiya K. Distribution of posterior corneal astigmatism according to axis orientation of anterior corneal astigmatism. *PLoS One.* 2015;10:e0117194.
9. Savini G, Næser K. An analysis of the factors influencing the residual refractive astigmatism after cataract surgery with toric intraocular lenses. *Invest Ophthalmol Vis Sci.* 2015;56:827-835.
10. An Y, Kim H, Joo C-K. Comparison of anterior segment measurements between dual and single Scheimpflug camera. *Journal of the Korean Ophthalmological Society.* 2016;57:1056-1062.
11. Chen D, Lam AK. Intrasession and intersession repeatability of the Pentacam system on posterior corneal assessment in the normal human eye. *J Cataract Refract Surg.* 2007;33:448-454.
12. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. *J Cataract Refract Surg.* 2013;39:1803-1809.
13. Abulafia A, Koch DD, Wang L, et al. New regression formula for toric intraocular lens calculations. *J Cataract Refract Surg.* 2016;42:663-671.
14. Barrett GD. An improved universal theoretical formula for intraocular lens power prediction. *J Cataract Refract Surg.* 1993;19:713-720.
15. Laboratories A. Alcon Toric Calculator. Available from: https://www.myalcon-toriccalc.com.
16. Ferreira TB, Ribeiro P, Ribeiro FJ, O'Neill JG. Comparison of methodologies using estimated or measured values of total corneal astigmatism for toric intraocular lens power calculation. *J Refract Surg.* 2017;33:794-800.
17. Ferreira TB, Ribeiro P, Ribeiro FJ, O'Neill JG. Comparison of astigmatic prediction errors associated with new calculation methods for toric intraocular lenses. *J Cataract Refract Surg.* 2017;43:340-347.
18. Inoue Y, Takehara H, Oshika T. Axis misalignment of toric intraocular lens: placement error and postoperative rotation. *Ophthalmology.* 2017;124:1424-1425.

11.4 DISCUSSION OF INFLUENCE OF PUBLICATION

This study showed that using TK values in an appropriate formula should be safe to use to calculate toric IOL powers, and in doing so, opened the door to numerous comparison studies assessing whether using TK and individual measurement of posterior corneal astigmatism would be more accurate than using population estimates of posterior corneal astigmatism in the current standard of estimation methods.

As previously mentioned, researchers in this field of astigmatism management, had generally expected that using TK values would significantly improve individual refractive outcomes. This has not been the case at all. What we have actually seen in publications since this article, have been comparisons showing benefit in using TK values only in eyes post laser vision correction (LVC).[1] In virgin eyes which have not undergone LVC, estimation methods have been shown to be very similar to TK involving methods.[2,3] So instead of easily accessible, individual measurement of posterior corneal astigmatism bringing an end to estimation methods, it has indicated that estimation methods were already doing a very good job, and has focused research efforts into looking for why the expected benefits have not been found.

Chapter 12

Summary, Future Directions and Conclusions

CHAPTER 12: SUMMARY, FUTURE DIRECTIONS AND CONCLUSIONS

12.1 SUMMARY OF FINDINGS

The overall objective of this thesis was to provide a more in depth understanding of posterior corneal astigmatism, from how it should be incorporated into estimation methods for IOL calculation, to assessment of the most modern, clinically useful technique for measurement, and comparing this individual measurement to an existing gold standard. The publications in included in this thesis have been instrumental in enhancing our understanding of the topic and have also led to new areas of focus for future research as outlined in the next section. The key findings can be categorised by each of the three main objectives:

1) To assess whether the contribution of posterior corneal astigmatism to total corneal astigmatism in eyes with high magnitude anterior corneal astigmatism becomes so minor that it can be ignored.

We found that there is a threshold for anterior corneal astigmatism, above which, the contribution of posterior corneal astigmatism becomes of no clinical relevance. This was important in confirming a refinement to the Goggin nomogram as a method for calculating toric IOL power. It is also an important piece of evidence that can be used to assess future measurements of posterior corneal astigmatism as we can interpret this result as indicating posterior corneal astigmatism magnitude in normal eyes does not increase in magnitude greatly despite anterior corneal astigmatism increasing significantly. Without a gold standard for measurement of posterior corneal astigmatism, observations such as this are vital.

2) To assess how measurement of posterior corneal astigmatism using optical coherence tomography (OCT) of the IOLMaster 700 compares to previous estimates.

The measurements of posterior corneal astigmatism that we found in the first, and largest study of the IOLMaster 700 are in keeping with previous measurements from a range of other modern devices. This is reassuring as this was the first widely used biometry device to use OCT in this manner and going forward, is likely to be one of the key devices used for practical application of posterior corneal astigmatism incorporation into toric IOL calculation.

Our findings that posterior corneal astigmatism has a vertical steep axis less commonly than previously thought implies that individual measurement of posterior corneal astigmatism should yield better refractive results than what we have achieved with population based statistical estimates of average posterior corneal astigmatism.

3) To assess whether IOLMaster 700 measurement of total corneal astigmatism, “total keratometry” (TK) is as accurate as Goggin nomogram adjusted keratometry (GNAK) values.

Individual measurement of posterior corneal astigmatism and incorporation of this into a measure of total corneal astigmatism on the IOLMaster 700 provides similar results to a current gold standard of Goggin nomogram adjusted keratometry values. Given the excellent published, prospective results attained with GNAK values, this shows it would be safe to use TK values with appropriate formulae.

12.2 FUTURE DIRECTIONS OF RESEARCH

When looking at the summary of outcomes from these related studies, an obvious progression in thinking emerges, showing that estimation methods such as the Goggin nomogram are performing well and can continue to be refined, individual measurement of posterior corneal astigmatism is possible with routine biometry equipment, and provides data which is equivalent to that of estimation methods. What interests me most about future research in the field of posterior corneal astigmatism is that if we assume we are indeed measuring it accurately, yet more recent research indicates no benefit over estimation methods in terms of refractive outcomes then we must be missing something which is contributing to refractive astigmatism.

Modern measurements of posterior corneal astigmatism have been quite consistent in terms of magnitude. This fits with our ability to use an average value for posterior corneal astigmatism to make a systematic adjustment and achieve excellent results. However, study two of this thesis indicated that the axis at which posterior corneal astigmatism acts is more variable than we had thought. Such variability should not be able to be adjusted for in a systematic way. Goggin nomogram results in terms of refractive outcomes as seen in study one of this thesis are some of the best, if not the very best published results of treating astigmatism. So, we have a conundrum where we are making a successful, systematic adjustment for posterior corneal astigmatism, yet at the same time we are aware that posterior corneal astigmatism when measured at an individual level is highly variable in direction and that refractive outcomes are not enhanced by using individual posterior corneal astigmatism measurement over estimation methods. The only logical conclusion is that there is an additional, currently unrecognised factor responsible for the discrepancy between measured corneal astigmatism and refractive astigmatism. This would have to be a systematic, consistent factor that swamps the contribution of posterior corneal astigmatism. Potential suspect factors which may be responsible include IOL tilt relative to the visual axis of the eye, and, some type of systematic error in the axis at which we measure biometry relative to our axis of refraction. There could of course be other potential causes or combinations of causes. This will be a fascinating area of research which this thesis has shown to be necessary.

12.3 CONCLUSIONS

The three independent studies that make up this thesis add to our understanding of posterior corneal astigmatism and how it impacts our treatment of astigmatism at the time of cataract surgery. Each study represents an important and necessary step in the research area of posterior corneal astigmatism, which has progressed more in the past five years than it did in the preceding century. The included studies indicate that individual measurement of posterior corneal astigmatism appears to be capable of providing similar results to both estimation methods and to historical methods of measurement. Estimation methods of working with posterior corneal astigmatism have been further refined and there is still room for further potential refinement. One of the most interesting points that this research has raised along with subsequent studies, is that potentially what we are making systematic adjustments for under the heading of posterior corneal astigmatism could be something as yet unrecognised and this is why we have not seen the anticipated benefits of individual measurement that we were expecting.

13. COMPLETE BIBLIOGRAPHY OF ALL CHAPTERS

References from Chapter 1: Introduction

1. Gutmark R, Guyton DL. Origins of the keratometer and its evolving role in ophthalmology. Survey of ophthalmology. 2010;55(5):481-97.

2. Javal É. Mémoires d'ophtalmométrie: annotés et précédés d'une introduction: G. Masson; 1890.

3. Tscherning M. "Physiologic Optics", English translation by C. Weiland. Philadelphia: The Keystone; 1904.

4. Southall JP. Helmholtz's treatise on psychological optics: Dover; 1962.

5. Lowe RF, Clark B. Posterior corneal curvature. Correlations in normal eyes and in eyes involved with primary angle-closure glaucoma. The British journal of ophthalmology. 1973;57(7):464.

6. Hockwin O, Weigelin E, Laser H, Dragomirescu V. Biometry of the anterior eye segment by Scheimpflug photography. Ophthalmic research. 1983;15(2):102-8.

7. Garner LF, Owens H, Yap MK, Frith MJ, Kinnear RF. Radius of Curvature of the Posterior Surface of the Cornea. Optometry & Vision Science. 1997;74(7):496-8.

8. Royston J, Dunne M, Barnes D. Measurement of the posterior corneal radius using slit lamp and Purkinje image techniques. Ophthalmic and Physiological Optics. 1990;10(4):385-8.

9. Royston J, Dunne M, Barnes D. Measurement of posterior corneal surface toricity. Optometry & Vision Science. 1990;67(10):757-63.

10. Dunne MC, Royston JM, Barnes DA. Posterior corneal surface toricity and total corneal astigmatism. Optometry & Vision Science. 1991;68(9):708-10.

11. Dunne M, Royston JM, Barnes DA. Normal variations of the posterior corneal surface. Acta ophthalmologica. 1992;70(2):255-61.

12. Edmund C. Posterior corneal curvature and its influence on corneal dioptric power. Acta ophthalmologica. 1994;72(6):715-20.

13. Patel S, Marshall J, Fitzke F. Shape and radius of posterior corneal surface. Journal of Refractive Surgery. 1993;9(3):173-81.

14. Lam AK, Douthwaite WA. Measurement of posterior corneal asphericity on Hong Kong Chinese: A pilot study. Ophthalmic and Physiological Optics. 1997;17(4):348-56.

15. Dubbelman M, Weeber HA, Van Der Heijde RG, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. Acta Ophthalmologica Scandinavica. 2002;80(4):379-83.

16. Snook RK. Pachymetry and true topography using the Orbscan system. Corneal Topography. 1995:89-103.

17. Leyland M. Validation of Orbscan II posterior corneal curvature measurement for intraocular lens power calculation. Eye. 2004;18(4):357.

18. Ho J-D, Tsai C-Y, Tsai RJ-F, Kuo L-L, Tsai I-L, Liou S-W. Validity of the keratometric index: evaluation by the Pentacam rotating Scheimpflug camera. Journal of Cataract & Refractive Surgery. 2008;34(1):137-45.

19. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. Journal of Cataract & Refractive Surgery. 2012;38(12):2080-7.

20. Hidalgo IR, Rozema JJ, Dhubhghaill SN, Zakaria N, Koppen C, Tassignon MJ. Repeatability and inter-device agreement for three different methods of keratometry: Placido, Scheimpflug, and color LED corneal topography. Journal of Refractive Surgery. 2015;31(3):176-81.

21. Jhanji V, Yang B, Yu M, Ye C, Leung CK. Corneal thickness and elevation measurements using swept-source optical coherence tomography and slit scanning topography in normal and keratoconic eyes. Clinical & experimental ophthalmology. 2013;41(8):735-45.

22. Akman A, Asena L, Güngör SG. Evaluation and comparison of the new swept source OCT-based IOLMaster 700 with the IOLMaster 500. British Journal of Ophthalmology. 2016;100(9):1201-5.

23. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. Journal of Cataract & Refractive Surgery. 2013 Dec 1;39(12):1803-9.

24. Ho JD, Liou SW, Tsai RJ, Tsai CY. Effects of aging on anterior and posterior corneal astigmatism. Cornea. 2010 Jun 1;29(6):632-7.

25. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. Journal of Refractive Surgery. 2015;31(2):98-102.

26. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of adjustment for posterior corneal curvature in toric intraocular lens calculation and selection. Journal of Cataract & Refractive Surgery. 2016;42(10):1441-8.

27. Preussner PR, Hoffmann P, Wahl J. Impact of posterior corneal surface on toric intraocular lens (IOL) calculation. Current eye research. 2015 Aug 3;40(8):809-14.

28. Reitblat O, Levy A, Kleinmann G, Abulafia A, Assia EI. Effect of posterior corneal astigmatism on power calculation and alignment of toric intraocular lenses: comparison of methodologies. Journal of Cataract & Refractive Surgery. 2016 Feb 1;42(2):217-25.

29. Dubbelman M, Sicam V, Van der Heijde G. The shape of the anterior and posterior surface of the aging human cornea. Vision research. 2006;46(6):993-1001.

30. Módis Jr L, Langenbucher A, Seitz B. Evaluation of normal corneas using the scanning-slit topography/pachymetry system. Cornea. 2004;23(7):689-94.

References from Chapter 9.3: Published Article 1

1. Royston JM, Dunne MC, Barnes DA. Measurement of posterior corneal surface toricity. *Optom Vis Sci*. 1990;67:757-763.

2. Dunne MC, Royston JM, Barnes DA. Posterior corneal surface to- ricity and total corneal astigmatism. *Optom Vis Sci*. 1991;68:708- 710.

3. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg*. 2012;38:2080-2087.

4. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior cor- neal astigmatism. *J Cataract Refract Surg*. 2013;39:1803-1809.

5. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of ad- justment for posterior corneal curvature in toric intraocu- lar lens calculation and selection. *J Cataract Refract Surg*. 2016;42:1441-1448.

6. Abulafia A, Barrett GD, Kleinmann G, et al. Prediction of refrac- tive outcomes with toric intraocular lens implantation. *J Cata- ract Refract Surg*. 2015;41:936-944.

7. Abulafia A, Hill WE, Franchina M, Barrett GD. Comparison of methods to predict residual astigmatism after intraocular lens implantation. *J Refract Surg*. 2015;31:699-707.

8. Klijn S, Reus NJ, Sicam VA. Evaluation of keratometry with a nov- el Color-LED corneal topographer. *J Refract Surg*. 2015;31:249- 256.

9. Hirji NK, Larke JR. Thickness of human cornea measured by top- ographic pachometry. *Am J Optom Physiol Sci*. 1978;55:97-100.

10. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg*. 2015;31:98-102.

11. Gudmundsdottir E, Jonasson F, Jonsson V, Stefánsson E, Sasaki H, Sasaki K. “With the rule” astigmatism is not the rule in the elderly. Reykjavik eye study: a population based study of re- fraction and visual acuity in citizens of Reykjavik 50 years and older: Iceland-Japan co-working study groups. *Acta Ophthal- mol Scand*. 2000;78:642-646.

12. Gudmundsdottir E, Arnarsson A, Jonasson F. Five-year refrac- tive changes in an adult population: Reykjavik Eye Study. *Oph- thalmology*. 2005;112:672-677.

13. Ho JD, Liou SW, Tsai RJ, Tsai CY. Effects of aging on anterior and posterior corneal astigmatism. *Cornea*. 2010;29:632-637.

14. Goggin M, Moore S, Zamora-Alejo K, Esterman A. Astigmatic neutrality in 1.9-mm coaxial microincision phacoemulsifica- tion. *J Refract Surg*. 2012;28:451-452.

15. Piaggio G, Elbourne DR, Pocock SJ, Evans SJ, Altman DG; CON- SORT Group. Reporting of noninferiority and equivalence ran- domized trials: extension of the CONSORT 2010 statement. *JAMA*. 2012;308:2594-2604.

16. Durkin SR, Goggin M. A one-point technique for per-operative corneal meridian identification. *Graefes Arch Clin Exp Ophthal- mol*. 2013;251:2481-2482.

17. Alpins NA. A new method of analyzing vectors for changes in astigmatism. J Cataract Refract Surg. 1993;19:524-533.

18. Coe R. It's the effect size, stupid: what "effect size" is and why it is important. Paper presented at: Annual Conference of the British Educational Research Association; September 2002; Ex- eter, United Kingdom.

19. Goggin M, Patel I, Billing K, Esterman A. Variation in surgically induced astigmatism estimation due to test-to-test variations in keratometry. *J Cataract Refract Surg.* 2010;36:1792-1793.

20. Ferreira TB, Ribeiro FJ. A novel color-LED corneal topographer to assess astigmatism in pseudophakic eyes. *Clin Ophthalmol*. 2016;10:1521-1529.

References from Chapter 10.3: Published Article 2

1. Akman A, Asena L, Güngör SG. Evaluation and comparison of the new swept source OCT-based IOLMaster 700 with the IOL- Master 500. *Br J Ophthalmol.* 2016;100:1201-1205.
2. Jhanji V, Yang B, Yu M, Ye C, Leung CK. Corneal thickness and elevation measurements using swept-source optical coherence tomography and slit scanning topography in normal and kera- toconic eyes. *Clin Exp Ophthalmol.* 2013;41:735-745.

3. Royston J, Dunne M, Barnes D. Measurement of posterior cor- neal surface toricity. *Optom Vis Sci.* 1990;67:757-763.
4. Dunne MC, Royston JM, Barnes DA. Posterior corneal surface to- ricity and total corneal astigmatism. *Optom Vis Sci.* 1991;68:708- 710.
5. Dunne M, Royston JM, Barnes DA. Normal variations of the poste- rior corneal surface. *Acta Ophthalmol (Copenh).* 1992;70:255-261.
6. Dubbelman M, Weeber HA, Van Der Heijde RG, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface de- termined by corrected Scheimpflug photography. *Acta Oph- thalmol Scand.* 2002;80:379-383.
7. Patel S, Marshall J, Fitzke F. Shape and radius of posterior corneal surface. *J Refract Surg.* 1993;9:173-181.
8. Edmund C. Posterior corneal curvature and its influence on corneal dioptric power. *Acta Ophthalmol.* 1994;72:715-720.
9. Dubbelman M, Sicam V, Van der Heijde G. The shape of the anterior and posterior surface of the aging human cornea. *Vis Res.* 2006;46:993-1001.
10. Prisant O, Hoang-Xuan T, Proano C, Hernandez E, Awad S, Azar DT. Vector summation of anterior and posterior corneal topo- graphical astigmatism. *J Cataract Refract Surg.* 2002;28:1636- 1643.
11. Módis L Jr, Langenbucher A, Seitz B. Evaluation of normal cor- neas using the scanning-slit topography/pachymetry system. *Cornea.* 2004;23:689-694.
12. Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measure- ment. *Am J Ophthalmol.* 2009;147:788-795.
13. Chen D, Lam AK. Intrasession and intersession repeatability of the Pentacam system on posterior corneal assessment in the normal human eye. *J Cataract Refract Surg.* 2007;33:448-454.
14. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38:2080-2087.

15. Miyake T, Shimizu K, Kamiya K. Distribution of posterior cor- neal astigmatism according to axis orientation of anterior cor- neal astigmatism. *PLoS One.* 2015;10:e0117194.

16. Gudmundsdottir E, Jonasson F, Jonsson V, Stefánsson E, Sasaki H, Sasaki K. “With the rule” astigmatism is not the rule in the elderly. *Acta Ophthalmol.* 2000;78:642-646.

17. Shajari M, Friderich S, Sadeghian MP, Schmack I, Kohnen T. Characteristics of corneal astigmatism of anterior and posterior surface in a normal control group and patients with keratoco- nus. *Cornea.* 2017;36:457-462.

18. Klijn S, Reus NJ, van der Sommen CM, Sicam VAD. Accuracy of total corneal astigmatism measurements with a Scheimpflug imager and a color light-emitting diode corneal topographer. *Am J Ophthalmol.* 2016;167:72-78.

19. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg.* 2015;31:98-102.

20. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior cor- neal astigmatism. *J Cataract Refract Surg.* 2013;39:1803-1809.

21. Abulafia A, Koch DD, Wang L, et al. New regression formula for toric intraocular lens calculations. *J Cataract Refract Surg.* 2016;42:663-671.

22. Ferreira TB, Ribeiro P, Ribeiro FJ, O’Neill JG. Comparison of astigmatic prediction errors associated with new calculation methods for toric intraocular lenses. *J Cataract Refract Surg.* 2017;43:340-347.

23. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of ad- justment for posterior corneal curvature in toric intraocu- lar lens calculation and selection. *J Cataract Refract Surg.* 2016;42:1441-1448.

24. de Jong T, Sheehan MT, Koopmans SA, Jansonius NM. Poste- rior corneal shape: comparison of height data from 3 corneal topographers. *J Cataract Refract Surg.* 2017;43:518-524.

25. An Y, Kim H, Joo C-K. Comparison of anterior segment measure- ments between dual and single Scheimpflug camera. *Journal of the Korean Ophthalmological Society.* 2016;57:1056-1062.

References from Chapter 11.3: Published Article 3

1. Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38:2080-2087.

2. LaHood B, Goggin M. Measurement of posterior corneal astig- matism by the IOLMaster 700. *J Refract Surg.* 2018;34:331-336.

3. Goggin M, Zamora-Alejo K, Esterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. *J Refract Surg.* 2015;31:98-102.

4. Goggin M, van Zyl L, Caputo S, Esterman A. Outcome of ad- justment for posterior corneal curvature in toric intraocu- lar lens calculation and selection. *J Cataract Refract Surg.* 2016;42:1441-1448.

5. LaHood BR, Goggin M, Esterman A. Assessing the likely effect of posterior corneal curvature on toric IOL calculation for IOLs of 2.50 D or greater cylinder power. *J Refract Surg.* 2017;33:730- 734.

6. American Society of Cataract and Refractive Surgeons. 2017 ASCRS Clinical Survey. Available from: http://supplements. eyeworld.org/h/i/377037466-ascrs-clinical-survey-2017

7. Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measure- ment. *Am J Ophthalmol.* 2009;147:788-795.

8. Miyake T, Shimizu K, Kamiya K. Distribution of posterior cor- neal astigmatism according to axis orientation of anterior cor- neal astigmatism. *PLoS One.* 2015;10:e0117194.

9. Savini G, Næser K. An analysis of the factors influencing the residual refractive astigmatism after cataract surgery with toric intraocular lenses. *Invest Ophthalmol Vis Sci.* 2015;56:827-835.

10. An Y, Kim H, Joo C-K. Comparison of anterior segment measure- ments between dual and single Scheimpflug camera. *Journal of the Korean Ophthalmological Society.* 2016;57:1056-1062.

11. Chen D, Lam AK. Intrasession and intersession repeatability of the Pentacam system on posterior corneal assessment in the normal human eye. *J Cataract Refract Surg.* 2007;33:448-454.

12. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior cor- neal astigmatism. *J Cataract Refract Surg.* 2013;39:1803-1809.

13. Abulafia A, Koch DD, Wang L, et al. New regression formula for toric intraocular lens calculations. *J Cataract Refract Surg.* 2016;42:663-671.

14. Barrett GD. An improved universal theoretical formula for intraocular lens power prediction. *J Cataract Refract Surg.* 1993;19:713-720.

15. Laboratories A. Alcon Toric Calculator. Available from: https:// www.myalcon-toriccalc.com.

16. Ferreira TB, Ribeiro P, Ribeiro FJ, O'Neill JG. Comparison of methodologies using estimated or measured values of total cor- neal astigmatism for toric intraocular lens power calculation. *J Refract Surg.* 2017;33:794-800.

17. Ferreira TB, Ribeiro P, Ribeiro FJ, O'Neill JG. Comparison of astigmatic prediction errors associated with new calculation methods for toric intraocular lenses. *J Cataract Refract Surg.* 2017;43:340-347.

18. Inoue Y, Takehara H, Oshika T. Axis misalignment of toric intraocular lens: placement error and postoperative rotation. *Ophthalmology.* 2017;124:1424-1425.

References from Chapter 11.4: Discussion of Influence of Publication

1. Lawless M, Jiang JY, Hodge C, Sutton G, Roberts TV, Barrett G. Total keratometry in intraocular lens power calculations in eyes with previous laser refractive surgery. Clinical & experimental ophthalmology. 2020 Aug;48(6):749-56.

2. Srivannaboon S, Chirapapaisan C. Comparison of refractive outcomes using conventional keratometry or total keratometry for IOL power calculation in cataract surgery. Graefe's Archive for Clinical and Experimental Ophthalmology. 2019 Dec;257(12):2677-82.

3. Lee H, Chung JL, Kim YJ, Kim JY, Tchah H. Prediction accuracy of standard and total keratometry by swept-source optical biometer for multifocal intraocular lens power calculation. Scientific reports. 2021 Feb 26;11(1):1-9

14. SUPPLEMENTARY MATERIALS

Supplementary Tables from Study 1

TABLE A

Preoperative Keratometric Astigmatism and Implanted IOL Powers

Rule	N	Preoperative Keratometric Astigmatism (Mean ± SD [Range])	Implanted IOL Sphere Power (Mean ± SD [Range])	Implanted IOL Cylinder Power (Mean ± SD [Range])
WTR	53	3.18 ± 1.33 D (1.70 to 9.00 D)	19.60 ± 8.32 D (-6.00 to 34.00 D)	4.00 ± 1.71 D (2.50 to 10.50 D)
ATR	60	2.95 ± 1.32 D (1.91 to 7.41 D)	19.18 ± 4.41 D (5.50 to 29.50 D)	3.64 ± 1.76 D (2.50 to 9.50 D)
Both	113	3.06 ± 1.32 D (1.70 to 9.00 D)	19.38 ± 6.51 D (-6.00 to 34.00 D)	3.81 ± 1.71 D (2.50 to 10.50 D)

rule = measured anterior keratometric astigmatism; SD = standard deviation; IOL = intraocular lens; WTR = with-the-rule; D = diopters; ATR = against-the-rule; both = includes WTR and ATR but excludes oblique

TABLE B

Postoperative and Targeted Refractive Astigmatism

Rule	N	Postoperative Refractive Astigmatism (Mean ± SD [Range])	Targeted Refractive Astigmatism (Mean ± SD [Range])
WTR	53	+0.65 ± 0.63 D (0.00 to 3.59 D[a])	+0.15 ± 0.10 D (0.01 to 0.34 D)
ATR	60	+0.90 ± 0.64 D (0.00 to 3.59 D)	+0.17 ± 0.12 D (0.01 to 0.55 D)
Both	113	+0.78 ± 0.64 D (0.00 to 3.59 D[a])	+0.16 ± 0.11 D (0.01 to 0.55 D)

rule = designated using anterior keratometric astigmatism; SD = standard deviation; WTR = with-the-rule; D = diopters; ATR = against-the-rule; both = includes WTR and ATR but excludes oblique
[a]Data include an eye with previous penetrating keratoplasty.

Supplementary Tables and Figures from Study 2

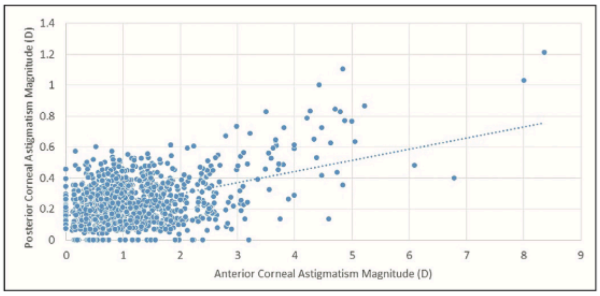

Figure A. Correlation between anterior and posterior corneal astigmatism magnitude for all orientations of anterior corneal astigmatism. D = diopters

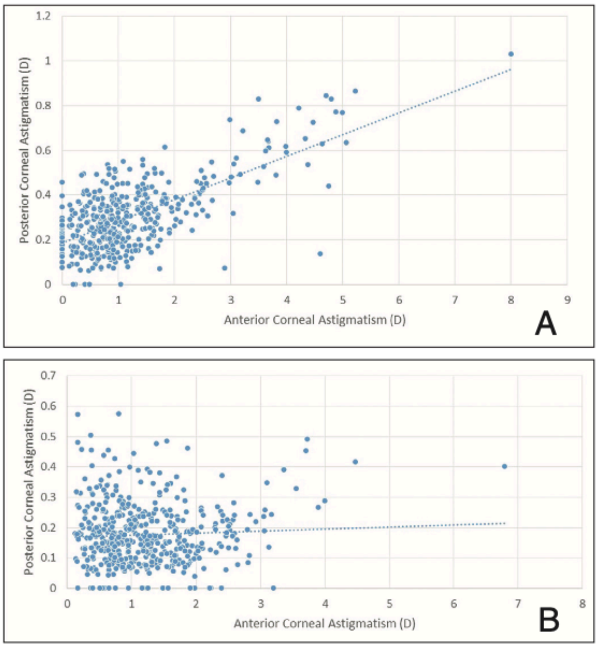

Figure B. Correlation between anterior and posterior corneal astigmatism magnitude when anterior corneal astigmatism steep axis is oriented (A) vertically and (B) horizontally.

TABLE A

Comparative Magnitude of Posterior Corneal Astigmatism Using Different Devices in Recent Studies

Author	Year	Eyes	Device	Average Magnitude (D)
Prisant et al.[10]	2002	40	Orbscan	0.66
Módis et al.[11]	2004	80	Orbscan	0.75
Ho et al.[12]	2009	493	Pentacam	0.33
Koch et al.[16]	2012	715	Gallilei	0.30
Miyake et al.[15]	2015	608	Pentacam HR	0.37
Klijn et al.[18]	2016	91	Cassini	0.35
Current study	2017	1098	IOLMaster 700	0.24

D = diopters

TABLE B

Comparative Percentage of Patients With Vertical Orientation of Measured Steep Axis of Posterior Corneal Astigmatism in Recent Major Studies

Author	Year	Eyes	Device	% Vertical Posterior Cornea Steep Axis
Ho et al.[12]	2009	493	Pentacam	96.1%
Koch et al.[16]	2012	715	Gallilei	86.6%
Miyake et al.[15]	2015	608	Pentacam HR	91.0%
Current study	2017	1,098	IOLMaster 700	73.3%