

Repeatability of measurements made with a Nidek autokeratometer ARK-700 on a test eye*

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Abstract

The purpose of this paper is to explore the repeatability of keratometric measurements as obtained with a Nidek autokeratometer ARK-700 on a test or artificial eye. Thus an automated keratometer was used on three separate occasions to obtain 40 successive autokeratometric measurements per occasion for the selected test eye. All radii of curvature obtained were transformed to dioptric powers and this data was studied using stereo-pair scatter plots and other methods. Hypothesis tests

were conducted to investigate differences between the means and variance-covariance matrices for the three samples. Although the means and variance-covariance matrices were statistically different (at a 95% level of significance) the differences from a clinical perspective were small.

Key words: autokeratometry, artificial, model or test eyes, repeatability, variability, short-term corneal variation

Introduction

Autokeratometers have become increasingly common in both clinical and research environments. The repeatability of these instruments needs to be known and understood so that clinicians and experimenters can determine how great the difference in repeated measurements must be to signify a real change in the measurements. In addition, accuracy and repeatability are important so that users are confident the devices provide a true measure of the surface curvature and power.

Multiple automated measurements have become a common source of data for many researchers¹⁻¹⁰. For

this reason one needs to be confident that the instrument provides accurate and repeatable measures of surface autokeratometry. Keratometric measurements are not constant, but vary continuously throughout the day and from day to day^{3,6}. Variation can occur in all three components of dioptric power, namely, the stigmatic, ortho-antistigmatic and oblique antistigmatic components. Because a test or model eye is static it is a useful tool to investigate issues such as the accuracy and repeatability of multiple keratometric measurements.

Some studies¹¹⁻¹⁴ have been published that have investigated the repeatability of keratometric meas-

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urements and the performance of automated and manual keratometers, both as individual instrument and as comparison between instruments. However, their findings are not always particularly meaningful since they used statistical methods that are not entirely satisfactory. Sometimes the mean values were calculated by merely averaging values for sphere, cylinder and axis as three separate independent entities. Thus important aspects of keratometric behaviour were ignored such as keratometric change, nature of variation and covariation between the components, hypothesis testing and data distribution characteristics.

Methods¹⁵⁻¹⁸ are now available whereby a complete representation and analysis of the keratometric measurements can be conducted. Cronje and Harris³ compared the keratometric variation found with a manual and an automatic keratometer, both on an eye and on a steel ball. They found that an automatic keratometer exhibited less variation than a manual keratometer when measuring a steel ball, while comparable amounts of variation were found when measuring the eye. Dunn and Harris⁷ conducted a study to investigate the short-term keratometric variation in an eye. They used a Humphrey automatic keratometer to obtain 50 successive keratometric measurements on the right eye of a subject. They found that the keratometric measurements are not constant but exhibit variation. In another study by Cronje-Dunn and Harris⁶, the influence of a fluid layer on keratometric variation was investigated. Here repeated keratometric measurements were made on a spherical polymethyl methacrylate (PMMA) button. They concluded by suggesting that the tear layer may also contribute to the variation of keratometric measurements.

It is the primary purpose of this paper to compare multiple samples of autokeratometric measurements using a simple, and approximately, stigmatic test eye (the eye is not purely stigmatic due to limitations in the manufacturing process). A test eye was used as it is expected to be more stable and consistent and less complicated to study than the human eye. Studying autokeratometric variation under such conditions can assist towards better understanding variation when the same instrument is used on a human eye.

These samples or measurements were obtained at the beginning, middle and end of a period of time over which various measurements with this and other instruments were obtained as part of the overall experimental activity.^{19, 20}

Methods

A Nidek ARK-700 autokeratometer was used to obtain 40 successive keratometric measurements on a test eye (model S/N 10990 as supplied by the instrument manufacturer) on three occasions each separated by six months; thus the three samples were determined over a total period of approximately one year. The vertex distance of the instrument was set to zero and so measurements were obtained in the surface plane of the test eye. The nominal refractive state of the test eye was -4.65 D for a vertex distance of 0 mm. The nominal radius of curvature of the first surface of the test eye was 8 mm which corresponds to surface power 42.1875 or approximately 42.2 D, for the nominal refractive index 1.3375.

The test eye was mounted in a holder made especially for this purpose and the holder and eye was aligned with the measurement axis of the autokeratometer. This method, in a sense, simulated the situation applying to a human subject instructed to fixate upon a particular point on the instrument's internal target during measurements. After proper placement and focusing the operator button was depressed to obtain the required measurements. The instrument was refocused after each individual measurement. The test eye was stationary in the holder and an attempt was made to not move the eye or instrument table between measurements although the instrument itself needed to move during refocusing. Each measurement was printed directly after it was obtained. It took about 26 minutes to obtain each sample. Using the same instrument and test eye, measurements were obtained again after six months, and then after twelve months. At each of the occasions 40 measurements were obtained. Naturally, it cannot be said that the exact same point on the test eye was measured by the instrument during the second or third measuring occasion but we anticipate that the measurement region was likely to be similar.

Statistical analysis

For each measuring occasion, the principal radii of curvature from the autokeratometer were converted to dioptric power matrices using a standard keratometric refractive index of 1.3375. The data were analyzed using mathematical methods developed by Harris and software developed by Harris, Malan and Rubin. The methods convert sphero-cylindrical powers in clinical notation into dioptric power matrices¹⁵⁻¹⁸. Stereo-pair



scatter plots, variance-covariance profiles of dioptric power matrices and hypotheses on variance and variances were determined.

In its symmetric form the dioptric power matrix can be written as

$$F = F_I \mathbf{I} + F_J \mathbf{J} + F_K \mathbf{K}$$

where

$$\mathbf{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{J} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \text{ and } \mathbf{K} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

These symmetric powers were plotted on three mutually orthogonal axes representing stigmatic ($F_I \mathbf{I}$), ortho-antistigmatic ($F_J \mathbf{J}$) and oblique antistigmatic ($F_K \mathbf{K}$) powers respectively. In these three-dimensional graphs each point represents a distinct power. For a sample of powers, an arithmetic mean of the dioptric power matrices can be determined and the variation of dioptric power is described by a 3x3 symmetric variance-covariance matrix \mathbf{S} with six distinct entries

$$\mathbf{S} = \begin{pmatrix} s_{II} & s_{IJ} & s_{IK} \\ s_{JI} & s_{JJ} & s_{JK} \\ s_{KI} & s_{KJ} & s_{KK} \end{pmatrix}$$

where the diagonal entries s_{II} , s_{JJ} and s_{KK} are the variances and the off-diagonal entries $s_{IJ} = s_{JI}$, $s_{IK} = s_{KI}$ and $s_{JK} = s_{KJ}$ are the covariances. The units of the entries are squared dioptres (D^2).

Results

Table 1 provides various statistics for the first (a), second (b) and third (c) set of keratometric measurements on the test eye, respectively. For example, the mean powers, variance-covariance matrices and the volume of the ellipsoids of constant probability density containing an estimated 95% of the population measurements (all about $0.002 D^2$; they do differ if more significant numbers are included) are indicated. The three sample means in Tables 1a to c are all very similar and the same could be said generally for the three variance-covariance matrices for the samples. The variances are small for all three samples and differences are only noted in about the fourth digit after the decimal point. Mostly the covariances are nearly zero; thus suggesting little evidence for linear relationships between the variances of various components of power.

Table 1a. Statistics for the first sample of autokeratometric measurements on the test eye are given. The sample mean (power), sample variance-covariance matrix and the volume of the ellipsoids of constant probability density containing an estimated 95% of the population measurements are indicated.

First Sample	Keratometric measurements
Mean (D) Spherocylindrical power Dioptric power matrix	42.19 – 0.02 x 46 42.1763I – 0.0005J + 0.0121K
Variance-covariance matrix (D^2)	$\mathbf{S} = \begin{pmatrix} 0.0003 & -0.0002 & 0.0001 \\ -0.0002 & 0.0007 & -0.0002 \\ 0.0001 & -0.0002 & 0.0005 \end{pmatrix}$
Volume (D^3)	0.0021328

Table 1b. Statistics for the second sample of autokeratometric measurements of the same test eye. Details same as for Table 1a.

Second Sample	Keratometric measurements
Mean (D) Spherocylindrical power Dioptric power matrix	42.19 – 0.02 x 38 42.1837I – 0.0019J + 0.0078K
Variance-covariance matrix (D^2)	$\mathbf{S} = \begin{pmatrix} 0.0004 & -0.0000 & -0.0001 \\ -0.0000 & 0.0003 & 0.0001 \\ -0.0001 & 0.0001 & 0.0003 \end{pmatrix}$
Volume (D^3)	0.0015193



Table 1c. Statistics for the third sample of autokeratometric measurements of the same test eye. Details same as for **Tables 1 (a)** and **(b)**.

Third Sample	Keratometric measurements
Mean (D) Spherocylindrical power Dioptric power matrix	42.20 – 0.03 x 150 42.1829I – 0.0079J + 0.0137K
Variance-covariance matrix (D ²)	$S = \begin{pmatrix} 0.0002 & -0.0000 & -0.0001 \\ -0.0000 & 0.0008 & -0.0000 \\ -0.0001 & -0.0000 & 0.0006 \end{pmatrix}$
Volume (D ³)	0.0025535

Figure 1 shows stereo-pair scatter plots in symmetric dioptric power space representing the first (a), second (b) and third (c) samples of autokeratometric measurements taken on the test eye, each with its associated 95% distribution ellipsoid, respectively. The origin for each plot is at the sample mean given in Table 1. Each point shown represents one measurement of autokeratometry. Generally the samples indicate little variation about the mean of measurements. However, the orientations for the ellipsoids are different and in Figure 1 (a), for instance, the spread of measurements extends mainly parallel to the antistigmatic plane. In Figure 1 (b) the ellipsoid is more spherical in shape with greater spread along the stigmatic axis but with some antistigmatic variation also. Figure 1 (c) shows variation of an antistigmatic nature.

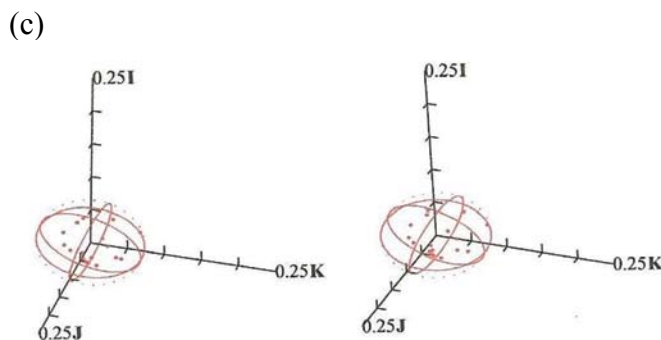


Figure 1. Stereo-pair scatter plots in symmetric dioptric power space representing the first (a), second (b) and third (c) samples, consisting of 40 autokeratometric measurements each, taken on the test eye over a period of about one year. The origin of each stereo-pair represents the applicable sample mean (see Table 1). The three mutually orthogonal axes represent the stigmatic, ortho-antistigmatic and oblique antistigmatic components of powers. Each point represents one autokeratometric measurement on the test eye (with anterior surface power of 42.2 D). The figures are stereo-pairs and should be viewed by allowing the eyes to drift into preferably an exo-posture (or, alternatively, by converging eyes to a point in front of the page) whereby a three-dimensional percept of the data can be obtained. Variation in autokeratometry is minimal for all samples.

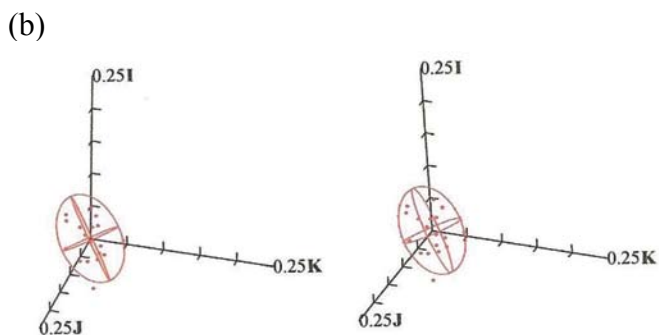
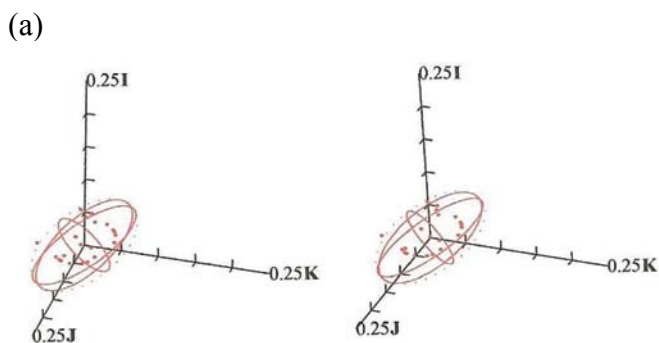


Figure 2 shows all the data of Figure 1 grouped in a single stereo-pair scatter plot and thus facilitating comparison of the test eye measurements for the three occasions. The main difference between the three ellipsoids is their orientation. The origin for this plot was the nominal power (42.20 D) of the first surface of the test eye.



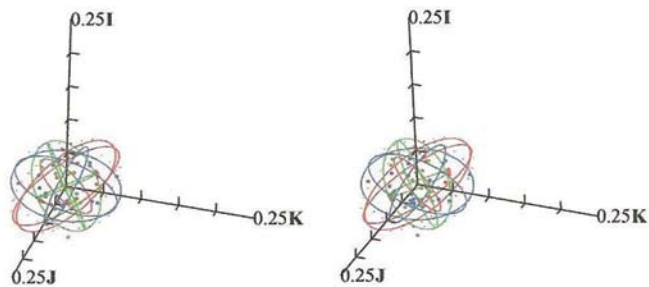
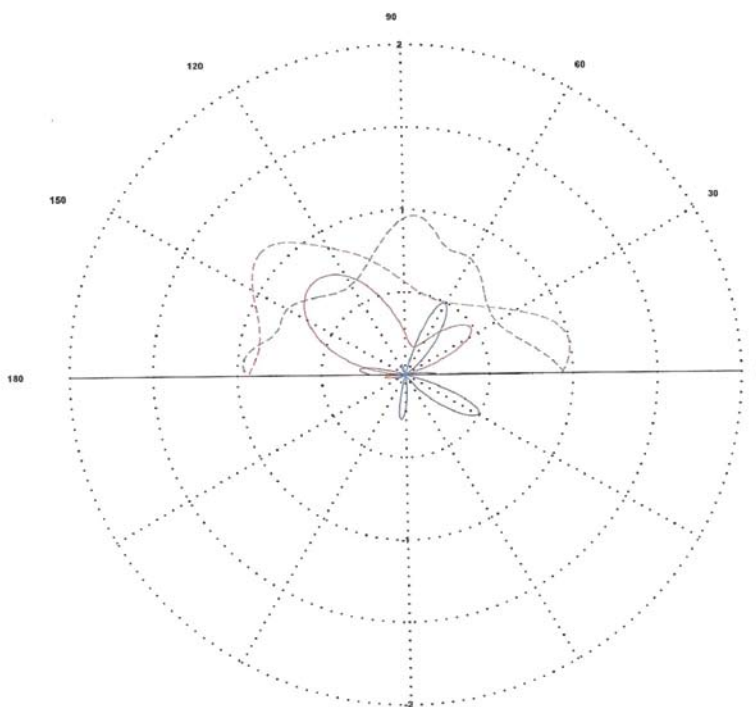


Figure 2. A comparison of the three samples of Figure 1 for the different measurement occasions is indicated. Red is used for the first, green for the second and blue for the third measurement occasion. The origin is the nominal power of 42.20 D in conventional terms.

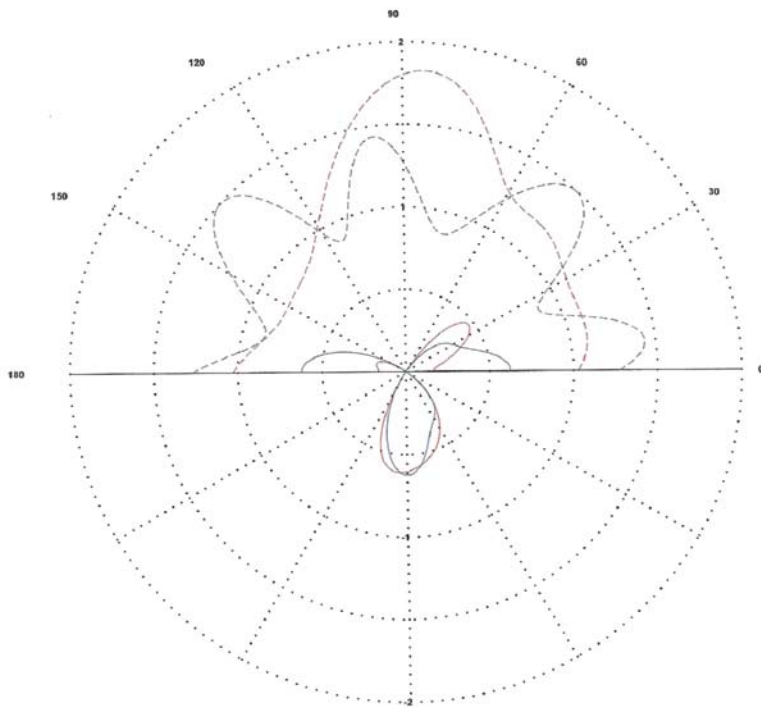
Figure 3 shows the profiles of skewness and 1/3 kurtosis representing the first (a), second (b) and third (c) occasions for measurements of the test eye. Such polar profiles provide a graphical presentation of

these statistics for f_{11} and f_{21} (of all power matrices F_i) for each meridian from 0 to 180°. From Figure 3 (a) one sees that there is a mainly mild platykurtosis for f_{11} and f_{21} . There is a positive skewness f_{11} for along 30° and 130°. For f_{21} there is a positive skewness along 60° and negative skewing along 90 and 150°. In Figure 3 (b) there is mostly slight leptokurtosis for f_{11} , and four local maxima of slight leptokurtosis for f_{21} . There is mild positive skewness along about 35° and 90° for f_{11} and mild positive skewness for f_{21} along 90° and 180°. In Figure 3 (c) there is a fairly uniform and mild leptokurtosis for both f_{11} and f_{21} . There is minor positive skewness for f_{11} along 30 and 80° and for f_{21} minor positive skewing along 30° and mild negative skewness along 120°. In summary, none of the samples exhibit serious departures from normality.

(a)



(b)



(c)

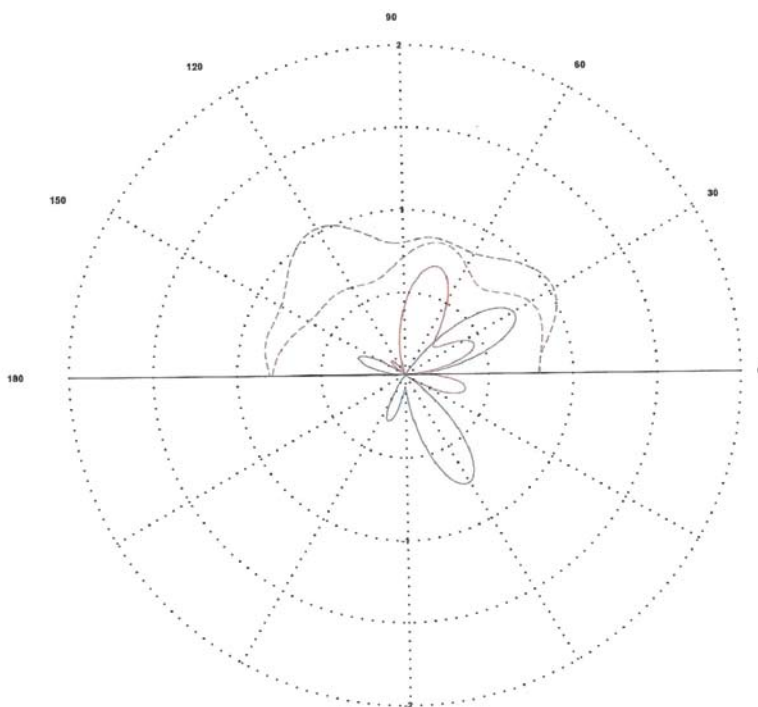


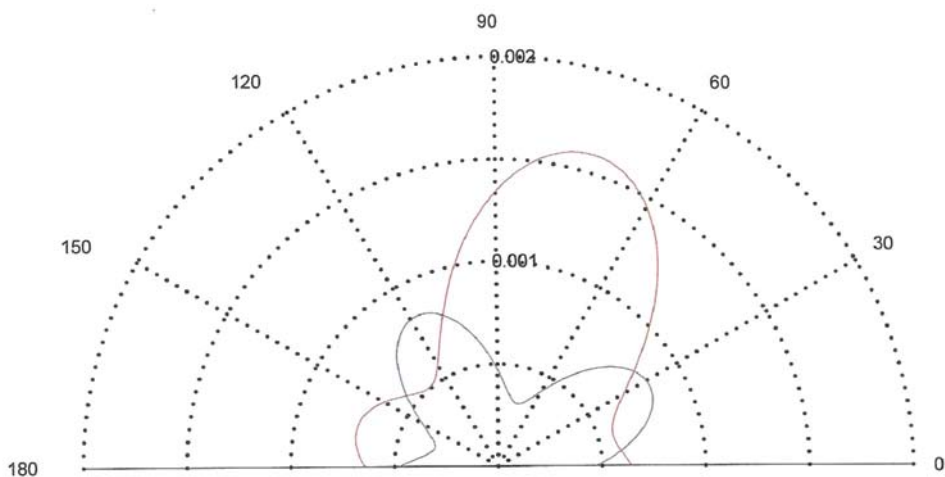
Figure 3. Polar plots of 1/3 skewness and kurtosis for meridians 0 to 180° for first (a), second (b) and third (c) occasions for auto-keratometry on the test eye. Solid lines represent skewness where red (= f_{11}) and blue (= f_{21}). Dashed lines represent kurtosis where red (= f_{11}) and blue (= f_{21}). Normal distributions have a skewness of 0 and a 1/3 kurtosis of 1. The radial coordinate has units D^2 .



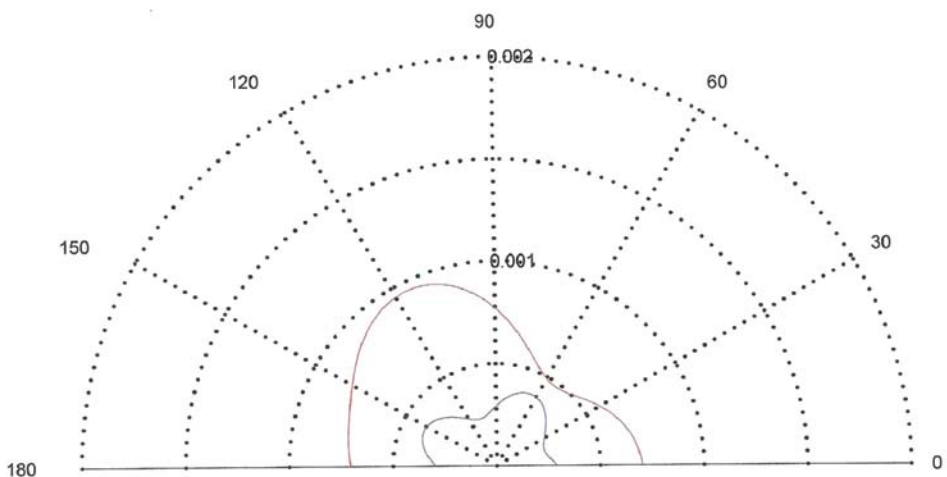
Figure 4 presents polar profiles of curvital (f_{11}) and torsional (f_{21}) variance for the first (a), second (b) and third (c) samples. Such profiles indicate the meridian(s) in which the components of power have maximum and minimum variation. These profiles give a visual representation of the curvital (f_{11}) and torsional (f_{21}) variances of autokeratometry across all meridians between 0 and 180° for the anterior surface of the test eye. Figure 4 (a) shows that for the greatest curvital variation occurred along meridians close to 80°. The torsional profile (f_{21}) has two lobes which are roughly symmetrical about 80°. It can be seen that the maximum variation occurred obliquely

in the 30° and 120° meridians while the minimum variation occurred in the horizontal and vertical meridians. Both the curvital and torsional variances were relatively small however. Figure 4 (b) shows the curvital profile elongated along the 115° meridian. The torsional profile is enclosed within the curvital one and so the torsional variance is less. The two lobes of the torsional power are roughly symmetrical about the 110° meridian. Figure 4 (c) shows an almost half circular curvital profile for f_{11} which indicates that the variance (of 0.001 D²) is close to being uniform across the meridians of the test eye.

(a)



(b)



(c)

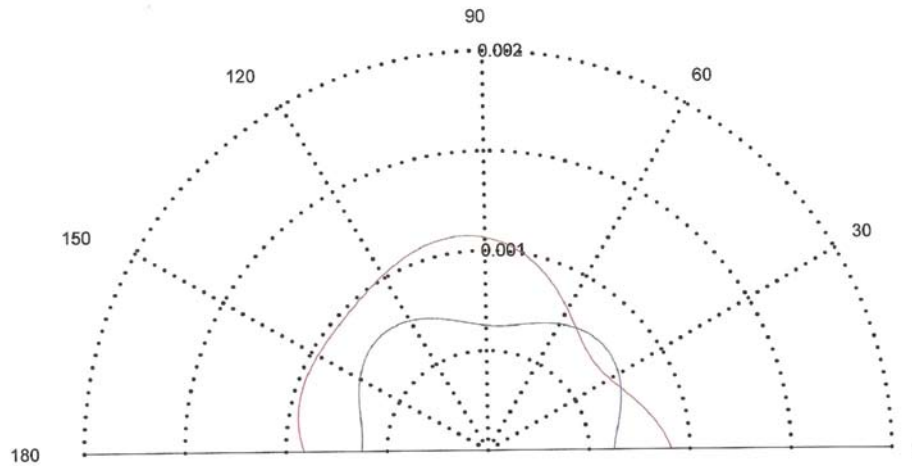


Figure 4. The polar profiles represent the variances for the first (a), second (b) and third (c) samples or occasions when the test eye was measured with an autokeratometer. Red and blue solid lines represent profiles for curvital (f_{11}) and torsional (f_{21}) variance, respectively. Such profiles can be used to determine the meridians in which the components of dioptric power have maximum and minimum variation.

Table 2 presents the results of hypothesis tests for multiple samples done on the variances and covariances. The test was done at a 95% level of confidence with the calculated value, $\mu \approx 33.003$ at $p = 0.05$. The null hypothesis was rejected since the calculated value was greater than the critical value (21.026). Thus

the alternative hypothesis indicates that the three variance-covariances matrices do indeed differ significantly at the level of confidence concerned (however, as earlier described the differences are very small from a clinical perspective).

Table 2. The results of the hypothesis test for the comparison of the three sample variance-covariance matrices (see Table 1). The level of significance is $p = 0.05$. The null hypothesis (H_0) of equality is rejected if the test statistic (μ) is larger than the critical value.

The χ^2 -distribution	Test statistic	Critical value	Result
$\chi^2 (0.05, 12)$	$\mu \approx 33.002988$	21.026	Reject H_0 ; the variance-covariance matrices are significantly different

Discussion

Variation of autokeratometric measurements is expected when multiple measurements are obtained using automated instruments, either over the short- or long-term on test or human eyes.¹⁻⁷ One of many factors which may play a role in variation could be variability due to possible complicated interactions between the subject or test eye, or the instrument and the instrument operator. This paper investigated the use of an automated instrument on a single test eye and found that minimal differences in keratomet-

ric variation were found between samples, despite these differences being statistically significant at a 95% level of significance. It is clear from the scatter plots (Figure 1) and Table 1 that from a clinical or practical perspective there is very little variation and the sample means are very comparable, except for the axes but since the cylinder powers are so small these differences in axis are clinically unimportant. Similar results for autokeratometry on test eyes have been reported previously³⁻⁵. The stereo-pair scatter plot representation used here allows for the display



of dioptric power in a manner that is both meaningful and through which a great deal of information can be more easily deduced. For all samples measured there was a tight cluster of measurements and thus minimal variation of autokeratometry on the test eye. (If there had been no variation, all the autokeratometric measurements would be represented by a single point only on each plot.)

In the study of the nature of variation of dioptric power, polar profiles of variation (Figure 4) have proven useful. They show how the variation changes across the meridians of the human or test eye and give clues to mechanisms or reasons underlying the variation.¹⁸ In Figure 4, curvital variances are mostly larger than torsional variances for corresponding meridians (although there are some exceptions). The variance-covariance matrices for the three samples (determined at six monthly intervals apart) were found to be statistically different at the 95% level of confidence. However, clinically, the differences are probably insignificant. Some of the reasons for these statistical differences include that there were differences between the mean cylinder axes for the three samples or another possibility is that slightly different points on the test eye were measured on different occasions. Also, the operator might have focused the instrument slightly differently on different occasions. Internal factors affecting the instrument might be other contributing factors perhaps. But the variances were very small on the test eye suggesting that results from the instrument were indeed remarkably repeatable. This might not be so true however for more complicated human and more dynamic eyes.

Conclusion

When comparing living eye measurements to the test eye measurements, the instrument itself appears to contribute little variation compared to that determined in a living eye. Because the amount of keratometric variation found when using the autokeratometer on the test eye is very small, it appears safe to assume that the keratometric variation found on the living eyes is mostly due to variation of the eye itself, or relating to the interactions between the eye and the instrument, but not to the instrument itself. Results of this study suggest that the Nidek ARK-700 autokeratometer provides clinically repeatable and accurate measures of keratometry on a test or static eye. But clinicians and researchers need to remember that the human eye is not static and thus greater variation can be anticipated when using such instruments.

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