New Techniques to Measure Lens Tilt, Decentration and Longitudinal Chromatic Aberration in Phakic and Pseudophakic Eyes

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With 7 Figures

Abstract

A new automated technique is presented to measure lens tilt and decentration in phakic and pseudophakic human eyes, along with new data on the variances of these variables in the phakic eye. Our data shows that the natural lens has variable orientation in different subjects and that it is significantly tilted towards the temporal side, relative to the fixation axis. Furthermore, polychromatic eccentric photorefraction is used for the first time to measure chromatic aberration in the eye. Interestingly, no significant chromatic aberration was found, perhaps because the fundal layers show wavelength-dependent reflection in different depths and with different angular distributions. This assumption is supported by the observation that chromatic aberration could be measured in two different artificial eyes with a "mono-layered retina".

Zusammenfassung

Es werden ein neues automatisiertes Verfahren zur Messung der Linsenkrümmung und Dezentrierung in phaken und pseudophaken menschlichen Augen und neue Daten, die die Streuung dieser Variablen im phaken Auge zeigen, vorgestellt. Unsere Daten zeigen, dass natürliche Linsen eine variable Orientierung bei verschiedenen Personen aufweisen und dass sie in Bezug zur Fixationsachse erheblich in Richtung Schläfenseite gekrümmt sind. Außerdem wird die mehrfarbige exzentrische Photorefraktion erstmals zur Messung der chromatischen Aberration im Auge verwendet. Interessanterweise wurde keine signifikante chromatische Aberration gefunden. Das liegt vielleicht daran, dass die Fundusschichten eine wellenlängenabhängigen Reflexion in verschiedenen Tiefen und mit verschiedenen Winkelverteilungen zeigen. Diese Annahme wird durch die Beobachtung gestützt, dass die chromatische Aberration in zwei verschiedenen Kunstaugen mit einer einschichtigen Netzhaut gemessen wurde.

1. Semi-Automated Measurement of Lens Tilt and Decentration by Analysis of the Purkinje Images in Phakic and Pseudophakic Eyes

1.1 Purkinje Images and Kappa

If a light source is positioned in front of the eye of a subject, three virtual images and one real image of this light source can be seen which originate at the refracting surfaces of the optics of the eye. These images have been named "Purkinje images", after the Czech anatomist Jan Evangelista Purkyně (1787–1869) who first made drawings of them in 1823 and recognized that they could permit the determination of lens shape and the distance of the lens center from the iris (Purkinje 1823). As expected from the presence of four major re-

fracting surfaces in the eye, four Purkinje images are recognized, the first originating from the air-cornea interface (P1, upright, sharp and bright), the second from the back side of the cornea (P2, upright, relatively bright but only visible if the light source is located in the periphery of the visual field), the third from the anterior lens surface (P3, upright and large, but diffuse and weak) and the fourth from the backside of the lens (P4, inverted, small, but bright and sharp) (Fig. 1).
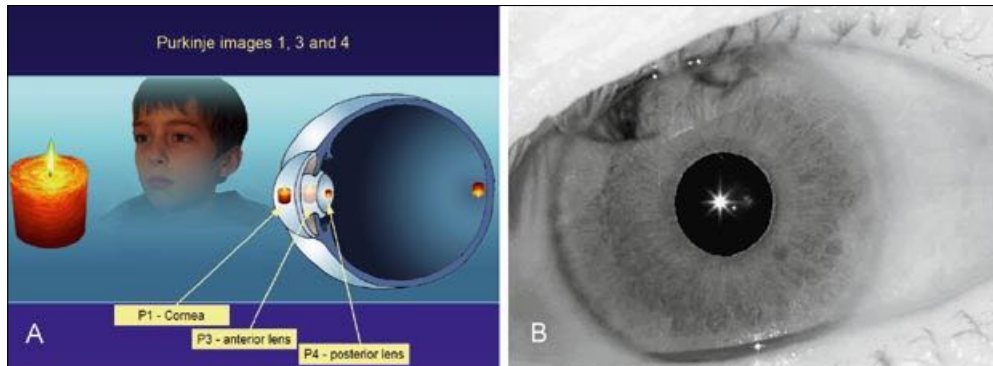

Fig. 1 (*A*): Illustration of Purkinje images 1, 3, and 4, and their orientations. (*B*): Original picture of Purkinje images 1, 4, and 3 (visible in this sequence, from left to right). The second Purkinje image is not shown, since it was not used in the measurement procedure described below.

P3, originating from the anterior lens surface, is difficult to detect, since it has low contrast and is diffuse because the small differences in refractive index between aqueous and lens capsular bag, and also because of the lenticular index gradient (see Fig. 1). Furthermore, it tends to disappear behind the iris already for small angular rotations of the eye since the anterior lens surface is rather flat. However, P3 and P4 need to be detected to permit measurements of the orientation of the lens. In addition, it has to be considered that the axis of fixation and the pupil axis diverge by the angle "kappa" (Fig. 2). The orientation of the fixation axis cannot be determined solely from Purkinje images since the position of the fovea cannot be determined from outside, using pictures, as shown in Figure 1 (*bottom*). It is necessary that the subject fixates a target that is presented under a defined angular position and that the position of the first Purkinje image in the pupil is recorded during fixation. The pupil axis, on the other hand, is defined by the eye position in which the first Purkinje image is centered in the pupil.

1.2 Measurement of Lens Tilt and Decentration Based on the Purkinje Images

Rather than tracking the positions of P1, P3, and P4 in the pupil separately to determine the orientations of the optical surfaces relative to the light source, a simplified procedure was employed. The procedure was first proposed by Tabernero et al. (2006) (a second "Purkinjemeter" was also recently published by Rosales and Marcos 2006). An advantage of the procedure is that nothing needs to be known about the linear regression equations which describe the movements of the Purkinje images as functions of eye position. As light
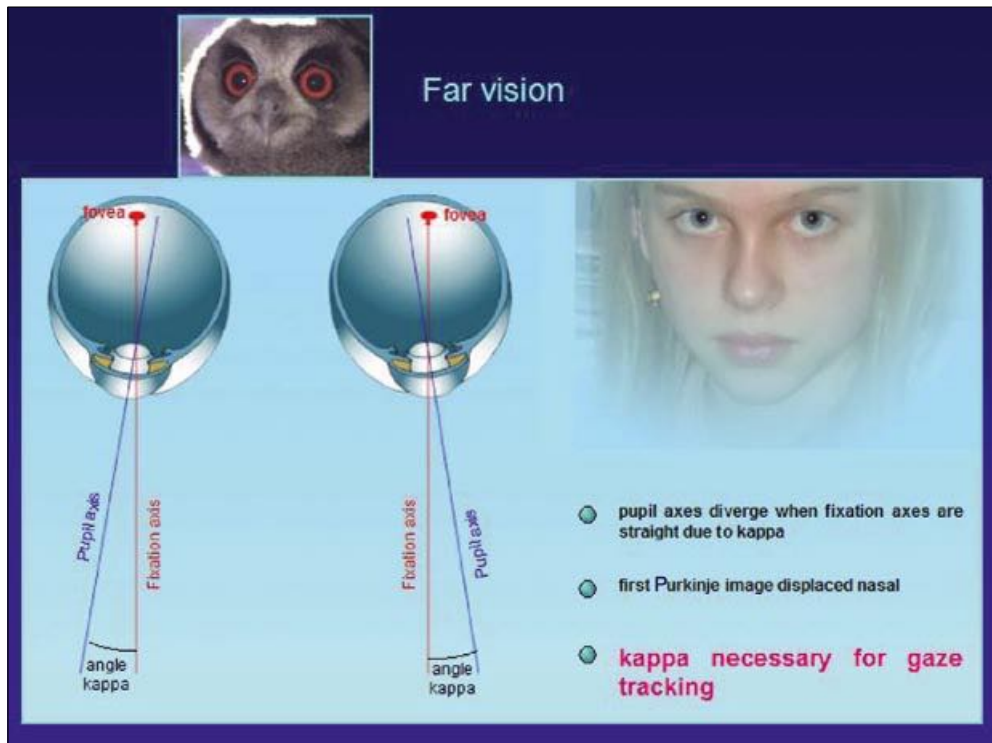
Fig. 2   The first Purkinje image is not centered in the pupil when the subject fixates a distant target behind the observer, presenting the light source, but rather nasally displaced. The displacement results from the fact that the fixation axis (connecting the fovea with the fixation target) emerges from the eye typically nasally from the pupil axis. The angle between both axes is "kappa". It ranges typically between 0 and 11° in humans (e. g. SCHAEFFEL 2002) but may be much larger in other vertebrates (e. g. 30 deg in the owl).

source, an infrared light emitting diode (IR LED) was used which was placed close to the camera aperture. Infrared light has the advantage that it cannot be seen and that the pupil remains large.

To measure the direction of fixation of the subject, kappa needs to be known. To this end, the subject had to fixate a target of known angular position – in this case a little green LED positioned next to the IR LED, just above the aperture of the lens of the video camera. From the position of the first Purkinje image relative to the pupil center, kappa can be determined, given that the "Hirschberg ratio" (HQ) is known. HQ is the angular rotation of the eye that is necessary to move the first Purkinje image in the pupil linearly by 1 mm. Typically, the HQ in humans is close to 12, with a standard deviation of about 8 % (e. g. SCHAEFFEL 2002). If gaze tracking should be very precise, individual measurement of HQ might be worthwhile. In the present case, however, a common value of 12°/mm provides sufficient precision for gaze tracking in all subjects.

Positions of P3 and P4 are now recorded for three different eye positions, separately for horizontal (x) and vertical (y) coordinates. Since the direction of gaze is "known" by the software, based on the position of P1 relative to the pupil center, there is no further need to provide fixation targets in the visual field at defined angular positions. The distance between P3

and P4 is plotted, both in x and y directions, versus angular gaze position. A linear regression through these points provides the eye position for which P3 and P4 would be exactly superimposed. For this gaze position, the crystalline lens is oriented perpendicular to the camera axis and the negative value of the respective gaze position provides lens tilt (TABERNERO et al. 2006, SCHAEFFEL 2008). In the next step, the centration of the lens relative to the pupil center can calculated from the position of the superimposed P3 and P4, relative to the pupil center.

These measurements require that the user marks the Purkinje images in the video frame with the computer mouse since automated detection was too noisy in the case of P3. Software to perform all these steps was developed in Visual C++. Positional data is stored and a regression analysis is automatically performed after the third measurement (Fig. 3, see top right).
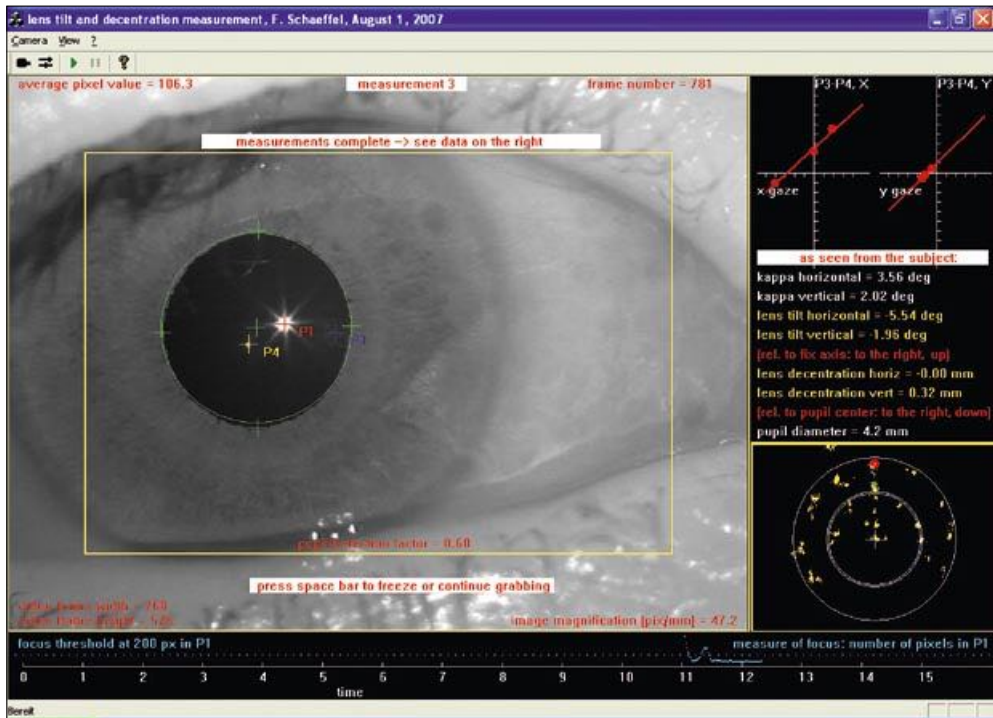

Fig. 3   Software output of the custom-developed program to measure lens tilt and decentration in a phakic subject. In the top, right, the distance between P3 and P4 is plotted as a function of the direction of gaze. A regression analysis is automatically performed to find the direction of gaze for which P3 and P4 would just be superimposed. In this gaze position, the crystalline lens is oriented perpendicular to the camera axis. Decentration of the lens, relative to the pupil center, can be determined from the linear distance of the superimposed P3/P4 from the pupil center (see output data on the right, middle).

1.3 Results of Measurements of Lens Tilt and Decentration in 11 Young Phakic Subjects

In our data set (originating from 11 young co-workers in the lab) both eyes showed a high degree of mirror symmetry regarding horizontal angle kappa and horizontal lens tilt, but not regarding horizontal lens decentration. There was a striking scatter in kappa and lens

tilt across subjects – some had small kappa and little lens tilt, but values of up to 10° were also observed (Fig. 4). Significant degrees of symmetry were also observed in the vertical angle kappa, vertical lens tilt, and decentration.
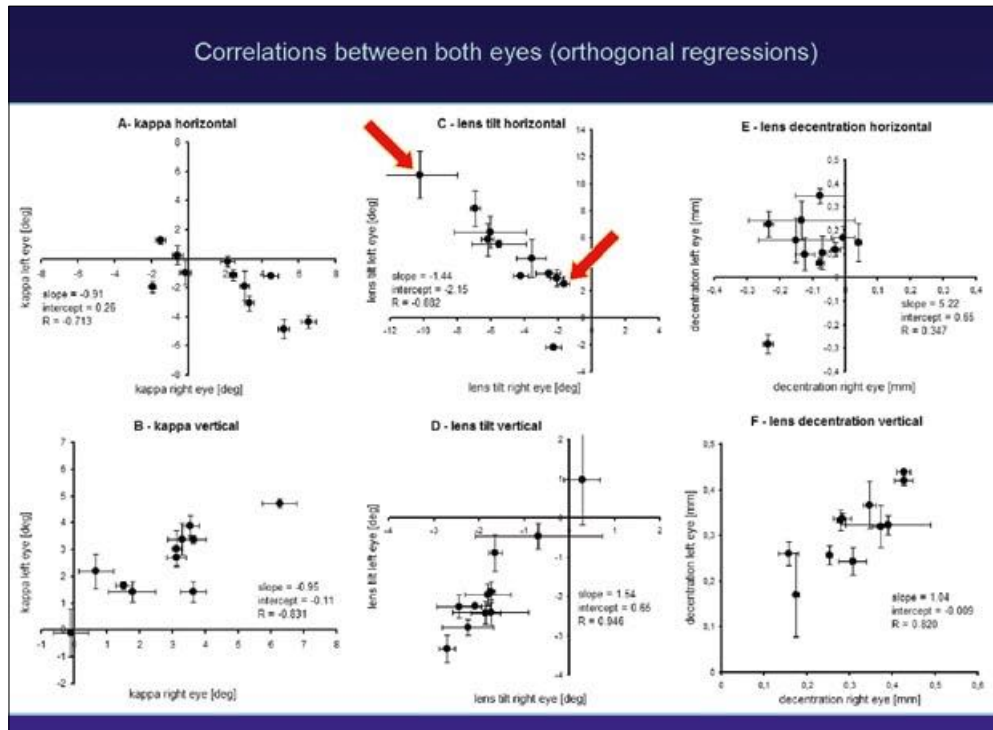

Fig. 4   Correlations of kappa, lens tilt, and lens decentration in both eyes, studied separately for the horizontal and vertical axis. Since a comparison of both eyes does not provide a dependent and an independent variable, orthogonal regression analysis was necessary. There was a surprisingly large variability in lens tilt among the different subjects (see red arrows in Fig. 4*C*). It is also striking that the lenses were tilted towards the temporal side, even if measured relative to the fixation axis (from SCHAEFFEL 2008).

1.4 Summary and Prospects

Apparently, there was little selective pressure in the course of evolution to position the lens exactly perpendicular to the "optical axis" of the eye, or to the "fixation axis". Within the range of scatter of lens tilts it appears possible to maintain a sufficient quality of the retinal image. Exactly the same conclusion was drawn by ARTAL and TABERNERO (2008). The design of the natural crystalline lens seems to leave the optics of the eye with little sensitivity to lens tilt.

In the case of pseudophakic eyes, the condition is changing. In particular, tilt and decentration become critical in the aspherical lenses (PIERS et al. 2007). At least, the proposed device can be nicely used to measure tilt and decentration of implanted artificial lenses (MESTER et al. 2009). In pseudophakic eyes, P3 is easily detected because the difference in refractive index is large between aqueous and the plastic lens material. Furthermore, there is no index gradient in the lens that diffuses the reflection.

2. Measurement of Longitudinal Chromatic Aberration by Polychromatic Eccentric Photorefraction

2.1 Eccentric Photorefraction in Infrared and White Light

Eccentric photorefraction is a technique to measure refractive state from a distance of 0.5 to 5 m in which measurements of the brightness distribution in the pupils can be fully automated, by use of digital video images (SCHAEFFEL et al. 1993). Typically, IR LEDs are used with an emission peak between 850 and 890 nm. Since they are scarcely visible, they do not stimulate a pupil constriction. Measurement are typically done in dim light, and the pupil remains large which reduces the measurement noise during analysis of the brightness distribution in the pupil because it is based on many pixels. The technique also has the advantage that both eyes can be measured simultaneously, and that high temporal sampling
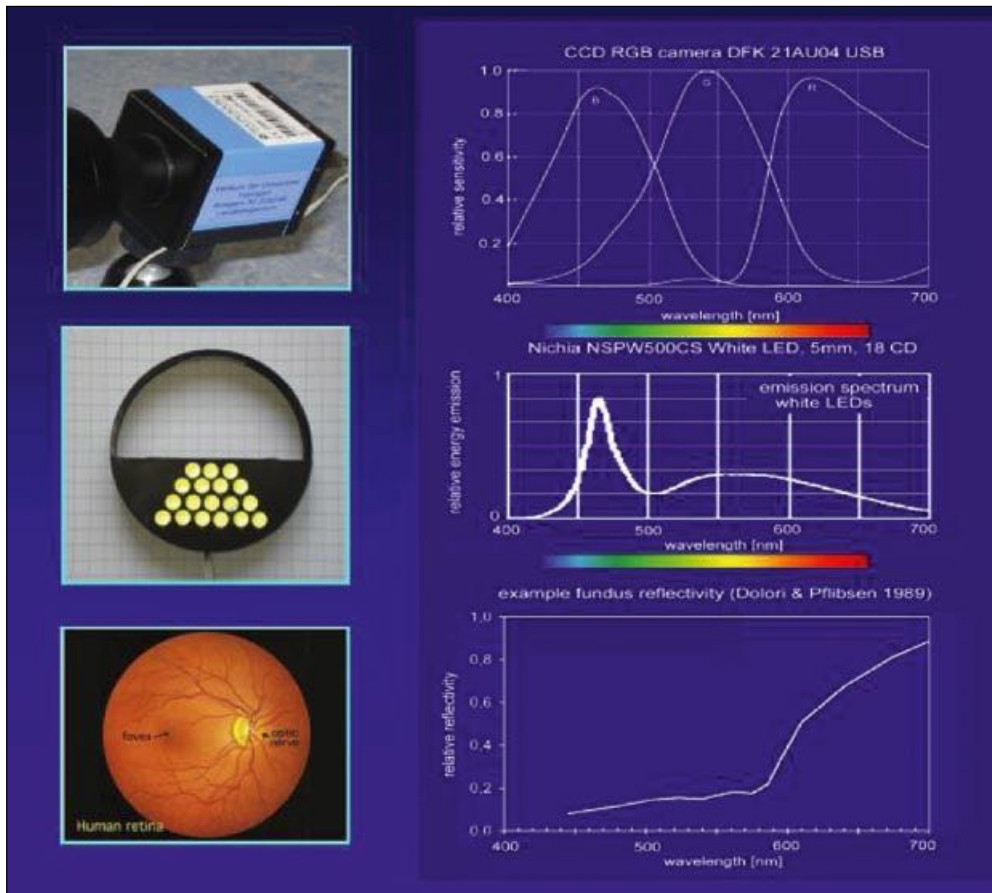

Fig. 5   Spectral human fundus reflectivity (after DOLORI and PFLIBSEN 1998, see curve on the *right*, *bottom*). The spectral emission of the high power white light LED in the photoretinoscope is shown in the middle. The spectral sensitivity of the single chip RGB CCD camera is shown in the top (available through The Imaging Source, Bremen, Deutschland).

rates can be achieved (depending on the frame rate of the camera). Furthermore, the measurements are not realized by the subjects and largely natural viewing conditions are possible (apart from the dim room illumination). Myopia, astigmatism and anisometropa are reliably detected, while hyperopia in young subjects may be partially masked by accommodation. A further limitation is the inter-individual variability of the calibration of the technique. If trial lenses are placed in front of the eye and the expected change in refractive state is compared to the measured one, deviations of up to 20 % may occur – an error of 0.2 D in the case of a one diopter lens, but already 1 D in the case of 5 D trial lenses. The optical reason for the inter-individual variability is still not understood (Seidemann and Schaeffel 2003).

If white light is used instead of infrared light, and only a short flash is presented rather than a continuous operation of the LEDs, refractions can be measured simultaneously at different wavelengths. Right after the flash, the pupil is still large because of the long latency of the light-induced pupil response. A problem is that the fundus shows low reflectivity in the blue end of the spectrum (Fig. 5) and it is necessary to provide sufficient light energy in the blue. In the current case, high power white light LEDs were used which had an emission peak around 420 nm. This peak overlaps nicely with the "blue channel" of the single chip CCD RGB camera DFK21 AU04 (TheImagingSource, Bremen, Germany).

2.2 Technical Issues in Polychromatic Photorefraction

Commercial video systems providing chromatic information have automatic white balance built in which adjust the gains of the blue (B), green (G) and red (R) channels. In the current case, one would like to measure the absolute brightness values in BGR and all automatic controls had to be switched off. Furthermore, the pixel values in the BGR channels had to be adjusted to provide similar pixel values to minimize the effects of non-linearities during the conversion of object brightness to pixel value. To this end, the gain of the B channel was manually set higher than the G and R channel. Thereafter, calibration curves were determined by taking pictures of a "white" surface with different aperture settings of the camera lens and recording the respective pixel values. The response curves were fit by exponential functions so that each pixel value was assigned a defined object brightness. Software was developed under Visual C++ to flash the white light LEDs through the USB port of the laptop, and to record a video frame during the flash. The software automatically analyzed the slope of the brightness profiles in the vertical pupil meridian in the B, G, and R channel (Fig. 6).

2.3 Calibration and Measurement Noise

The technique was calibrated simultaneously in B, G, and R, by holding various trial lenses in front of the right eye of 6 subjects. Interestingly, no differences were found in the changes of the brightness gradients in the pupil with changing lens powers for the B, G, and R channels. However, the well-known inter-individual variability in the calibration of eccentric photorefraction showed up again – the trial lens induced slightly different changes in the slopes of the brightness profiles in the pupils of different subjects. However, this should not represent a major problem, since the expected longitudinal chromatic ab-
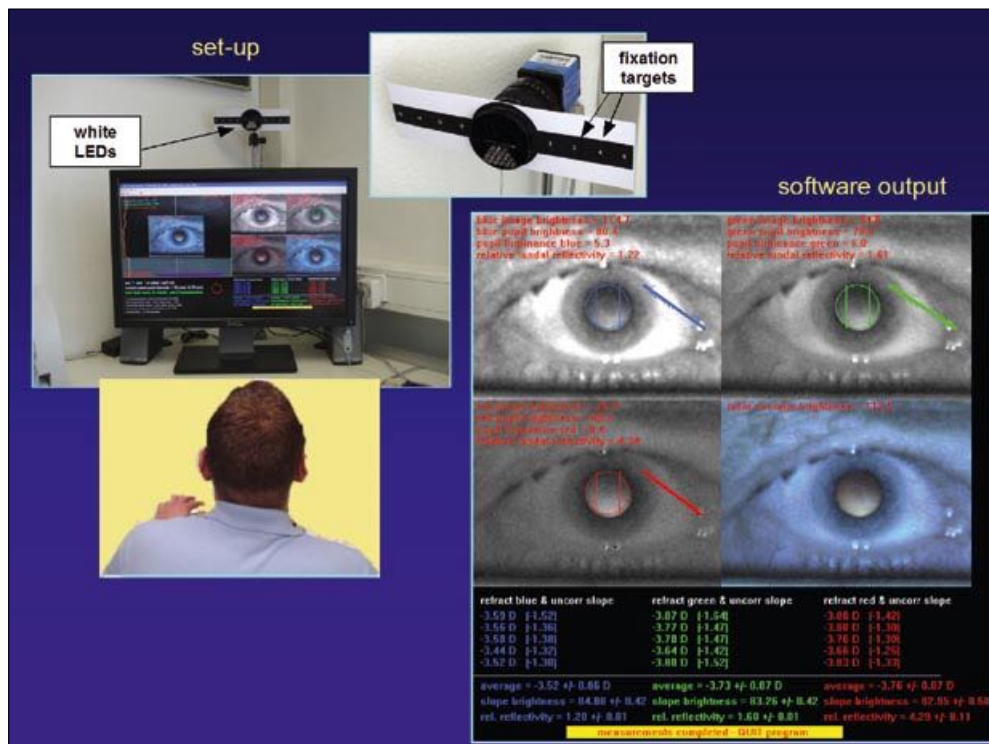
Fig. 6 Measurement set-up (*top left*) with a subject in front of it, USB video camera with white light photore-tinoscope and black cardboard with fixation targets at ±1, 2, 3, 4, 5°, seen from 1 m distance (*top, middle*), and frames showing the output of the B, G, and R channel (*right*, *bottom*). BGR frames appear in black and white here because the output of each channel was loaded into the remaining two other channels before display, to improve contrast and visibility on the screen. *Bottom right* shows the results of five consecutive measurements. Note that the standard deviations of these five measurements were very low, here below 0.1 D.

erration should be in the range of 1 D, much more than variability in the inter-individual calibrations (at the most, about 20 %). For an expected difference of 1 D, 20 % would only be equivalent of about 0.2 D. Repeated measurements in B, G, and R gave standard deviations of only about 1/10 of a diopter – again, one would not expect that noise could limit the possibility to measure longitudinal chromatic aberration.

2.4 Results

The technique permitted also the evaluation of fundus reflectivity in B, G, and R across the visual field, as well as measurements of the longitudinal chromatic aberration in different angular positions (data not shown here). Foveal refractions of 11 subjects are shown as measured in B, G and R (Fig. 7). Except for two subjects, who showed more myopia in the blue as expected from typical longitudinal chromatic aberration, the refractions remained largely independent from the wavelength in which they were measured.
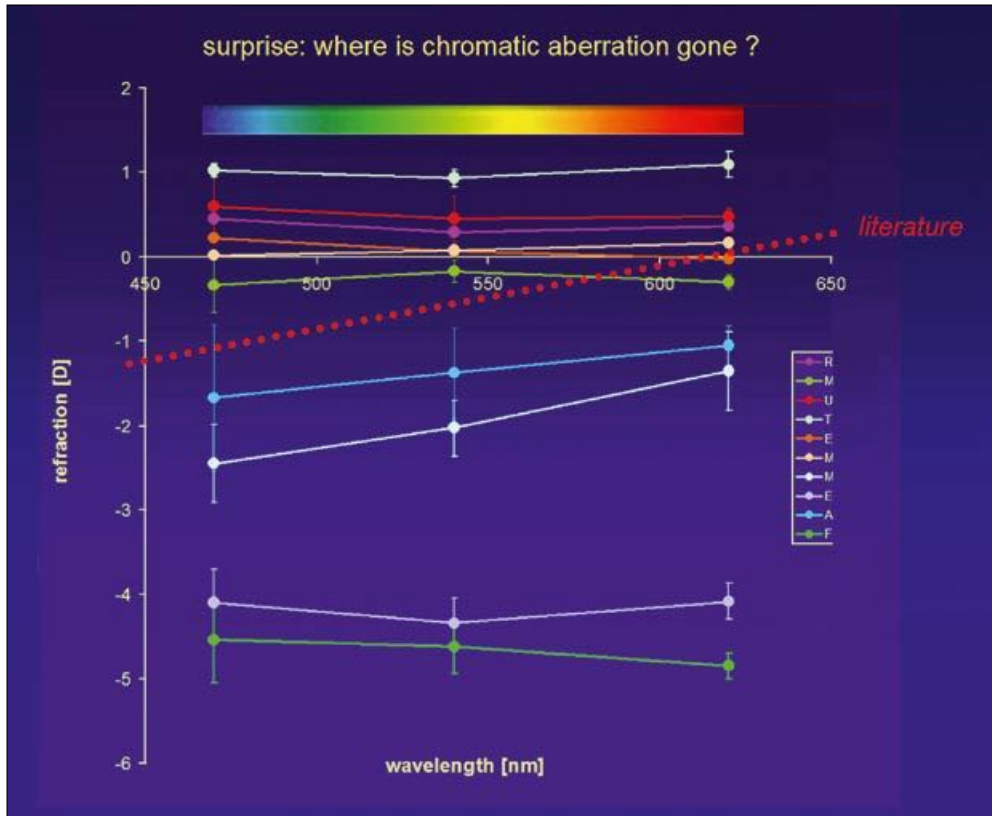
Fig. 7   Refractive states of 11 subjects, measured at 460, 540, and 620 nm. Except for subjects M und A, the refractions remained similar in the blue, green, and red. Literature data on longitudinal chromatic aberration are also shown for comparison as dotted red line.

Polychromatic photorefraction has provided unexpected results – namely the lack of an effect of wavelength on refractive state. The most likely explanation could be that the light in reflected at different layers in the fundus. If red light would penetrate deeper into the fundus, an apparently longer and more myopic eye would be measured. This effect could counter-balance the effect of longitudinal chromatic aberration, originating from dispersion in the ocular media of cornea and lens. In humans, one diopter is equivalent to a longitudinal shift in axial length of about 330 µm – about the thickness of the retina.

Measurements with the device in two different artificial eyes with "single layered fundus" (plastic or cardboard) showed longitudinal chromatic aberration in the expected magnitude (data not shown).

While the mechanism underlying the lack of longitudinal chromatic aberration in our measurements could not be identified with confidence, future measurements with quasi-monochromatic light could help to clarify this issue. Perhaps such studies would also help to finally understand the reasons for the inter-individual variability in the calibration of photorefraction. Of particular interest are the two subjects in which longitudinal chromatic aberration was, in fact, detected since they may show also other difference in calibrations.

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References

Artal, P., and Tabernero, J.: The eye's aplanatic answer. Nature Photonics *2*, 586–589 (2008)

Dolori, F. C., and Pflibsen, K. P.: Spectral reflectance of the human ocular fundus. Appl. Opt. *28*, 1061–1077 (1989)

Mester, U., Sauer, T., and Kaymak, H.: Decentration and tilt of a single-piece aspheric intraocular lens compared with the lens position in young phakic eyes. J. Cataract Refract. Surg. *35*, 485–490 (2009)

Piers, P. A., Weeber, H. A., Artal, P., and Norrby, S.: Theoretical comparison of aberration-correcting customized and aspheric intraocular lenses. J. Refract. Surg. *23*, 374–384 (2007)

Purkinje, J.: De examine physiologico organi visus et sytematis cutanei (Breslau, Universität Breslau 1823). Citation by Wade, N. J., and Finger, S.: The eye as an optical instrument: from camera obscura to Helmholtz's perspective. Perception *30*, 1157–1177 (2001)

Rosales, P., and Marcos, S.: Phakometry and lens tilt and decentration using a custom-developed Purkinje imaging apparatus: validation and measurements. J. Opt. Soc. Am. A. Opt. Image Sci. Vis. *23*, 509–520 (2006)

Schaeffel, F.: Kappa and Hirschberg ratio measured with an automated video gaze tracker. Optom. Vis. Sci. *79*, 329–334 (2002)

Schaeffel, F., Wilhelm, H., and Zrenner, E.: Inter-individual variability in the dynamics of natural accommodation in humans: relation to age and refractive errors. J. Physiol. *461*, 301–320 (1993)

Seidemann, A., and Schaeffel, F.: An evaluation of the lag of accommodation using photorefraction. Vision Res. *43*, 419–430 (2003)

Tabernero, J., Benito, A., Nourrit, V., and Artal, P.: Instrument for measuring the misalignments of ocular surfaces. Opt. Express. *14*, 10945–10956 (2006)

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