



Keynote Lecture New standards for analyzing astigmatic outcomes

Thomas Kohnen



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T. Kohnen: *Consultant and Research* for Alcon, J&J, Lensgen, Oculentis, Oculus, Presbia, Schwind, Zeiss. *Consultant for* Allergan, Bausch & Lomb, Geuder, Med Update, Santen, Staar, Thieme, Ziemer.

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FROM THE EDITOR

Setting standards for astigmatism analysis

Douglas D. Koch, MD, Thomas Kohnen, MD, PhD, FEBO

Astigmatism analysis is a complex topic. Analyzing astigmatic outcomes requires two elements: (1) scalar or nonvector analysis, since the magnitude of refractive astigmatism is a predictor of visual function, and (2) vector analysis, which, by recognizing that astigmatism is bivariate – that is, has magnitude and angle – is required to calculate astigmatic change. Stokes in 1849 was the first to recognize a fundamental principle of vector analysis of astigmatism. One must first double the angles to create vector values that enable correct analytical approaches.

A large number of methods of analyzing astigmatic change have been proposed in recent years. Those that follow the principles of double-angle bivariate analysis are accurate and provide valuable insights. Unfortunately, some methods of analyzing astigmatic change are not valid because they do not adhere to these principles, resulting in misleading analyses that fail to advance the science. Further complicating this area is the recent recognition that astigmatic data are not normally distributed.² New statistical approaches that account for this are required and are now available.

To address these issues, the editors of the *Journal of Cataract e-Refractive Surgery* initiated a working group to update and establish astigmatic reporting guidelines. The goal was to provide the basic elements of accurate reporting of astigmatic change, incorporating correct vector mathematics and statistical methodology. The guidelines are based on sound optical principles that avoid misleading results and allow authors, peer reviewers, and readers to easily understand, assimilate, and compare published reports of low-order astigmatic corrections.

Together with an international team of authors, we present the work in two parts. The first paper is an overview of astigmatism, including definitions, measurement technologies, and sources of error and variability (page +++). The second paper describes our recommended methodology for analyzing astigmatic outcomes (page +++). This approach is based on the optics of corneal and lenticular astigmatism, as well as contemporary vector analysis and statistical approaches. We want to emphasize that what we propose is not exclusive; that is, that suthors may wish to provide additional valid analyses to better characterize their outcomes. We believe that implementing these analytical and statistical methods will bring accuracy, consistency, and clarity to astigmatiam reporting.

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Standards for Analyzing Astigmatic Outcomes Part I: Astigmatism Basics Part II: Recommended Statistical Methods



Journal of Cataract & Refractive Surgery*

CONSTRUCTION CONSTRUCTION







Acknowledgment

Jack T. Holladay, MD, MSEE¹ Kristian Naeser, MD, DSMC³ Adi Abulafia, MD, PhD² Li Wang, MD, PhD¹ R. Doyle Stulting, MD, PhD⁴



In December 2020, The Journal of Cataract and Refractive Surgery (JCRS) formed a committee to reach and publish a consensus on clear and accurate astigmatism reporting guidelines to benefit JCRS authors and all researchers. The committee consisted of clinicians and researchers with expertise in this area. Following a series of virtual meetings, several of the committee members prepared the two manuscripts -- one on background and the second on standards for analyzing astigmatism. In addition to the authors of this paper, we want to acknowledge and thank the other members of the committee who made important contributions to the concepts incorporated in the written result of this project: Graham D. Barrett (MD, Australia), Laure Gobin (PhD, Belgium), and David Smadja (MD, Israel).





Standards for Analyzing Astigmatic Outcomes Part I: Astigmatism Basics





Thomas Kohnen, MD, PhD, FEBO¹ Kristian Naeser, MD, DSMC³ Jack T. Holladay, MD, MSEE² R. Doyle Stulting, MD, PhD⁴ Li Wang, MD, PhD² Adi Abulafia, MD, PhD⁵ Douglas D. Koch, MD²





REVIEW/UPDATE

Standards for analyzing astigmatic outcomes: part I: astigmatism basics

Thomas Kohnen, MD, PhD, FEBO, Kristian Næser, MD, DSMC, Jack T. Holladay, MD, MSEE, R. Doyle Stuliting, MD, PhD, Li Wang, MD, PhD, Adi Abulafia, MD, PhD, Douglas D. Koch, MD

Adigmeters is the difference between the orthogonal principal planes of minimal and movinel powers of a toric truthoc, lens, or retraction. Comeal astigmation is a common condition, and studies indicate that over 60% of individues have more than 0.50 displays of astigmation. Comeal astigmation is measured in various ways, and measurements from different devices are usually not interchangeable because of variations in technology and the cointerchangeable because of variations in technology and the coincet regions that are imaged. The integrity of the coular surface is ortically important for accurately measuring comeal astigmation. Golfmang the ocular surface before patients astigmation. Golfmang the ocular surface before patients astigmation measure ments and retractive surfaces. It is adversarial surgery cars significantly improve the accuracy of preoperative astigmation astigmation and retractive to solve an attaces before octain a stagement and retractive to accuracy of preoperative astigmation astigmation. pretenticly Simulationments when measuring connect antigradium. When a discrepancy is astigration meridian and magnitude occurs between the measurements, it is advisable to settle or at least minimize this discrepancy by repeating the measurements after optimizing the ocular surface. Posterior connect astigmation is an important component of total connect astigmation is an also induce visually applicant reflective astigmation and ideely should be accounted for in tone immocular lens planning.

J Catavart Rehort Surg 2025; #1-7 Capyright © 2029 Published by Wolkers Kluwer on behalf of ASCRS and 25CR5

A stigmatism analysis can be a complex, daunting, and sometimes contentious endeavor because of the complex nature of the topic, the variety of approaches available, and the shifting terminology. Over the past 3 decades, a variety of analytical methods have been proposed for predicting the residual refractive astigmatism after cataract and refractive surgery with the dual goals of guiding surgeons to provide optimal correction of astigmatism and enabling researchers to analyze and present outcomes of procedures that after astigmatism. Although many of the new developments are helpful, the lack of general consensus on terminology and approach make it increasingly difficult to effectively compare and evaluate research in the area of astigmatism.

To bring clarity to the topic of astigmatian analysis for all current and future researchers, the *Journal of Catanut & Refractive Surgery Sormed* a working group to (1) establish autgmatic reporting guidelines based on sound optical principles and (2) provide new astigmatism calculation tools that simplify the process and allow researchers to reliably calculate accurate and reproducible results.

DEFINING ASTIGMATISM

In a spherical (stigmatic or point-like) optical system, a point in the object space is focused as a point image. An object located in the far point is focused on the retina. Objects from any other positions are defocused.³

In a regular autigmatic optical system, an object point is focused as 2 mutually perpendicular line segments delineating the Sturm interval.1 Stated another way, astigmatism is the difference between the orthogonal principal planes of minimal and maximal powers of a toric surface, lens, or refraction. The curvature difference can be transformed to dioptric power using the radii of curvature and refractive indices of the refractive surface and surrounding media." The optical effects of ocular astigmatism. are blurring at all fixation distances because of a lack of point focus and, when corrected with cylindrical lenses, causes distortion in various meridians because of unequal magnification of the retinal image. Sphere and regular astigmatism are lower-order aberrations, correctable with spectacles or contact lenses. However, the optical quality of the human cornea is infertor to a diffraction-limited lens, with mean higher-order aberrations (also termed irregular

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Astigmatism







Corneal astigmatism: frequency

ARCHITE

Prevalence of corneal astigmatism before cataract

surgery

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cornealer Astigmatismus vor Katarakt OP [Dpt]

$58\% \le 0,5D$; $70\% \le 1D$ high astigmatism (>3D) rare!





Corneal astigmatism: measurements



Kerat

Important for measurements:

- Measure 2 or 3 times to confirm results
- Prior ocular surface optimization (artificial tears)
- Measure anterior and posterior astigmatism if possible

Kohnen T et al. Standards for analyzing astigmatic outcomes. Part I: Astigmatism basics. J Cataract Refract Surg (in press, 6/2025)

CT





Studies on posterior corneal astigmatism

- The mean magnitude of CApost was appr. -0.3 D
 - Ho et al. (2009): -0.33 D (0.00–0.94)
 n = 493, Scheimpflug imaging (Oculus Pentacam)
 - Koch et al. (2012): -0.30 D (0.01–1.10):
 n = 715, Scheimpflug imaging (Ziemer Galilei DAS)
 - Tonn et al. (2014): -0.33 D ± 0.18
 n = 3818, Scheimpflug imaging (Oculus Pentacam)



- Incoming parallel rays are refracted through the anterior and posterior corneal surface (in accordance with Snell's law)
 - with real refraction index numbers (1 for air, 1.376 for cornea, 1.336 for aqueous)
- refracted rays, instead of parallel rays, reach the posterior corneal surface





Lens tilt as an influence on astigmatism





Kohnen T et al. Standards for analyzing astigmatic outcomes. Part I: Astigmatism basics. J Cataract Refract Surg (in press, 6/2025)



What is known

REVIEW/UPDATE

Standards for analyzing astigmatic outcomes: part I: astigmatism basics

Thomas Kohnen, MD, PhD, FEBO, Kristian Næser, MD, DSMC, Jack T. Holladay, MD, MSEE, R. Doyle Stulting, MD, PhD, Li Wang, MD, PhD, Adi Abulafia, MD, PhD, Douglas D. Koch, MD

- Astigmatism is the difference between the two main orthogonal planes of a toric surface or lens
- Over 60% of people have more than 0.5 D of corneal astigmatism
- With more cataract and elective lens surgeries, predicting residual astigmatism has become crucial
- Despite many measurement methods, inconsistent terminology and approaches hinder comparisons



What this paper adds

REVIEW/UPDATE

Standards for analyzing astigmatic outcomes: part I: astigmatism basics

Thomas Kohnen, MD, PhD, FEBO, Kristian Næser, MD, DSMC, Jack T. Holladay, MD, MSEE, R. Doyle Stulting, MD, PhD, Li Wang, MD, PhD, Adi Abulafia, MD, PhD, Douglas D. Kock, MD

- We suggest a consistent use of terminology and provide clear explanations and definitions for measuring astigmatism
- The integrity of the ocular surface is critically important for accurately measuring corneal astigmatism
- We provide clear and accurate astigmatism reporting guidelines based on sound optical principles





Standards for Analyzing Astigmatic Outcomes

Part II: Recommended Statistical Methods





Douglas D. Koch, MD¹ Jack T. Holladay, MD, MSEE¹ Kristian Naeser, MD, DSMC³ Adi Abulafia, MD, PhD² Li Wang, MD, PhD¹ R. Doyle Stulting, MD, PhD⁴ Thomas Kohnen, MD, PhD, FEBO⁵





REVIEW/UPDATE

Standards for analyzing astigmatic outcomes Part II: Recommended statistical methods

Dunglas D. Kuch, MD, Jack T. Holluday, MD, MSEE, Kristian Narser, MD, DSMC, Adi Abulafia, MD, PhD, Li Wang, MD, PhD, R. Doyle Stalling, MD, PhD, Thomas Kolmen, MD, PhD, FEBO

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J Carantet Reflect Guy 2005, eth-6 Copylight & 2005 Aubiliand by Indiana Navier on benefit of ASO/IS and ESO/IS.

This second paper produced by the Journal of Catstart 6- Semactive Surgery astignation working group describes the recommended methodology for analyzing satigmatic onto miss. This approach is based on the optics of connect and iteratival astignations as well as contemponey vector analysis and statistical approaches. The term "astigmation" will be used throughout this

eaction of the document to indicate regular astigmation.^{1,15} Surgically induced astigmatism (31A) is the astigmatic component of the sangically induced refractive change (SBIC). The SECC can be bricken down into spherical equivalent and astigmatic (SLA) components. The opherical equivalent of a refraction is characterized by a single mimber. By contrast, astigmation is characterized by both a quantity and a direction.² As will be discussed below, estigmatic analysis of the SLA includes both universite and invariate analysis.

Repair astgradian can be expressed in plus minus, or cross-cylinder format. The plus lemma is used for his communication. A tork refractive surface is characterized by its prefrageral pensipal mandams of maximal and minuted power the magnitude of astgradian M (M > C) is the absolute difference on preservoir time principal metrikane. The direction of astigmation Θ is defined as the metidian at most positive (or least negative) power. The natigmation M along for metrikan Θ is symbolicial as (M $\notin \Theta$).

NONVECTOR METRICS

The magnitude of the reflective astignation—imagnetive of disation—is a producter of visual function. Therefore, comparing the magnitudes of preoperative and postoperative antigonation or residual postoperative astignation from maliple independent decases, independent of astignatic direction, is a valuable component of astignatic reported (II) mean and median refractive astignation with SDs and tanges and (2) percentages of eps with postoperative refinitive astignation (or connex) astignation as a statistic) within cartain diopine intervals, speadly \$4.25 display (I), 0.50 10, 0.57 10, 1.06 10, and 1.10 dipending on the dataset. Substitution comparising on the dataset astignation as a statistical substitution.

Although the goals of refractive corneal surgery and catatact surgery with forte intraocular lenser (IOLs) are the

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Analyzing astigmatic outcomes

- 1. What do we want to know?
 - How well does the patient see...uncorrected vision
 - But it is affected by spherical error so not specific enough
 - Actual amounts of residual astigmatism: scalar values
 - How accurate are the outcomes compared to the predicted: vector prediction error





Analyzing astigmatic outcomes

- 2. What do we want to know?
 - Refractive astigmatism: scalar values
 - % of eyes with ≤ 0.25, 0.5, 0.75 D etc.
 - Especially useful for procedures that target 0 astigmatism, eg, LASIK





Figure 1: Cumulative histogram of dioptric bins







Analyzing toric IOL astigmatic outcomes

- How accurate is the formula for hitting the predicted targets?
 - More complicated for toric IOLs
 - The target is not zero due to 0.75 D IOL steps at IOL plane





Analyzing astigmatism outcomes

- Complicated!
- Astigmatism has 2 variables:
 - Power or magnitude
 - Meridian or axis
 - You don't get reliable information by analyzing either in isolation
 - Bivariate analysis is mandatory





What variables should we analyze?

3. We want to compare the magnitude <u>and</u> angle of the postop refractive astigmatism to predict:

- Vector prediction error
- Vector difference between "Actual" and "Predicted"
- This describes the true accuracy of the formula/procedure
- Critical data in order to refine formula and procedures to improve outcomes





To analyze astigmatism

- Break it down into cartesian values:
 - $x = C^* \cos(2^* \alpha)$
 - y = C*sin(2*α)
- Perform calculations on x and y separately
- Reassemble x and y into the astigmatic value in conventional notation





Single-angle vs. double-angle plots











Example of pre- and postop data







What about statistical analysis

- You can have a mean error—centroid--of zero and a huge spread (large confidence ellipse)
- You can have a small spread but a large mean error
- Only the *vector prediction error* takes both into account





Example comparing formulas





Toric IOL calculation with Abulafia-Koch





Why can't we analyze power & angle separately?

• Because it gives incorrect answers

ARTICLE

Rethinking the optimal methods for vector analysis of astigmatism



Douglas D. Koch, MD, Li Wang, MD, PhD, Adi Abulafia, MD, Jack T. Holladay, MD, Warren Hill, MD

Purpose: To evaluate the accuracy and usefulness of certain methods of analyzing astigmatic vectors.

Setting: Cullen Eye Institute, Baylor College of Medicine, Houston, Texas.

Design: Case samples.

Methods: Using 2 sample cases for analysis of corneal surgically induced astigmatism and an actual toric intraocular lens (IOL) case, univariate analyses from the ASSORT program were compared to double-angle plots of preoperative and postoperative astigmatism and prediction errors. Results: Certain univariate figures for analyzing the 2 sample cases were misleading. For the toric IOL case, some of the key outcome vectors were inaccurate.

Conclusions: ASSORT's univariate analysis of astigmatic vectors can be unpredictably erroneous and misleading. Recommended vector analyses should include double-angle plots with centroids and confidence ellipses of preoperative and postoperative astigmatism and the prediction errors, along with means and standard deviations of these vector magnitudes.

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1



Statistics: new insights in bivariate analysis

- Data are not normally distributed
- Requires different stats than have been used in the past
- Holladay et al: R Project for Computing (Rand Wilcox)
- Instead of ellipse: convex polygon to display the data

ARTICLE

Astigmatism analysis and reporting of surgically induced astigmatism and prediction error

Jack T. Holladay, MD. MSEE, Rond R. Wilcox, PhD, Douglas D, Koch, MD, Li Wang, MD, PhD

Purpose: To provide a method for determining the vector the , when added to the preconstition satignation, results in no prediction error (PE) and to specify satisfied methods for evaluating velocities are independent only the WMA contribution convex or given.

Setting: Baylor College of Machine, Hoaston, Taxas, and University of Southern California. Los Angeles, California.

Design: Petrospective consecutive case series

Mathedia: An energy and 3 classed undering the interview performed. 3 formulas were easilabled (generic ways can be the energy of the case) ways performed a section of a specially included ways related (generic ways energy of the table case) before a section of the section of the energy of the section of

Fasults: The mean values for the vector scordule enjoys ion. PEs wore not of least if or the 3 formulas and 3 debases. The Barrett and Holistavitor e calculators were statistics y superior to the vector controls for 3 mervels (0.4%, 1.3), and 1.3(%) in the high antigradient debasel.

Conclusions: Fits dual ast grantism and vester coselute ast planarism FE mean values and SDs are useful out require doctored y large doctores to dome tot ore a profisical difference, whereas essenting proceedings in C25 directors (b) steps from 2.65 to 2.0 Directails of foreness with fair fever occess clarge hore whereas the a *P* value. Details angle plots are expenditly useful to 4 sub as a to grantic vector FEs, and a DFN confidence convex polygen shells the case when donite Lorse neuron Casesian.

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1



Wrap-up function in R

- Simplify the use of 28 functions
- Perform analysis in a batch mode
- Only need to upload data once for all analyses:
 - IOL power calculation
 - Astigmatism analysis

Statistics of Prediction Error



	Spherical Equivalent (Mean≠	0)
7 8	9 10	11 12
Mean	Median	MeanAE
13 14	15 16	5 6
MedianAE	RMSAE	Intervals









Mean Convex Polygon Preop_Corneal_Astig

Mean Convex Polygon Postop_MR_astig









ARTICLE

Spherical equivalent prediction analysis in intraocular lens power calculations using Eyetemis: a comprehensive approach

2

Youv Ken-Tor, PhD, Adi Abulafie, MD, PhD, David Zedok, MD, Thomas Kohnen, MD, PhD, Giacomo Serini, MD, Kenneth J. Hoffer, MD, Yuost Benjamini, PhD

Purpose: To compare 3 different parameter, camp Experime, an online ansighted too designed to reasoning the phrecial equinalant predictor errors (2000-Pto), of intracular lane (EO) power solutions formales after outstand surgers.

Setting: het.kine.

Deskgr: Famospective case series.

Methods: The study completed 2 distinct surgery. Dataset 1 inducts standardsree successful calance aurgery. Dataset 1 inducts standard sets, whereas Dataset 2 induces was with induced standard sets, whereas the Standard 2 induced access the 2 docests, admining to SC deputients for evoluting accurse, based on fournames and process. The load incorporate induced instants are proceed. The load incorporate obsard 1 tests for comparing the immund mean of the data, adlated to the tests socialized by CC, induced 1, SPR/T, Helps, and Damet Universit # Stall, tormales in Dataset 1, seen orderate from the SCL we want were used for the comparison on the test social sector with the very complete the comparison.

Evaluating and comparing prediction accuracy of intraocalar lens (1013 power calculations after cataract surgery are essential for improving the ourcomes in dinical practice and for enabling researchers to make significant advancements in the field. It has been more than 4 docades since Hoffer KI introduced a systematic approach to evaluate the precision of 101, power calculation formulas, methods, and instruments in the field of ophthalerology. Since then, many publications and updates focusing on reviews methodologies for analysis and reporting outcomes have been published.^{1,14} of the ISUB and its designated KOV version: Bantel Track Herstoconce (Track (KON)

Results: For Denated 1, the triansed mean SEG-PE values of all formation were not algorithment from zero, IUUE test approximation and accuracy compared with all other formatio, assorption Heighs (P < 0.4). For Dataset 2, SUM is triangle disputed means SEG-PE was algorithment from zero (0.59 dispute (D), P < 0.11, unlike the Truck OCC4 (0.10 D, P < 10), in addition, Truck (OCC4 (0.10 D, P < 10), in addition, Truck (OCC4 (0.10 D, P < 10)).

Conclusions. The online analysis lod provides a streamlined approach for assessing the penintron accuracy of SEG relations offer costance surgery, effectively evaluating travelase, precision, and sensel accuracy through the use of achierced statistics methods.

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Optimal analysis and comparison of postoperative spherical equivalent prediction errors (SEQ-PEs) pose considerable challenges. One challenges to the heteroscodarticity of the data, a condition where the dependent variable (SEQ-PE) exhibits unequal variance for different values of independent variables, such as axial length and lematometry. The heteroscodartic nature of these data was discussed at length by Holladay et al, who advocated that it should be addressed by applying adtoward statistical solutions, such as mixed to test, ⁵⁵⁶

Another challenge is constant optimization that leads to a zero mean SEQ-PE in the analyzed data sample, a process

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An online analysis tool for SEQ-PE & astigmatism assessment

- Provides a streamlined approach for evaluating SEQ-PE and astigmatism
- Analysis adheres to the ISO standards for Accuracy, encompassing both "trueness" and "precision"
- Utilizes robust t-tests (univariate and bivariate) to compare the trimmedmean of data, accounting for heteroscedasticity
- Includes standard threshold tests to ensure comprehensive analysis







Summary: Analysis of astigmatic outcomes

- Scalar values for magnitude of astigmatism
- Vector prediction errors
 - Double-angle plots for display and further analysis
 - Centroids and convex polygons
 - Stats using R 1 or Eyetemis 2
- JCRS committee submitted 2 position papers to establish these guidelines



Standards for analyzing astigmatic outcomes Part II: Recommended statistical methods

Dunglas D. Kuch, MD, Jack T. Holloulay, MD, MSEE, Kristian Naeser, MD, DSMC, Adi Abulafia, MD, PhD, Li Wang, MD, PhD, R. Doyle Studing, MD, PhD, Thomas Kohnen, MD, PhD, FEBO

- Astigmatism analysis requires both scalar and vector outcomes
- Vector prediction error is key to assessing changes from corneal or lens procedures
- Vector analysis uses double-angle plots, doubling axes or meridians

What is known

• Astigmatic data often deviate from normal distribution and need non-Gaussian methods



What this paper adds

REVIEW/UPDATE

Standards for analyzing astigmatic outcomes Part II: Recommended statistical methods

Dunglas D. Kuch, MD, Jack T. Holladay, MD, MSE5, Kristian Narser, MD, DSMC, Adi Abulafia, MD, PhD, Li Wang, MD, PhD, R. Doyle Studiing, MD, PhD, Thomas Kolmen, MD, PhD, PEBO

- We present a full method to analyse astigmatic outcomes using both scalar and vector values
- We suggest statistical tools suited for both normal and non-normal data
- Two calculation tools are introduced to simplify and standardise astigmatism analysis
- These are the recommended methods for reporting in JCRS





Setting standards for astigmatism analysis (editorial)

Standards for Analyzing Astigmatic Outcomes

Part I: Astigmatism Basics Part II: Recommended Statistical Methods

June 2025 issue



Journal of Cataract & Refractive Surgery*

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Thank you for your attention and the invitation to Egypt

Thomas Kohnen



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