Corneal back surface power – interpreting keratometer readings and what predictions can tell us

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Corneal back surface power – what does the keratometer say or predictions tell us?

Achim Langenbucher[1], Timo Eppig[1], Simon Schröder[1], Alan Cayless[2], & Nóra Szentmáry[3,4]

[1] Department of Experimental Ophthalmology, Saarland University, Homburg/Saar, Germany

[2] School of Physical Sciences, The Open University, Milton Keynes, United Kingdom

[3] Dr. Rolf M. Schwiete Center for Limbal Stem Cell Deficiency and Aniridia Research, Saarland University

[4] Department of Ophthalmology, Semmelweis-University, Mária u. 39, 1085 Budapest, Hungary

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Corresponding author:

Prof. Dr. Achim Langenbucher

Department of Experimental Ophthalmology

Saarland University

Kirrberger Str 100 Bldg. 22

66424 Homburg, Germany

Tel: +49 6841 1621218

Email: achim.langenbucher@uks.eu

Abstract

The classical Javal's rule allows estimation of refractive cylinder from keratometric astigmatism using scaling for vergence transformation, with an additional half dioptre of cylinder against-the-rule. With increasing popularity of toric intraocular lenses it has been shown that keratometric astigmatism does not fully reflect the entire astigmatism of the phakic or pseudophakic eye.

Researchers mostly argue that this mismatch is primarily due to astigmatism of the corneal back surface, and some papers propose correction strategies to consider this mismatch with the keratometric values. In this Technical Note we address this issue using a vector analysis and show the consequences of this correction on the front and back surface as well as total astigmatism of the cornea. As examples we focus on the correction strategies proposed by Abulafia and by Savini, frequently used in clinical practice.

The main conclusion is that, since corneal tomographers do not systematically show zero total astigmatism in situations where keratometry measures astigmatism against-the-rule of around 3 dioptres, there may be reasons other than the corneal back surface for this mismatch between keratometry and total astigmatism. A number of possible sources of this mismatch are proposed.

Key words:

Total corneal astigmatism, corneal back surface astigmatism, keratometric astigmatism, correction

Text body

Keratometry is a traditional optical method for measuring the curvature of the corneal front surface. The principle involves measuring a virtual image of two reference marks projected onto the cornea and reflected from the corneal tear film. With some simplifications the height of this image is proportional to the radius of curvature of the corneal front surface. This technique was later adopted for videokeratoscopy or Placido topography.

Keratometry typically outputs corneal power. The cornea is a meniscus lens with a convex front surface and a concave back surface. Since keratometers are basically restricted to measuring corneal front surface curvature, corneal power is estimated from front surface radius based on several assumptions. These include a fixed ratio of front to back surface radius, fixed central thickness, and predefined refractive indices of air (n_a), cornea (n_c), and aqueous humour (n_{ah}). Additionally, although the cornea consists of layers with differing optical properties, a simplified model with constant refractive index is usually used.

The conversion from front surface radius to corneal power uses a default value for the keratometer index, either $n_k = 1.332$ (Zeiss calibration) or $n_k = 1.3375$ (Javal calibration). Both are based on the schematic Gullstrand model eye from 1909, with front and back surface radii of 7.7 and 6.8 mm respectively, central thickness of 500 µm and refractive indices $n_a = 1.0$, $n_c = 1.376$, and $n_{ah} = 1.336$. Using this Zeiss / Javal calibration gives a corneal power of 43.12 / 43.83 dpt for the Gullstrand model eye, referring to the corneal front vertex / back vertex power of the cornea respectively.

From Javal's rule or Grosvenor's modifications (2) we know that the internal astigmatism of the eye adds around half a dioptre against-the-rule and therefore the total astigmatism is not fully reflected by the keratometric measurement. From cataract surgery with implanted intraocular lenses (IOL) we note that even when replacing the crystalline lens with a rotationally symmetric artificial lens, keratometric astigmatism (KA, orientation Kaxis between 0 and 180°) based on measurement of the corneal front surface somewhat overestimates the astigmatism in situations with-the-rule and underestimates in situations against-the-rule. This implies that lens astigmatism is not the only reason for mismatch between KA and refractive cylinder.

In the last 5 years several researchers have addressed this issue (1,3-8). In 2016 Abulafia (1) and in 2017 Savini (8) analysed a series of eyes after cataract surgery with keratometry (or corneal topography) and refractometry, and developed regression formulae for deriving the total corneal astigmatism (TCA) from the KA for use e.g. in toric IOL power calculations. With others (3,4,6,7) they argued the missing link between KA and TCA to be the astigmatism of the corneal back surface making a systematic contribution of astigmatism against-the-rule (1,8).

In this Technical Note we would like to elucidate the terms front and back surface (FA, BA), and keratometric astigmatism (KA) of the cornea in more detail and present to ophthalmologists the clinical consequences of both papers. A commonly used graphical representation for astigmatism is the *double-angle plot* (Jaffe and Clayman (9), Holladay (10)). Since astigmatism is a cylindrical correction, it is symmetrical under a rotation of 180 degrees. In the double angle representation, this variation is presented on a polar plot over the full 360 degrees, with each two degrees on the plot corresponding to one degree of change in the astigmatism axis. Thus, in this type of plot, an astigmatism axis of 0 degrees appears to the right of the plot, 45 degrees at the top, 90 degrees to the left and 135 degrees at the bottom, returning to 180 degrees at the right hand side (coincident with zero degrees). The magnitude of the astigmatism is plotted in the radial direction, from zero at the centre to 3 dioptres at the periphery. This double-angle plot, commonly used by ophthalmologists and clinicians, has the advantage that with-the-rule values are displayed on the left, and against-the-rule values on the right. In a mathematical formulation, we plot $KA\cos(2*K\text{axis})$ and $KA\sin(2*K\text{axis})$ on the x and y axes respectively.

In all plots, the astigmatism axis is indicated at multiple positions by blue lines. For this purpose we used a representation of spherocylindrical power of the cornea using vergences. All calculations were performed using a vector representation as described by Alpins (11). Without restricting generality, initial assumptions include a keratometric equivalent (KEQ) power of 43.11 dpt and a corneal thickness of 500 µm. Refractive indices and the ratio of front to back surface radii were adopted from the Gullstrand schematic model eye.

Figure 1 shows the calculation strategy. For simplicity the scheme is restricted to astigmatism, but all calculations were performed with spherocylindrical vergences. The x-y-plane of all plots refers to a double-angle representation of KA, and the absolute value / axis orientation of the target variable stated in the title of the plot is indicated by short blue lines. The steps detailed below correspond to the numbered labels in Figure 1:

1) KA is shown in a double-angle plot as described above.

2) KA is split into FA and BA astigmatism, respectively. Front surface equivalent and astigmatic power are derived from KEQ and KA by multiplying both cardinal meridians by $(n_c-1)/(n_k-1)$, and back surface equivalent and astigmatic power from KEQ and KA by multiplying both meridians by $(n_a-n_c)/(n_k-1)$.

3) The vergence (FEQ with FA) is transformed to the back surface plane of the cornea.

4) After adding in the back surface astigmatism BA we obtain the uncorrected total corneal astigmatism at the back surface plane.

5) The astigmatic correction (COR) provided by Abulafia (1) or Savini (8) is added to the FA to obtain the corrected front surface astigmatism FAc.

6) The vergence (FEQ with FAc) is transformed to the back surface plane of the cornea.

7) After adding in the back surface astigmatism BA we obtain the corrected total corneal astigmatism at the back surface plane.

8) The difference of the corrected (top 7) and uncorrected (top 4) vergences yields the astigmatic correction at the back surface plane (CORb).

9) The correction at the back surface plane is added to the BEQ and BA to obtain the refractive power of the corneal back surface as proposed by Abulafia and Savini .

Figure 2 shows the calculation result for the total corneal astigmatism TCA using the correction published by Abulafia (1) (2c) or by Savini (8) (2d). In both papers the correction has to be considered for KA, but describes the effect of corneal back surface astigmatism. If transformed to the corneal back surface based on the strategy explained above and shown in Figure 1, this yields a corrected back surface astigmatism as displayed in Figure 2a (Abulafia) or Figure 2c (Savini), respectively.

The neutral point on a double angle plot refers to the keratometric astigmatism vector where the total corneal astigmatism is zero. Ideally, when no correction is required, the netural point should fall in the centre of the plot (i.e. at the origin). If the neutral point does not lie in the centre, this implies that a correction is required. From Figures 2b and d we see that the 'neutral point' TCA (asterisk) is no longer central, but shifted to the right by around half a dioptre. This means that for both correction concepts zero TCA is expected for a measured KA of around half a dioptre with-the-rule. Assuming that the keratometer correctly measures corneal front surface curvature (invariant to rotation) and that this correction should be considered at the back surface plane according to the calculation strategy shown in Figure 1, then Figure 2a shows that BA is expected to be zero with a measured KA of around 2.7 dioptre against-the-rule (asterisk, Abulafia), and Figure 2c shows that BA is expected to yield zero values for all KA values located on the dashed circle in the double angle plot (Savini).

Take home message:

In the literature, keratometric or topographic astigmatism is often misunderstood as astigmatism of the corneal front surface, and the astigmatism of the corneal back surface ignored. Following the assumptions of a keratometer, the fixed ratio of front to back surface curvature means that keratometric astigmatism must be split into a front surface astigmatism (somewhat higher than keratometric astigmatism with the same axis orientation) and a back surface astigmatism (much smaller and with an axis orientation perpendicular to keratometric astigmatism, which in part compensates the front surface astigmatism).

Assuming that total corneal astigmatism as provided by keratometry requires some correction, and also assuming a proper corneal front surface measurement, this correction must consequently be considered at the corneal back surface (1,3-8). This means that in a double angle plot of KA, TCA no longer has its neutral point (zero astigmatism) in the centre. Instead, if the keratometer measures values around half a dioptre with-the-rule, the total corneal astigmatism should be zero on average.

If the corneal back surface curvature is held responsible for the mismatch between keratometric astigmatism and total corneal astigmatism as proposed in many papers (e.g. Abulafia and Savini), this means that the neutral point of corneal back surface astigmatism no longer matches the neutral point of keratometric astigmatism, but is somehow shifted to the left in the double angle plot. For the correction proposed by Abulafia, the corneal back surface should have zero astigmatism in situations where the keratometric astigmatism shows around 3 dioptres astigmatism against-the-rule (Figure 2a), and for the correction proposed by Savini the corneal back surface is expected to have zero astigmatism in all situations of keratometric astigmatism indicated by the ring shaped structure at Figure 2c.

Since modern corneal tomographers based on scanning or rotating slit projection technology or optical coherence topography can measure corneal front and back surface curvature, and given that the corneal back surface astigmatism does not systematically show zero astigmatism in situations where keratometry measures astigmatism against-the-rule of around 3 dioptres, there may be other reasons than the corneal back surface for this mismatch between keratometry and total astigmatism of the eye. This mismatch could also result from tilt (angle kappa), decentration of the lens or a decentred fovea causing a tilt of the visual axis in the eye.

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Figures

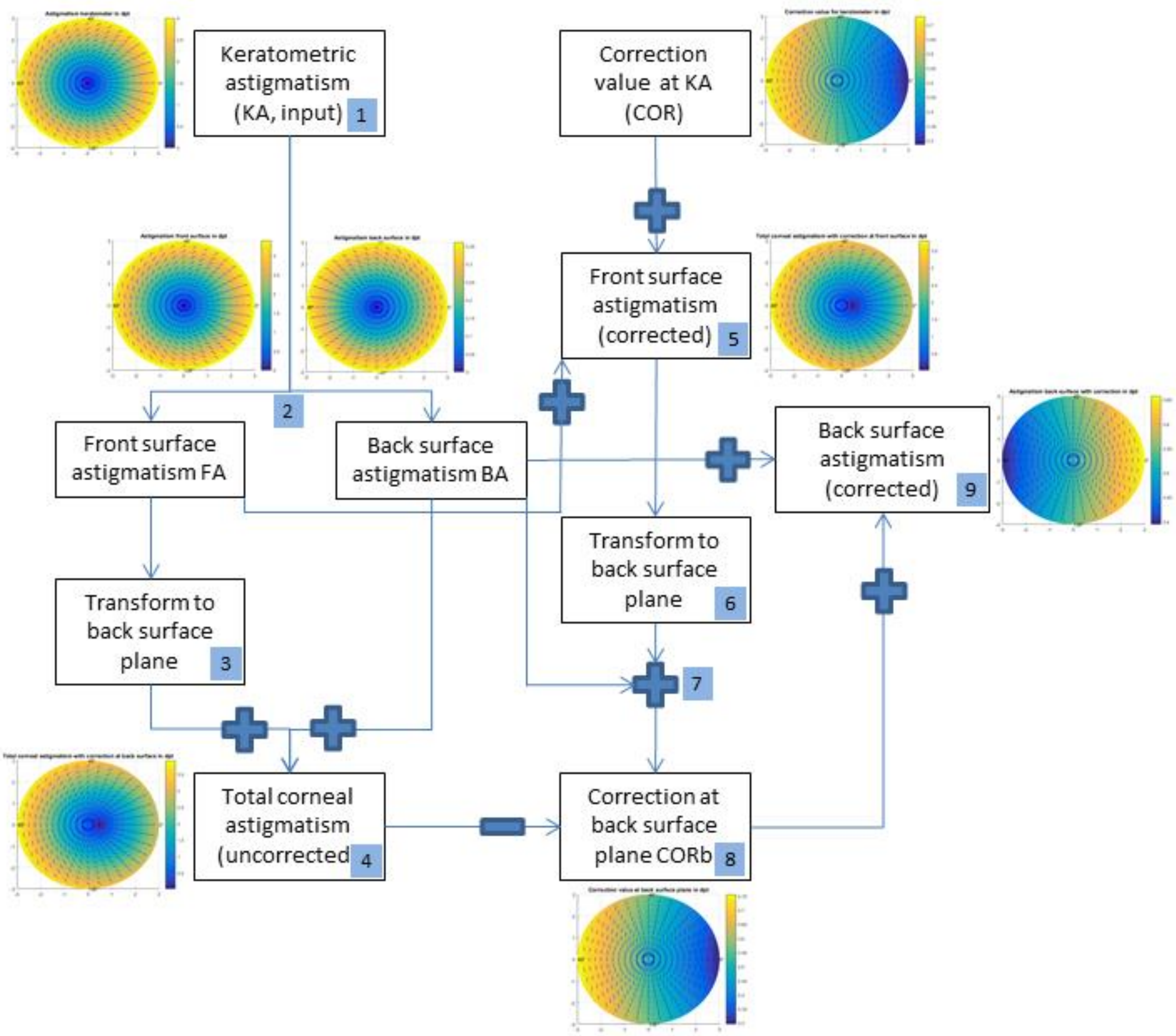

Figure 1: Strategy of deriving the back-surface astigmatism from keratometric astigmatism and correction value as described by Abulafia (1) or Savini (8). This figure uses as an example the correction value published by Abulafia. Keratometric astigmatism is split into front surface and back surface astigmatism: the front surface astigmatism is larger than the keratometric astigmatism and the back surface compensates the front surface astigmatism in part (axis is flipped by 90°). If we subtract the uncorrected total corneal astigmatism from the corrected total corneal astigmatism, we obtain the correction at the back surface plane. Adding this correction to the back-surface astigmatism we obtain the corrected back surface astigmatism as a target variable.

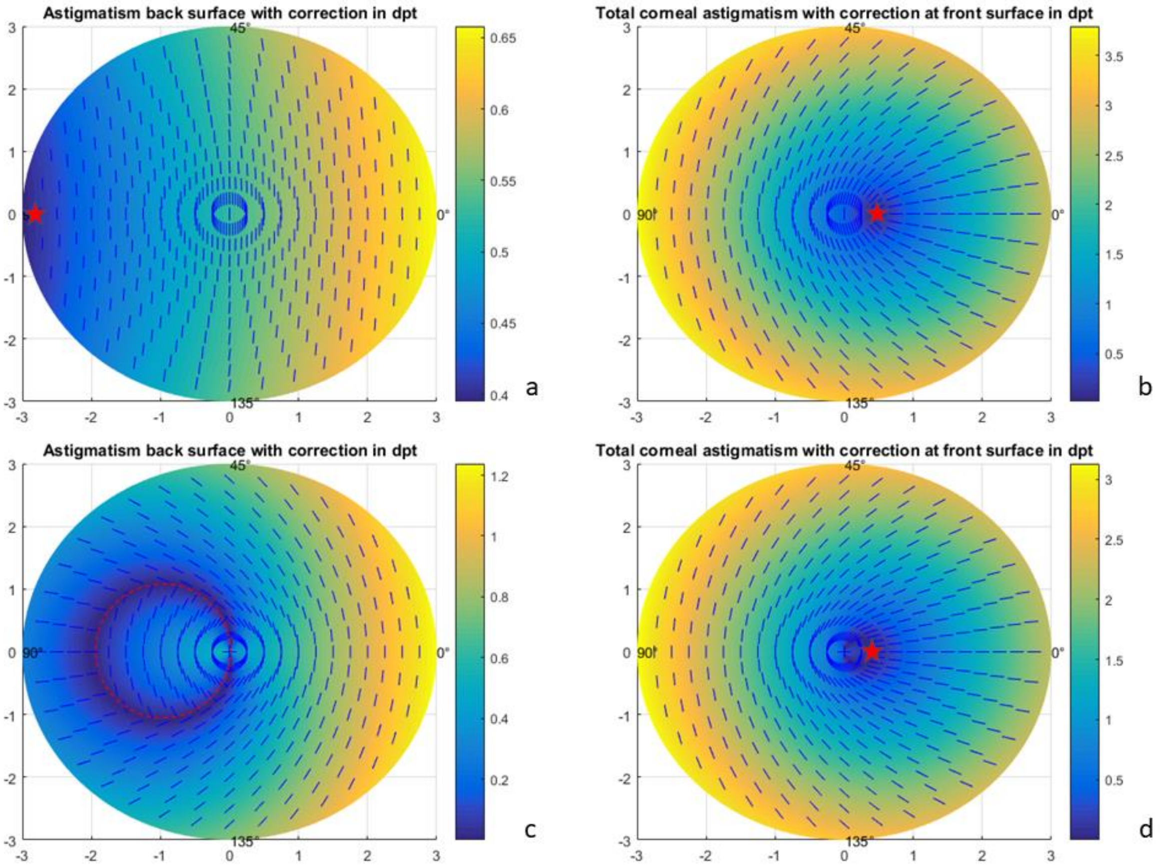

Figure 2: Total corneal astigmatism TCA with correction according to Abulafia (1) (Figure 2b) and Savini. (8) (Figure 2d) and respective corrected back surface astigmatism BA (Figure 2a and c) in a double angle representation derived from the calculation scheme shown in Figure 1. The absolute value of the astigmatism is colour coded (range shown on the colour bar), and the orientation of the astigmatic axis is shown with short blue lines in each plot, where horizontal lines refer to an astigmatic axis at 0°/180° and vertical lines to an axis at 90°/270°. The asterisks in Figure 2c and d indicate that for a KA of around 0.5 dioptre with-the-rule (0°) the TCA is expected to be zero. The asterisk in Figure 2a and the dashed circle in Figure 2c indicate that for a KA of 2.7 dioptres against the rule (90°, Abulafia) or KA values located at the ring (Savini) the BA is expected to be zero. Inside the circle the astigmatic axis is flipped by 90°.