New Possibilities of Corneal Diagnostics Using Videokeratometry (Part 1)

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Introduction

The market introduction in 1989 of the first videokeratometer based on the Placido principle marked the beginning of a new phase in corneal surface diagnostics. With earlier instruments local corneal radii were calculated by means of distance comparison, i.e. by comparing the distances between the individual rings of the Placido disk as reflected by the cornea with the corresponding distances in stored images of calibration globes of different sizes. While they were excellent for rendering spherical surfaces, these early instruments had great difficulty in determining the true shape of the cornea. Additional errors resulted from measuring results being distance-dependent (25). The contact lens fitting recommendations that were obtained from these instruments were consequently of little value (3). In the meantime many of these early shortcomings have been overcome. Improved computing algorithms have made the videokeratometer a very useful tool for measuring the shape of the corneal surface and displaying it in a variety of ways (11, 32), diagnosing keratoconus and last not least for fitting contact lenses (24). The three major drawbacks of instruments based on the Placido principle are their inability, first, to measure the centre of the cornea with precision; second, to obtain data up to the limbus; and third, to perform measurements on a turbid or scarred cornea. All these drawbacks can be avoided by the use of alternative measuring methods. As yet, however, neither scanning photogrammetry (PAR device© 2, 8) nor the split-field method (Orbscan©, 1) have found wide acceptance.

The present author has cooperated with the Oculus company in developing a software supplement for identifying and classifying keratoconic eyes (4). This paper presents new possibilities of corneal diagnosis using the Haag-Streit/Oculus keratograph. It focuses in particular on a method of mapping the corneal surface by means of Fourier analysis. Although this method has existed for some time, it has been seldom used in clinical practice. Furthermore, the paper elucidates the significance of height values as opposed to conventional methods of displaying sagittal and tangential radii, as well as the new corneal indices. Finally it gives a detailed presentation of Zernike polynomials as a tool for analyzing corneal aberrations.

Fourier Analysis

a) Basics

Named after the French physicist Jean Baptiste Joseph Fourier (1768-1830), this mathematical method permits decomposition of any periodical function (Fig. 1) in terms of trigonometric sine and cosine functions (**Fourier analysis**, Fig. 2). The fundamental wave, known as the first harmonic, is a sine wave whose period is equal to that of the wave being analyzed. The period of the second harmonic is half that of the first (thus giving two sine waves), the period of the third harmonic is a third as long as that of the first (giving three sine waves) etc. Summing up all the constituent wave components gives the original function (**Fourier synthesis**).

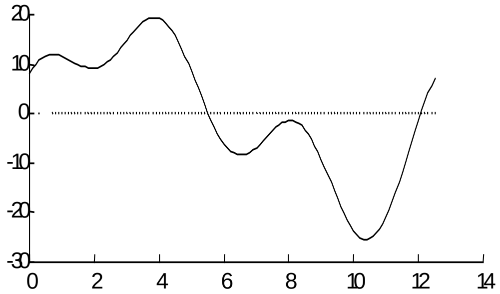


Fig. 1 Periodic function to be analyzed

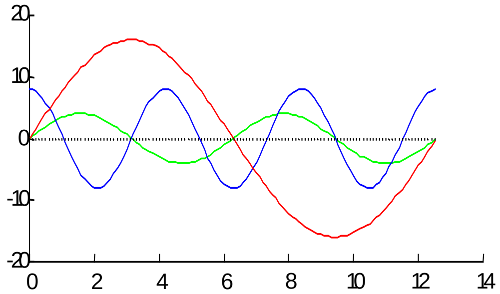


Fig. 2 Decomposition into two sine waves and one cosine wave

b) Fourier analysis performed by the keratograph

The keratograph performs a Fourier analysis on the topographic image by breaking it down into its individual components as described above. The first step is to divide the image into individual concentric rings. Then the curvature on each ring is decomposed into separate sine and cosine waves by means of Fourier transformation. The resulting components of all rings are regrouped and displayed in separate images showing, respectively, zero order, first order, second order components etc. Some interesting characteristics are found when the individual wave components are studied in isolation from each other in this manner (9, 15, 26):

Spherical equivalent

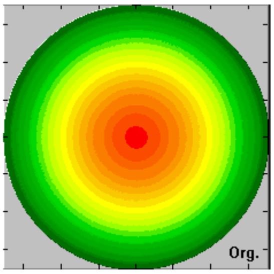


Fig. 3

This image consists solely of the zero order wave component in the form of the arithmetic mean of all radii of each individual ring (Fig. 3). This value can also be interpreted as the spherical equivalent of the radii of each ring. Assuming the cornea to have the shape of an ellipsoid of revolution, the spherical component permits an approximate calculation of the eccentricity of the cornea. In a normal eye corneal eccentricity ranges below 0.85.

Decentration

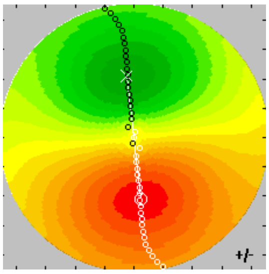


Fig. 4

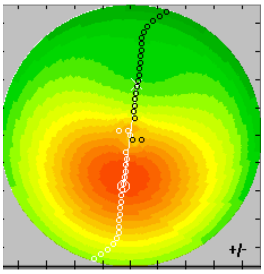


Fig. 5

The first-order wave is a regular sine wave which achieves a minimum and a maximum over a given radius ring (Fig. 4). It serves as a measure of the tilt between the optical axis of the videokeratoscope and the optical apex of the cornea. It is important to note that this function yields relative, not absolute values, since its arithmetic mean is zero. In a normal cornea maximum decentration rarely exceeds 0.45 mm. Combining the spherical and the tilt component gives a very good representation of the shape and orientation of a keratoconus (Fig. 5).

Regular astigmatism

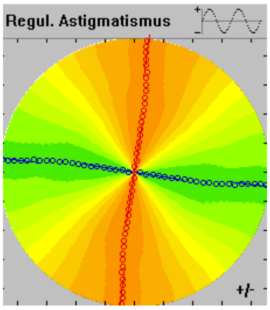


Fig. 6

The second-order wave represents a regular sine wave of double frequency, meaning that it achieves two minima and two maxima over a radius ring. Keratoconus is often associated with a rotation of the astigmatic axis from the center to the periphery, resulting in impressive whirl patterns (Fig. 6). This function also yields only relative values.

Experience has shown that that the magnitude and axis position of central astigmatism obtained by Fourier analysis are in closer agreement with subjective refraction than are the analogous values of the calculated keratometer data (Sim K) of the overview diagram. This is due to the fact that any decentration or major corneal aberration (e.g. trefoil or four-lobed defect) influences the amplitude and axis position in keratometer measurements.

Irregularities

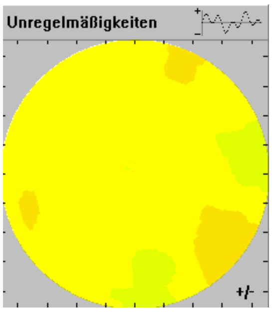


Fig. 7

All remaining wave components add up to give the irregularities of the corneal ring under measurement, again expressed as relative values (Fig. 7). In a normal cornea the arithmetic mean of all irregularities is less than 0.030 mm. An inverse relationship obtains between the degree of irregularity and the best potential visual acuity obtainable.

Fourier indices

Calculations based on the individual components yield indices which permit a quick numerical characterization of the corneal surface:

Fourier-Indizes	
Sphär. RMin=	7.63mm
Sphä. Exzentrizität=	0.62
Max. Dezentr.=	0.23mm/188°
Astigma. zentral=	0.16mm/178°
Astigma. peripher=	0.22mm/5°
Unregelmäßigkeit=	0.030

Fig. 8

Spherical RMin	minimal radius of curvature of the spherical component
Spher. Eccentricity	corneal eccentricity calculated from the spherical component. This must not be confused with the eccentricity at 30°, which is determined according to the sagittal radii method.
Max.Decentration	maximum value and position of decentration in the “Decentration” diagram
Astigma. central	curvature difference and axis position of regular, central astigmatism
Astigma. peripheral	curvature difference and axis position of regular, peripheral astigmatism
Irregularities	mean of all deviations in the “Irregularities” diagram

Pathological values are highlighted in red as a matter of course.

c) Applications of the Fourier display mode in keratoconus

In keratoconus one finds the following deviations from the image generated by a normal eye, each of which may be more or less pronounced depending on the stage of the disease. The most illustrative images are often obtained by combining spherical components with all other components:

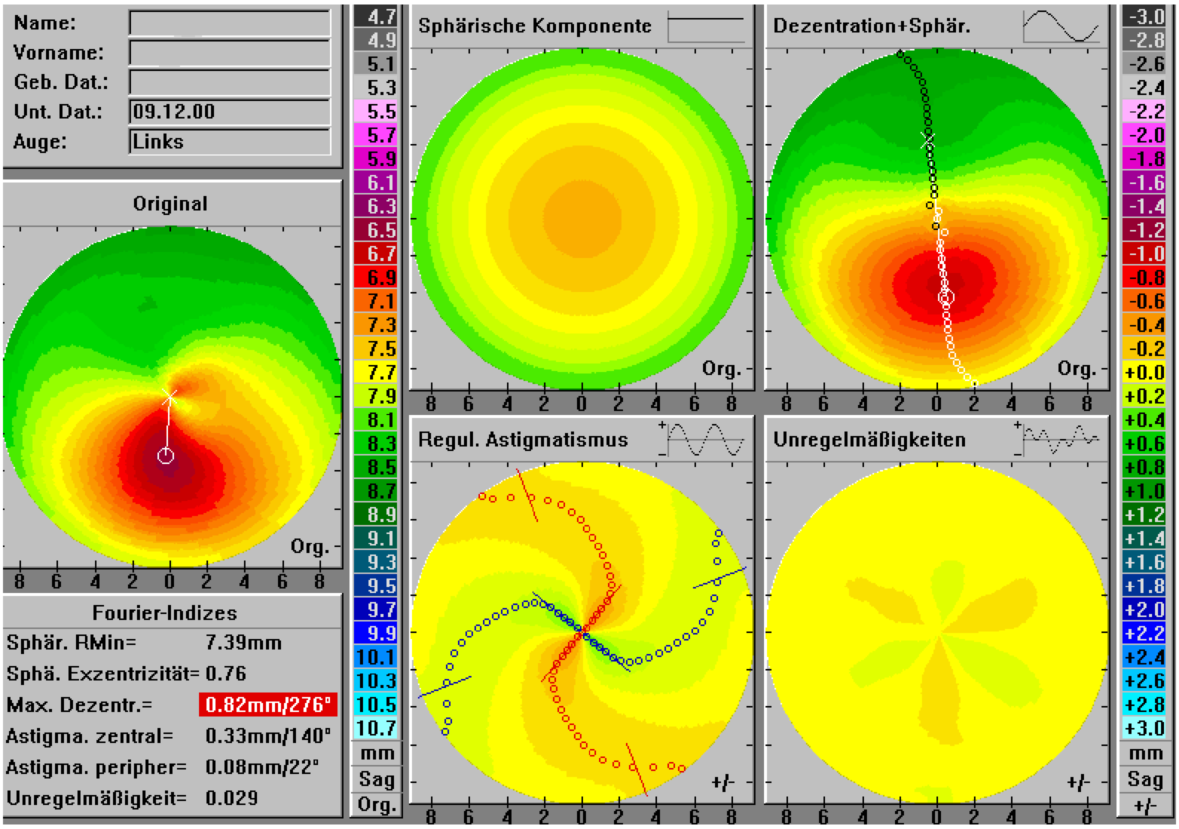


Fig. 9The “Fourier Analysis” window in a case of keratoconus

“Spherical equ.”

The minimal radius of curvature is steeper and usually less than 6.90 mm, while eccentricity may exceed 0.85. However, both parameters are subject to considerable variation and may not be used as indices in isolation from each other.

“Decentration + spher.”

The direction of decentration is usually vertical or approximately vertical (as opposed to horizontal or approximately horizontal in the healthy eye) and depends on the apex position of the cone, which is represented very clearly in the combined presentation mode.

The degree of decentration is usually greater than in the normal eye, exceeding 0.45 mm. However, this parameter too is subject to variation and not to be used as an index.

“Regular astigmatism”

Whereas in astigmatism the axis runs in a straight line, in keratoconus it not infrequently undergoes a rotation from the center to the periphery, thus taking on a spiral appearance.

“Irregularities”, resp., “Irregularities + spherical equivalent”

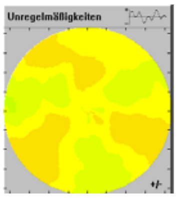


Fig. 10a

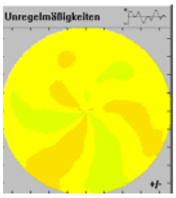


Fig. 10b

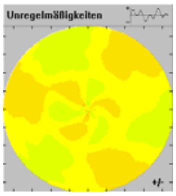


Fig. 10c

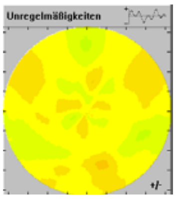


Fig. 10d

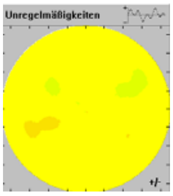


Fig. 11a

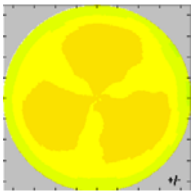


Fig. 11b

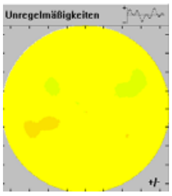


Fig. 12a

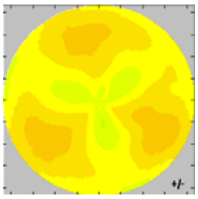


Fig. 12b

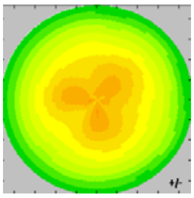


Fig. 13a

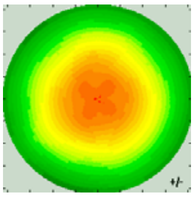


Fig. 13b

In keratoconi of various degrees of severity one often encounters images with more or less clear-cut three or four-leafed shapes (Fig. 10a-d). These are indicative of higher-order corneal aberrations, referred to in the context of Zernike polynomials as trefoil or four-lobed defect. Combining these irregularities with the spherical component often renders them more distinct. (Figs. 11 and 12). Fig. 13 shows a particularly clear example of trefoil and four-lobed effects.

“Fourier Indices”
Abnormal values are highlighted in red as a matter of course.

Exceptionally fascinating results can be obtained from a **Fourier analysis of height data**. Combining the spherical component with the vertical decentration component here gives a very clear picture of the development and different degrees of severity of keratoconus (4). This image is shown in the menu item “Indices” under the designation “Decentration”.

Representation of Height Data

This display method uses the three-dimensional corneal height model generated in the course of the mathematical evaluation and serving as an internal basis for all following calculations. The use of height data offers the following

<u>Advantages:</u>

- Height data contain a variety of information, which, however, only becomes accessible through further calculations. This advantage is not available when working from secondarily calculated sagittal or tangential radii.
- Height data can serve to define standards independent of the type of instrument being used.
- Height data are relatively insusceptible to fixation artifacts, thus lessening the probability of pseudokeratoconus occuring (6, 10, 22).
- Height data give a more accurate representation of the true shape of the corneal surface. They can be used directly for fluo image simulation as well as for calculating the posterior surface of contact

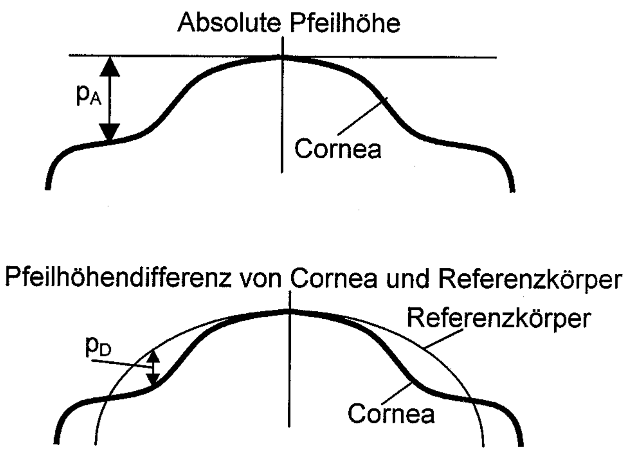
lenses. Comparison with the fluo image of a contact lens shows that the use of height data for locating the position of the apex in keratoconus gives far more accurate results than one would expect from a display method based on sagittal and tangential radii.

- Height data can serve as a starting point for analyzing various aberrations of the corneal surface by means of Zernike polynomials (13, 17-19, 23, 29-31). Furthermore they can be used for keratoconus quantification (14, 28).
- They permit direct quantification of corneal reduction in laser surgical interventions.

Disadvantages:

- This type of representation will at first be unfamiliar to the novice.
- Fine variations in the corneal surface are masked by the spherocylindrical components of the cornea and can only be made visible by special techniques (decomposition into Zernike polynomials).

Height data can be shown either in absolute or in relative terms (in the latter case as differences in height between measurement and reference surface):



Absolute arrow height, P_A, (in a meridian section) is the difference in height between a local point on the corneal surface and a plane which makes contact with the cornea in its center.

The difference in arrow height, P_D, between cornea and reference body, may either be positive or negative:
negative: measurement below reference body,
positive: measurement above reference body.

Fig. 14 Definition of height values

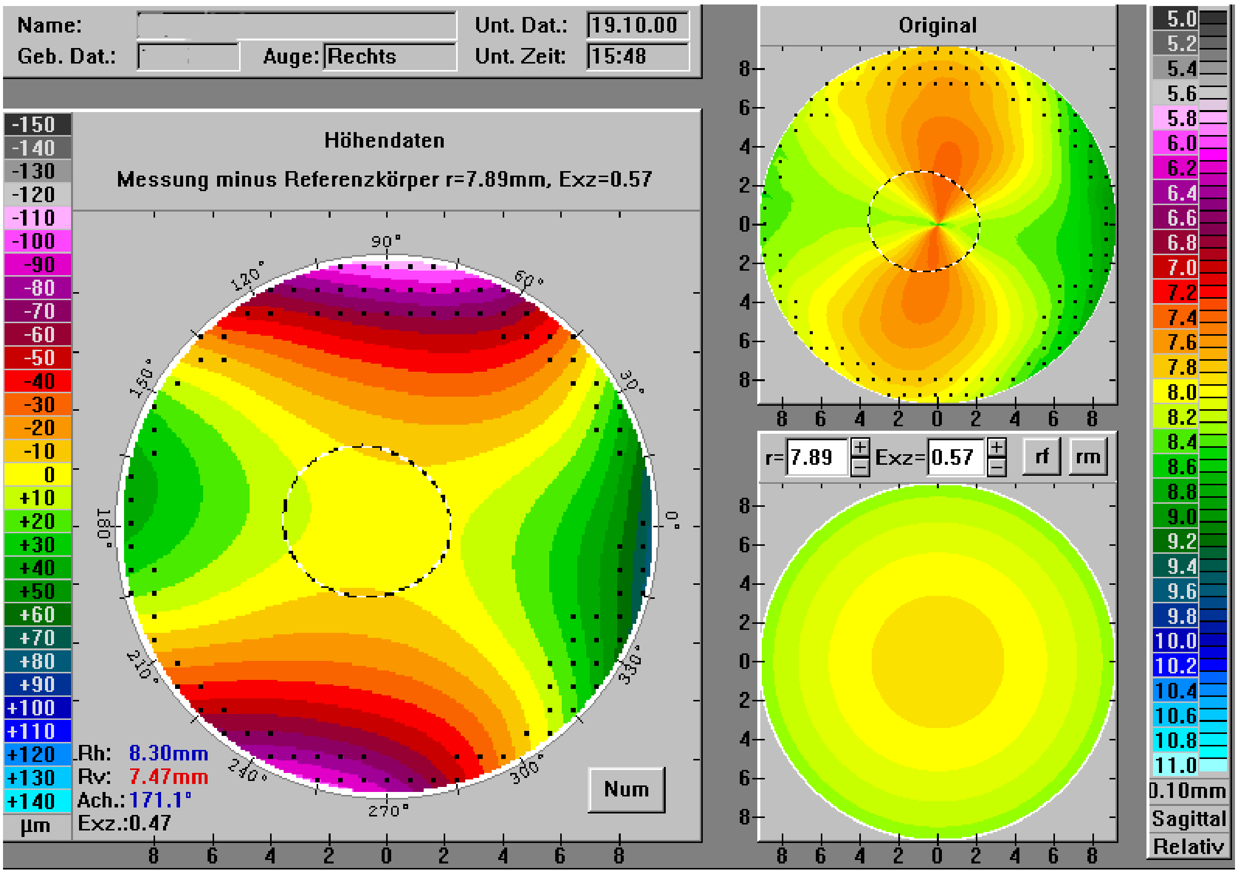


Fig. 15 The "height representation" window in the case of an astigmatic cornea

The map at the top right shows a **reduced image of the sagittal and tangential radii of the corneal surface**.

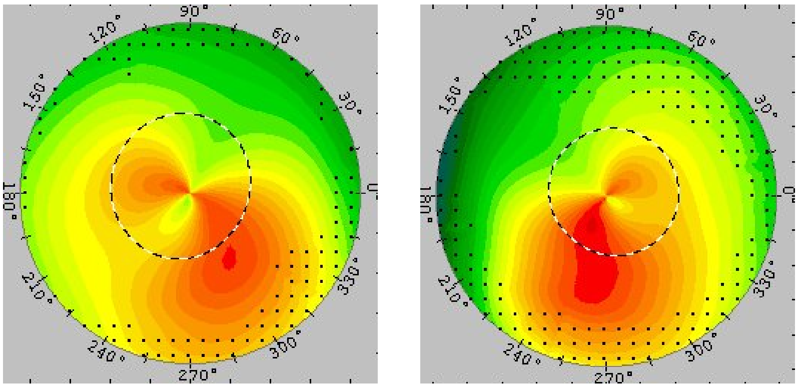
The "height data" window is bordered by two color bars with identical color increments. The right color bar corresponds to the overview display and contains radial values. The left color bar contains height data, classifying deviations from the reference body into 10 µm intervals. Clicking with the left mouse button permits the user to change the resolution for better readability.

The large map on the left is a graphic representation of height data shown in terms of differences in arrow height between the measuring point (cornea) and the reference body. The figures at the bottom left give the simulated ophthalmometric values including axis position and mean eccentricity at 30°. Clicking the "**Num**" button displays a polar coordinate system showing local height data. This permits an assessment of the fit of spheroaspherical or quadrant lenses of known apex depth.

The map at the bottom right shows a topographic image of a **rotationally symmetric reference body**. If the "**rm**" button is active, as in the default setting, the reference body is calculated from the mean central curvature radius and an eccentricity 0.1 greater than that of the cornea. These parameters are ideal for displaying normal or astigmatic corneas, and they are frequently used in manual topometry programs. Activating the "**rf**" button causes the reference body to be calculated using the flat central curvature radius and an eccentricity 0.1 greater than that of the cornea. This setting is especially suitable for cases of keratoconus, as the position of the apex is displayed immediately.

Applications of the height display method

The conventional method of imaging keratoconi by means of sagittal or tangential radii is prone artificial distortion. For example, it not infrequently leads to an inaccurate location of the apex position (2, 4, 7, 8). Clinical findings in conjunction with fluo images show that images based on height data yield more accurate results. The conus apex is always located at the end of the loop-like bulge of the contour lines. In the fluo image the apex is located somewhat closer to the loop due to the tilt of the lens on the eye.



Right eye   Left eye

Fig. 16
Representation based on
sagittal radii

The hour-glass shape in the center is an artifact inherent to the display method. In the right eye the apex appears to be located inferior and nasal, while in the left eye it appears to be located inferior.

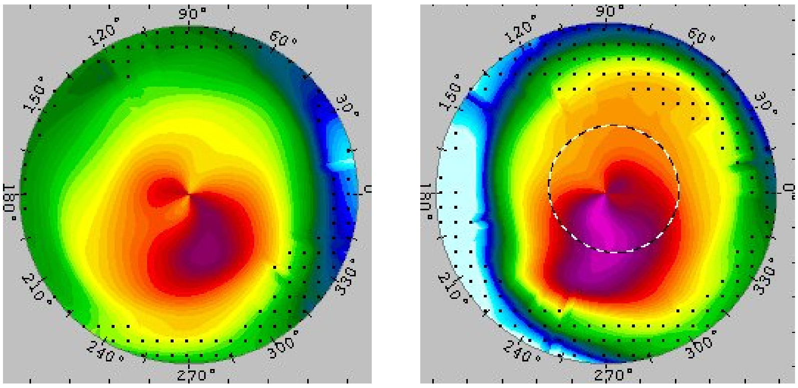


Fig. 17
Representation based on
tangential radii

Same problem as with sagittal radii; nevertheless, often yields more intuitive results (27, 33).

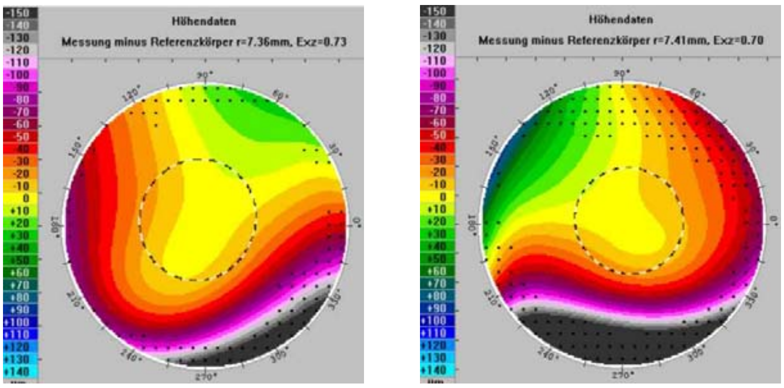
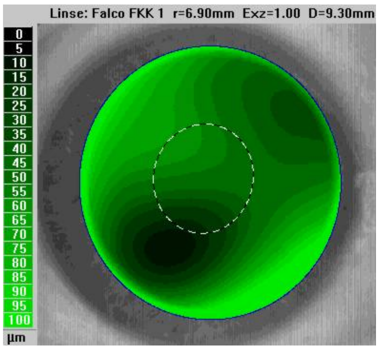


Fig. 18
Representation based on
height data

In both eyes the apex position appears to be located temporal towards the lower pupillary margin. This is in agreement with clinical findings (ophthalmoscopy in regressive light) and the fluo image.



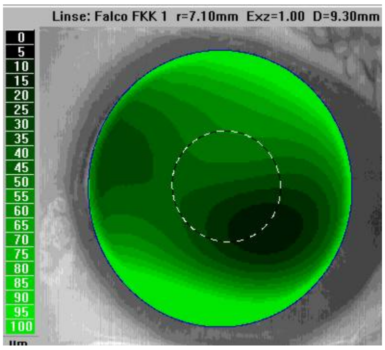


Fig. 19
Simulated **fluo image**
Right eye: lens contact in the apical area temporal and inferior to the pupillary margin as well as nasal and superior. Left eye: lens contact around the temporal/inferior temporal pupillary margin as well as nasal between 9 and 10 o´clock.