Comparison of toric intraocular lens tilt and decentration measurement using dynamic Purkinje-meter and anterior segment optical coherence tomography

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Aims. To present a new method of dynamic Purkinje-metry and to verify it by comparison with a commercially available anterior segment optical coherence tomography CASIA2.
Patients and Methods. A dynamic Purkinje-meter with a movable fixation target was assembled. A coaxial circular pattern formed by infrared LEDs was projected onto the eye and evoked Purkinje images (1st, 3rd, 4th = P1, P3, P4). The measurement was performed on 29 eyes with an implanted toric IOL (intraocular lens), under mydriatic conditions, with reference to the visual axis. The IOL tilt was calculated from the position of a fixation target at the moment of P3 and P4 superposition. The IOL decentration was determined based on the relative position of P1 during on-axis fixation and of P3 and P4 superposition during off-axis fixation. A custom-developed software was used for distance measurements. Using CASIA2, the IOL position was fully calculated by the device.
Results. The mean absolute difference between CASIA2 and Purkinje-meter values was 0.6° ± 0.4° for the tilt magnitude and 10° ± 10° for the tilt direction, and 0.11 mm ± 0.08 mm for the decentration magnitude and 16° ± 14° for the decentration direction. There was no statistically significant difference between the values determined by the two methods for the tilt and decentration direction. The differences were statistically significant for the tilt and decentration magnitude.
Conclusion. The values of IOL tilt and decentration direction are similar for both devices. The values of IOL tilt and decentration magnitude measured by Purkinje-meter are higher than those from CASIA2, but overall, they correspond to the values presented in other published studies.

Key words: intraocular lens position, intraocular lens decentration, intraocular lens tilt, Purkinje images, anterior segment optical coherence tomography, CASIA2

Received: March 7, 2024; Revised: April 30, 2024; Accepted: May 15, 2024; Available online: June 11, 2024
https://doi.org/10.5507/bp.2024.017

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INTRODUCTION

Nowadays, an integral part of cataract and refractive surgery is the correct calculation of the optical power of the implanted intraocular lens (IOL). However, if the lens is not properly seated and its position changes, it can significantly affect postoperative refraction and patient's satisfaction with the resulting quality of vision[1-8]. For that reason, the interest in the correct IOL position has increased and methods to measure the IOL position have significantly evolved. This is also related to the number of published studies dealing with different methods used for IOL tilt and decentration assessment. However, it is difficult to compare these studies, as no universal reference axis (or point) exists across the studies[5].

In clinical practice, methods used to measure the IOL position are based on ultrasound biomicroscopy (UBM), optical coherence tomography (OCT), Scheimpflug principle, and analysis of the position of Purkinje images (so-called Purkinje-meters). Unlike other methods, UBM enables imaging of tissues even through opaque media, on the other hand, it has a limited signal penetration depth (max. 4 mm) and as a contact method cannot be used in traumatized corneas and in the postoperative period, moreover, the pressure of the probe on the eye causes deformation of the eyeball during the examination and thus affects the measurement results[9-11]. A review study of commercially available anterior segment OCT systems indicates an imaging depth in the range of 2–7 mm (ref.[12]). A new option for imaging the anterior segment is CASIA2 (Tomey Corp., Nagoya, Japan), which provides a scanning depth of 13 mm and thus can visualize the lens in its entire thickness, moreover, the measurement is not dependent on the diameter or shape of the pupil[13]. The device can detect the IOL boundaries and then evaluate the IOL position automatically[14]. With Scheimpflug imaging and the IOLMaster 700 biometer, pupil dilation is necessary, otherwise the lens is not imaged to its full lateral extent[15]. A dilated pupil can make referential anatomical structures difficult to identify, and measurement is inaccurate[11,16]. None of these methods process information about the lens position directly and further image processing is necessary.

Systems based on the analysis of Purkinje images allow us to determine the IOL position based on the localization of light reflexes from the anterior surface of the cornea and from the anterior and posterior surfaces of the lens, i.e., 1st, 3rd, and 4th Purkinje image (P1, P3, and P4). The Purkinje-meters discussed in the published studies have a static arrangement with one or more fixed fixation targets[17-19]. Our dynamic Purkinje-meter combines the construction of static Purkinje-meters with dynamic examination of the IOL position according to the optical axis of the IOL, presented by Guyton et al.[20]. This device follows the concept of the Purkinje-meter developed and described in the 1990s by Cendelin et al.[21]. The advantage of the dynamic arrangement is primarily the possibility of a defined change in the fixation point position associated with a dynamic evaluation of the relative position of the Purkinje images. To our knowledge, any available study does not compare the IOL tilt and decentration measured using a dynamic Purkinje-meter and AS OCT (anterior segment optical coherence tomography).

The aim of the study was to verify the possibility of the IOL position measurement with the new Purkinje-meter by comparing the measured values of IOL tilt and decentration with the results from a commercially available anterior segment optical coherence tomography system.

MATERIAL AND METHODS

Patients

This study included patients who underwent cataract surgery on one or both eyes and had no other significant ophthalmologic comorbidities. Patients, who had corneal opacities or were not able to focus on the fixation target during the measurement (for example due to the presence of nystagmus), were not included in the study. All patients had 1-piece hydrophilic acrylic toric IOL (T-*flex* Aspheric Toric[22], Rayner Intraocular Lenses Ltd, Hove, UK) implanted in their eye(s). All the operations were performed by the same surgeon. IOL position measurements were performed under mydriatic conditions.

The study included 29 pseudophakic eyes (14 OD and 15 OS) of 20 patients (5 men and 15 women). The mean age was 70 ± 9 years (range 53 to 88 years). IOL position measurements were performed from 5 days to 15 months after the cataract surgery, using both measurement methods during the same postoperative control. The mean spherical component of the toric IOL power was 18.1 D ± 4.6 D and the mean cylindrical component was 2.7 D ± 0.8 D.

This work was performed in accordance with the Declaration of Helsinki. All patients were informed about the nature of the study and signed an informed consent to participate in this study.

Purkinje-meter Measurements

Description of the Device

For the purpose of this work, the dynamic Purkinje-meter was built (the scheme and the photograph of the device is shown in Fig. 1). Using the Purkinje-meter, Purkinje images are produced in the eye, their relative position is measured and subsequently computerized or converted to data on the IOL position. The mechanical device for measuring the position of Purkinje images is based on slit lamp parts. The body of the unit is movable to focus accurately on the observed image. The dominant component of the device is a disc with control and lighting elements, described below. Purkinje images used for IOL measurements are evoked using 12 IR (infrared) LEDs forming a static circle located in the central part of the disc around the camera porthole; the IR LEDs can be displayed also as a semicircle for easier identification of Purkinje images during the examination (according to Tabernero et al.[17]). The disc is rotatable, except for the central part with the infrared LEDs – this has a fixed position so that the evoked Purkinje images are stable. The device contains a red lighting fixation target which is moved by the examiner on a slide bar situated on the rotatable disc; the target can be moved to any position within the circle of a diameter 44 cm and the plane of

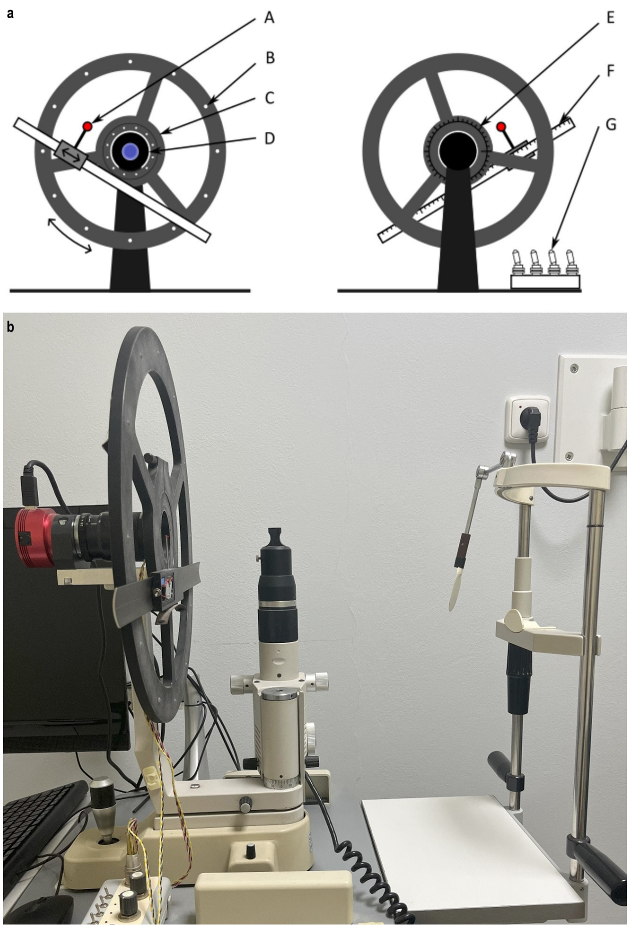

Fig. 1. The scheme (**a**) and the photograph (**b**) of the dynamic Purkinje-meter. Description of the scheme from the side of the patient (left): a red lighting movable fixation point (A), white LED diodes for better illumination of the measured field (B), a circle of infrared LED diodes producing Purkinje images in the eye (C), a camera objective (D); description of the scheme from the side of the examiner (right): a protractor (E), a sliding bar with a ruler (F), a control panel with lever switches (G) for setting lighting elements.

the fixation target is in a distance 40 cm from the patient's eye. The working distance of 40 cm is ensured by locking the focus of the camera objective; however, the camera objective must be movable in order to adapt to different shapes of the face and to the position of the eyes of the examined persons. For better illumination of the measured field, 12 white LEDs arranged in a circle are placed at the outer periphery of the rotatable disc. The Purkinje images are captured by a camera (ZWO ASI224MC Color Camera 1.2M with high sensitivity in the near-IR region and a Computar 55 mm TEC-55 telecentric lens); the camera is attached to the moving body of the Purkinje-meter in the place where a microscope is placed in a conventional slit lamp. The examinator follows the image from the camera on the computer monitor. To ensure minimal movement of the patient's head, as with most ophthalmological devices, the device includes headrests for the chin and forehead, to which an occlusion for the non-examined eye is attached.

Measurement procedure

During the examination, a patient sits in a chair facing the Purkinje-meter, keeping his chin and forehead resting on a support and having the unexamined eye covered with an occlusion. At the beginning of every measurement, values on the disc (both on the scale bar and the protractor) are set to zero.

A video recording of the examined eye with evolved Purkinje reflections is recorded throughout the measurement and the examiner observes it on the computer monitor. The examination begins with the patient's on-axis fixation (i.e., fixation on the target, which is set to zero). Subsequently, the examiner starts to move the fixation light (i.e., the examiner rotates the disc and moves the bar) to achieve the superposition of the 3rd and 4th Purkinje images, which are caused by the reflection of light from the front and back surfaces of the lens. At the moment of P3+P4 superposition achievement, the examiner notes down the values from the sliding bar and the protractor – magnitude, and direction of the fixation stimulus displacement, respectively.

From the on-axis fixation (Fig. 2A), the information about the visual axis of the eye, which is used by Purkinje-meter as the reference, is obtained; from the off-axis fixation with P3+P4 superposition (Fig. 2B), the information about the axis and center of the IOL is obtained. IOL tilt is defined as the angle between the IOL axis and the reference axis; IOL decentration corresponds to the distance between the center of the IOL and the reference axis. In the case of the P3+P4 superposition of the toric IOL, we can register the 3rd Purkinje image which is extended in the direction copying the toric axis of the IOL.

IOL Tilt Calculation

The tilt of the lens is characterized by two values: the tilt magnitude (degrees) and the tilt orientation (degrees). The direction of the lens tilt corresponds to the angle measured by the protractor on the Purkinje-meter at the moment, when the superposition of P3 and P4 is reached. The amount of tilt (α) can be calculated using the tangent function based on the knowledge of 1) the examination distance (which is constantly 40 cm) and 2) the position of the fixation point (target) at the moment of P3 and P4 superposition (the *FP* value in centimeters can be read from the scale bar during the measurement), see the equation below:

$$\mathrm{tg}\,\alpha = \frac{FP}{40}$$

IOL Decentration Calculation

As in the case of the IOL tilt, the decentration of the lens is characterized by two values: the decentration magnitude (millimeters) and the decentration orientation (de-

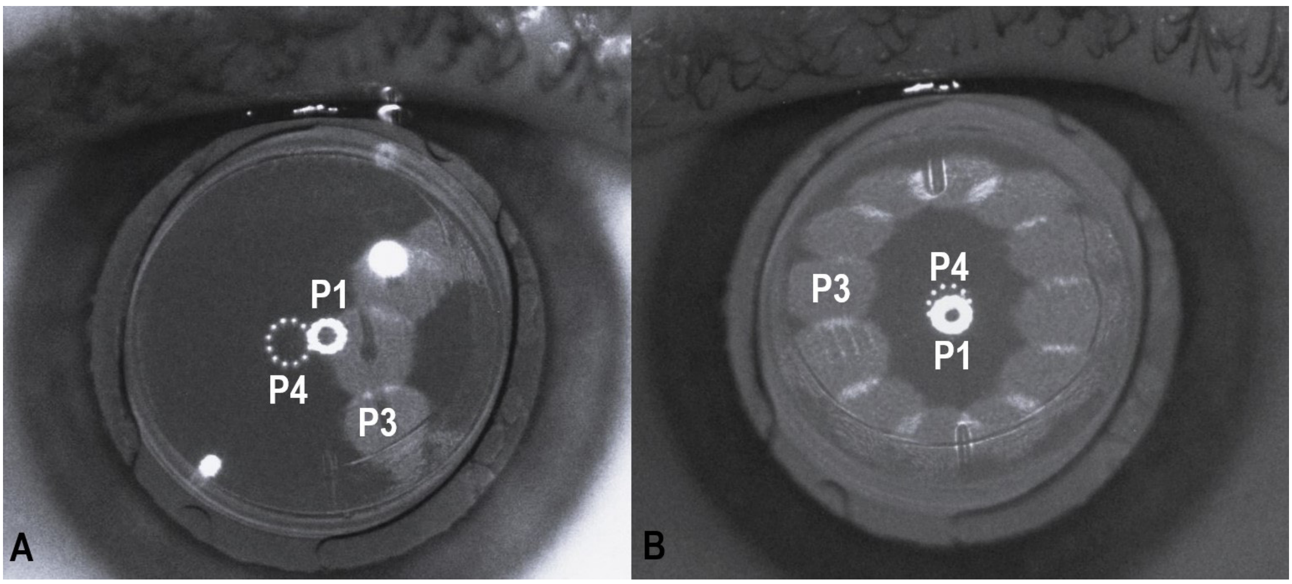

Fig. 2. Screenshot of a video recording on the dynamic Purkinje-meter. **A.** On-axis fixation. **B.** Off-axis fixation with the P3+P4 superposition (the P3 extension copying the toric axis of the IOL is visible). P1/P3/P4, 1st/3rd/4th Purkinje image.

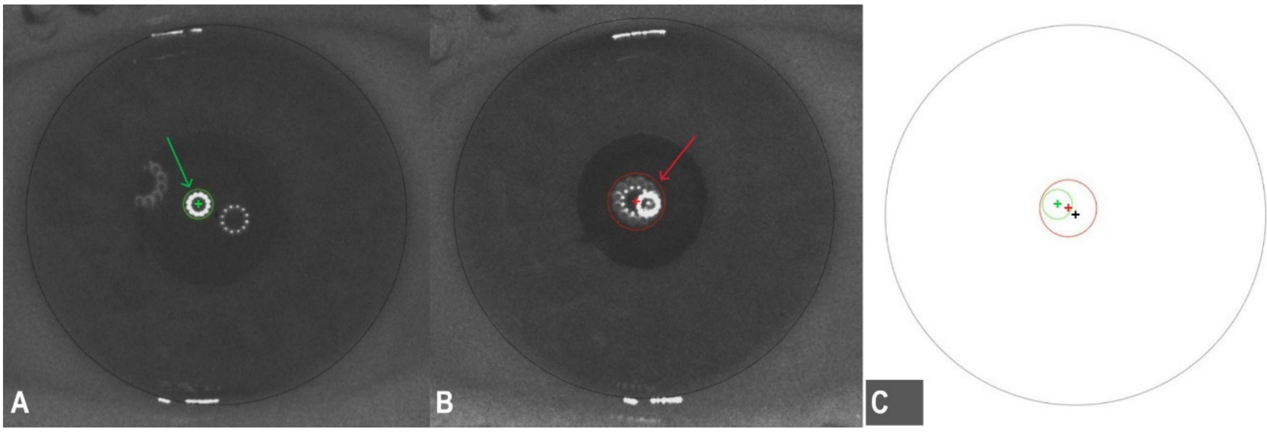

Fig. 3. Custom software image processing of video screenshots of the eye with Purkinje images. **A.** Interpolation of the 1st Purkinje image during on-axis fixation (green). **B.** Interpolation of the centered P3+P4 during off-axis fixation (red). **C.** relative position of P1 center (green), P3+P4 center (red) and center of the corneal limbus (black).

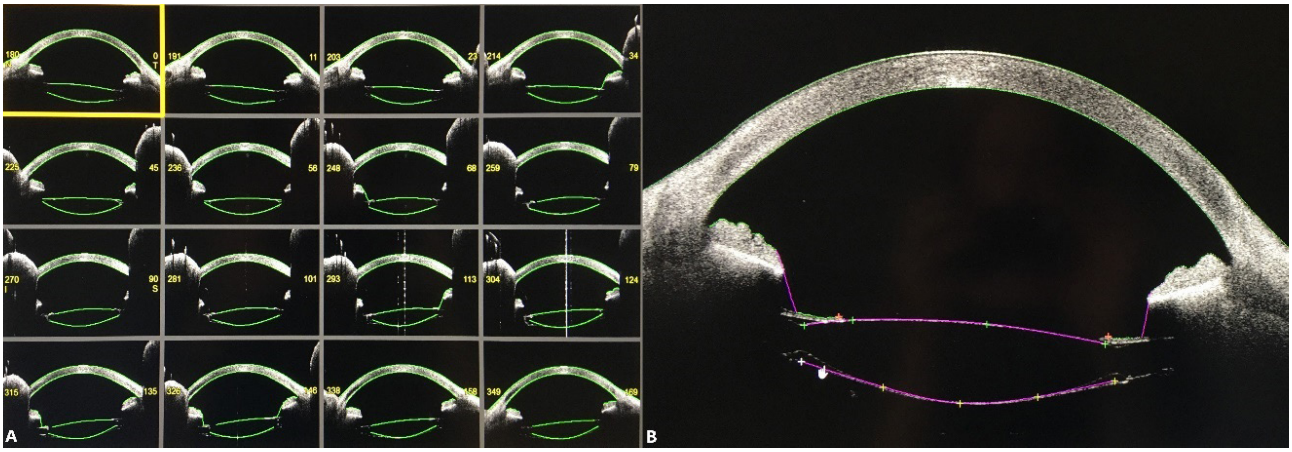

Fig. 4. AS OCT visualization of the anterior segment of the eye. **A.** 16 cross-sections with automatically detected IOL boundaries (green). **B.** One cross-section with manually traced IOL boundaries (pink).

grees). The IOL decentration was determined relative to the visual axis, which means relative to the position of the 1st Purkinje image during the on-axis fixation (i.e., zero rotation of the eyeball).

To evaluate the IOL decentration, a custom-developed software was used. The essence of this software is the possibility of calculating relative positions of any interlaced circles through embedded illustrations or photographs. In the custom software, video screenshots of the eye with the Purkinje images captured during the on-axis fixation and during the off-axis fixation (P3 and P4 superposition) were overlayed (Fig. 3). After the calibration of the custom software to the value of patient's corneal diameter ("white to white"), it is possible to determine the relative position of the center of P1 during on-axis fixation and of the center of P3+P4 superposition during off-axis fixation, and thus the final value of the IOL decentration magnitude and direction is obtained.

AS OCT Measurements

CASIA2 (Tomey Corp., Nagoya, Japan) is an anterior segment OCT that (unlike other commercially available systems used to measure the lens position) can automatically detect boundaries of the lens without the need for further processing. It is necessary to check the trace lines on the anterior and posterior surface of the crystalline lens before conducting analysis, otherwise accurate image correction cannot be achieved. If the device does not recognize the lens boundaries at all or traces them incorrectly, it is possible to draw the outline of the lens manually using the edit trace button[14]. Subsequently, the device itself calculates the tilt and decentration of the lens based on the measured data in sixteen different cross-sections (Fig. 4A). The automatic detection of IOL boundaries was always checked for all 16 cross-sections, and the IOL outlines were in the majority of cases adjusted manually as needed (Fig. 4B). The IOL decentration and tilt values measured by the instrument can be found in the device Post-op Cataract protocol.

The reference used by this AS OCT is a corneal vertex normal. This axis intercepts the cornea at the point called corneal vertex[23], which has been proven to be the closest point on the cornea to the intersection of the ideal visual axis with the cornea[24-26].

Statistical Analysis

The values of IOL decentration and tilt measured with AS OCT and dynamic Purkinje-meter and absolute values of differences between those measurements were evaluated using mean values and standard deviations. Statistical analysis was performed using Microsoft Excel and a statistics online calculator Statistics Kingdom[27]. Data distribution for normality was checked using Shapiro–Wilk's test. Paired values of the parameters measured using the two methods were tested with a paired t-test in the case of a normal data distribution, or with a non-parametric Wilcoxon signed-rank test if the observed data set did not correspond to a normal distribution. The *P*-value smaller than 0.05 was considered statistically significant. The relationship between values from different methods was evaluated using Pearson's correlation coefficient. A Bland-Altman plot was used to visualize the difference between the values measured using the two compared methods.

RESULTS

IOL Tilt

The mean IOL tilt magnitude measured using AS OCT and Purkinje-meter was 5.6° ± 1.3° (range from 2.5° to 7.5°) and 6.0° ± 1.4° (range from 2.4° to 8.3°), respectively. The Pearson's correlation coefficient was high (0.90). The IOL tilt magnitude values were lower for AS OCT ($P<0.05$). The mean absolute value of the difference between the values of the IOL tilt magnitude measured using the AS OCT and Purkinje-meter was 0.6° ± 0.4° (independently of the direction of the vector) and the mean vector difference magnitude was 1.2° ± 0.8° (the vector difference represents the difference between the tilt vector according to AS OCT and the tilt vector according to Purkinje-meter).

The mean IOL tilt direction measured using AS OCT and Purkinje-meter was for right eyes (OD) 200° ± 17° and 200° ± 12°, respectively, and for left eyes (OS) 341° ± 18° and 338° ± 17°, respectively. The Pearson's correlation coefficient was high (0.98). The difference of IOL

Table 1. Mean magnitude and direction of IOL tilt measured using AS OCT, using Purkinje-meter and the absolute and vector values of the difference between the values measured using the AS OCT and Purkinje-meter.

IOL tilt	Magnitude	Direction
AS OCT (mean ± SD)	5.6° ± 1.3°	200° ± 17° (OD) / 341° ± 18° (OS)
Purkinje-meter (mean ± SD)	6.0° ± 1.4°	200° ± 12° (OD) / 338° ± 17° (OS)
Absolute difference (mean ± SD)	0.6° ± 0.4°	10° ± 10°
Vector difference magnitude (mean ± SD)	1.2° ± 0.8°	---
Pearson's correlation coefficient	0.90	0.98
Paired test	$P<0.05$	$P=0.554$

Pearson's correlation coefficient and *P*-value based on a paired test (t-test or Wilcoxon test).

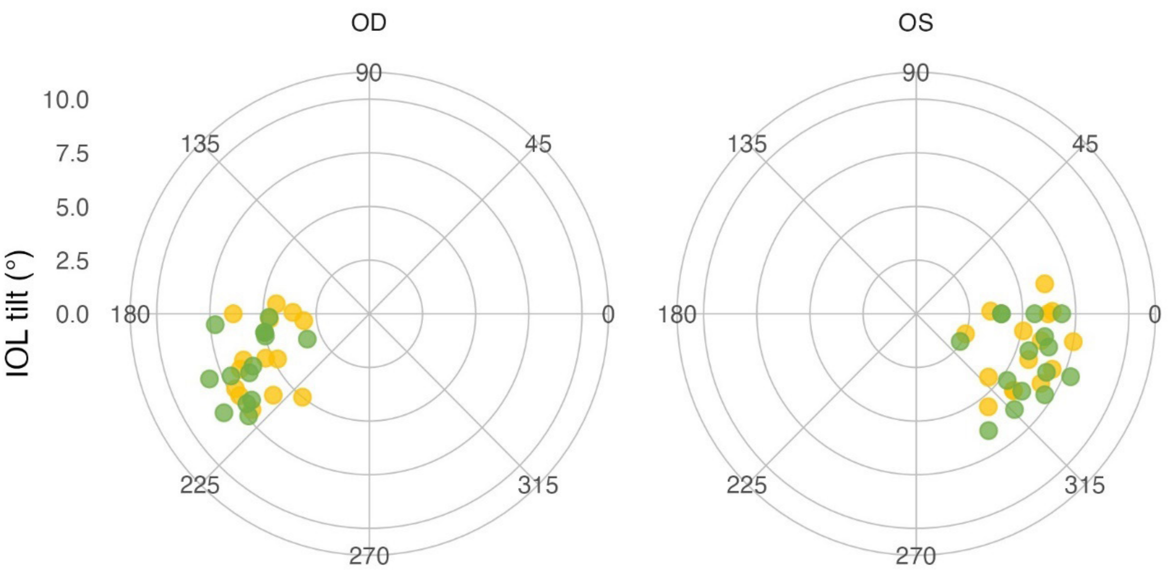

Fig. 5. The diagram of IOL tilt considering both the magnitude and the direction of tilt. The length between the dot and the origin of coordinates is the tilt magnitude, each ring represents 2.5°. The azimuth is the orientation of IOL tilt in degrees. Zero-degree corresponds to the nasal side of the patient's right eye (OD) and to the temporal side of the patient's left eye (OS). The yellow dots are for values from AS OCT and the green dots are for values from Purkinje-meter.

tilt direction values between both devices was statistically insignificant (*P*=0.554). The mean absolute value of the difference between the values of the IOL tilt direction measured using the AS OCT and Purkinje-meter was 10° ± 10°.

The IOL tilt data are listed in Table 1 and the IOL tilts are graphically shown in polar plots (Fig. 5).

IOL decentration

The mean IOL decentration magnitude measured using AS OCT and Purkinje-meter was 0.23 mm ± 0.15 mm (range from 0.02 mm to 0.67 mm) and 0.32 mm ± 0.18 mm (range from 0.04 mm to 0.70 mm), respectively. The Pearson's correlation coefficient was high (0.82). The IOL decentration magnitude values were lower for AS OCT (*P*<0.05). The mean absolute value of the difference between the values of the IOL decentration magnitude measured using the AS OCT and Purkinje-meter was 0.11 mm ± 0.08 mm (independently of the direction of the vector) and the mean vector difference magnitude was 0.13 mm ± 0.07 mm (the vector difference represents the difference between the decentration vector according to AS OCT and the decentration vector according to Purkinje-meter).

The mean IOL decentration direction measured using AS OCT and Purkinje-meter was for right eyes (OD) 174° ± 41° and 179° ± 37°, respectively, and for left eyes (OS) 264° ± 111° and 267° ± 107°, respectively. The Pearson's correlation coefficient was high (0.98). The difference of IOL decentration direction values between both devices was statistically insignificant (*P*=0.430). The mean absolute value of the difference between the values of the IOL decentration direction measured using the AS OCT and Purkinje-meter was 16° ± 14°.

The IOL decentration data are listed in Table 2 and the IOL decentrations are graphically shown in polar plots (Fig. 6).

To analyze the agreement between data from AS OCT and from Purkinje-meter, Bland-Altman plots were constructed for all measured parameters: IOL tilt magnitude, IOL tilt direction, IOL decentration magnitude and IOL decentration direction (Fig. 7).

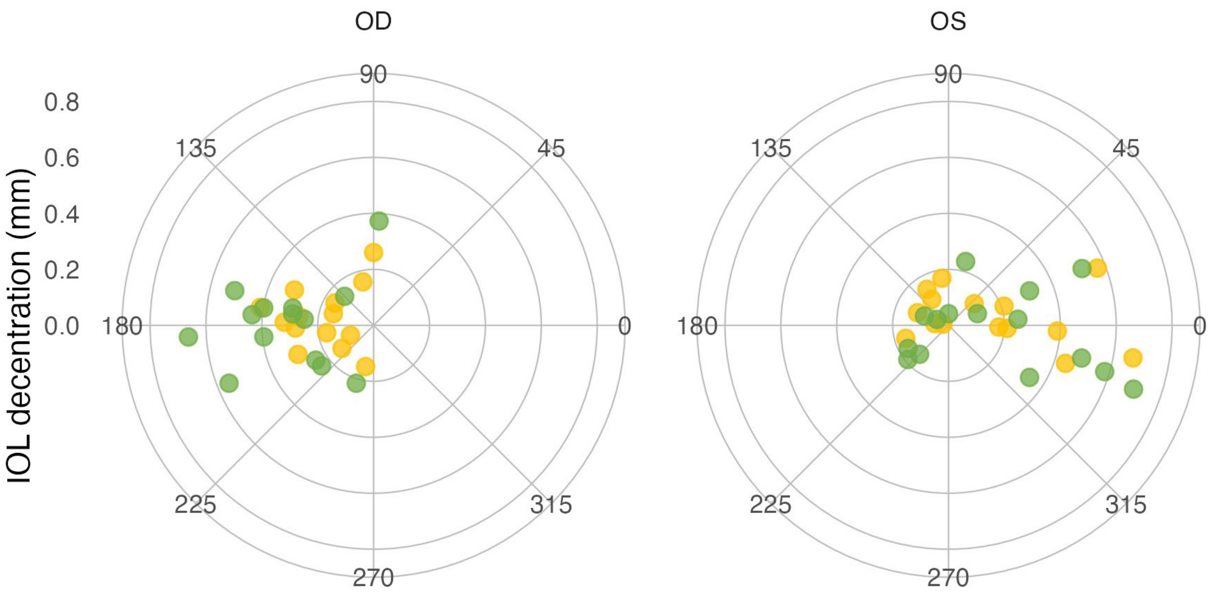

Fig. 6. The diagram of IOL decentration considering both the magnitude and the direction of decentration. The length between the dot and the origin of coordinates is the decentration magnitude, each ring represents 0.2 mm. The azimuth is the orientation of IOL decentration in degrees. Zero-degree corresponds to the nasal side of the patient's right eye (OD) and to the temporal side of the patient's left eye (OS). The yellow dots are for values from AS OCT and the green dots are for values from Purkinje-meter.

Table 2. Mean magnitude and direction of IOL decentration measured using AS OCT, using Purkinje-meter and the absolute and vector values of the difference between the values measured using the AS OCT and Purkinje-meter.

IOL decentration	Magnitude	Direction
AS OCT (mean ± SD)	0.23 mm ± 0.15 mm	174° ± 41° (OD) / 264° ± 111° (OS)
Purkinje-meter (mean ± SD)	0.32 mm ± 0.18 mm	179° ± 37° (OD) / 267° ± 107° (OS)
Absolute difference (mean ± SD)	0.11 mm ± 0.08 mm	16° ± 14°
Vector difference magnitude (mean ± SD)	0.13 mm ± 0.07 mm	–
Pearson's correlation coefficient	0.82	0.98
Paired test	*P*<0.05	*P*=0.430

Pearson's correlation coefficient and *P*-value based on a paired test (Wilcoxon test).

DISCUSSION

The main finding of the study is that the developed dynamic Purkinje-meter is a suitable tool for determining decentration and tilt of the implanted IOL. Both for IOL decentration and IOL tilt, the magnitude values measured by AS OCT are lower than values from the dynamic Purkinje-meter and the direction values measured by both methods are similar.

Overall, the data from the Purkinje-meter correlated well with the data from AS OCT – the value of the Pearson's correlation coefficient for the individual evaluated parameters was 0.82 and higher.

In 2022, Calzetti et al. published a study[28] in which they evaluated the repeatability of CASIA2 measurements of IOL tilt and decentration using the Bland-Altmann method. The accuracy of automatically detected IOL boundaries was checked in all 16 anterior segment cross-sections, as in our study. The limits of agreement (LoAs) shown in the published plots are very similar to those presented in our results (Fig. 7). Therefore, the repeatability of CASIA2 measurements is within similar LoAs as the difference between CASIA2 and Purkinje-meter measurements, so the inaccuracies can be caused by the CASIA2 lower repeatability.

As it is shown in the Bland-Altmann plots (Fig. 7), from a clinical point of view, a good agreement is achieved in the IOL tilt magnitude, which could be related with the fact that this parameter involves only normally distributed data. The LoAs have here even a smaller range than those presented in CASIA2 repeatability study[28]. As the tilt up to 2–3° is common and clinically insignificant for any IOL design[29], tilt magnitude differences within the LoAs do not have a significant effect on the aberrations of the eye. Significant changes in the quality of retinal images are observed for 5° tilt[10]. Unlike the tilt magnitude, the tilt direction has a smaller effect on the resulting aberrations, so the limits are clinically acceptable here as well.

For the IOL decentration magnitude, the LoAs have a similar range as those presented in CASIA2 repeatability study[28]. As the decentration up to 0.2–0.3 mm is common and clinically insignificant for any IOL design[29], the decentration magnitude differences within the LoAs do not cause significant changes in the resulting aberrations of the eye. Significant changes in the quality of retinal images are observed for 0.5 mm decentrations[10]. The decentration magnitude has a more significant effect on the resulting aberrations than the decentration direction, therefore clinically acceptable limits are here as well.

However, even such a difference between the measured values using these two methods is not a problem for clinical operation. Based on our experience and after viewing the video documentation from the Purkinje-meter measurements, it can be stated that more significant discrepancies occurred in patients with poorer cooperation during the examination or if the quality of the video recording of the examination was poorer. Increasing the use of the Purkinje meter in daily practice can enhance the operator's practical experience and improve patient cooperation.

Polar plots in Fig. 5 show the influence of the laterality of the eye on the direction of IOL tilt – for OD it is on average 200° (for both methods), while for OS it is 341° (using AS OCT) and 338° (using Purkinje-meter) on average. Thus, in both eyes, the IOLs tend to tilt in the inferotemporal direction, and it can be therefore argued that there is an axial symmetry along the vertical axis (so called mirror symmetry) between the IOL tilt in the right

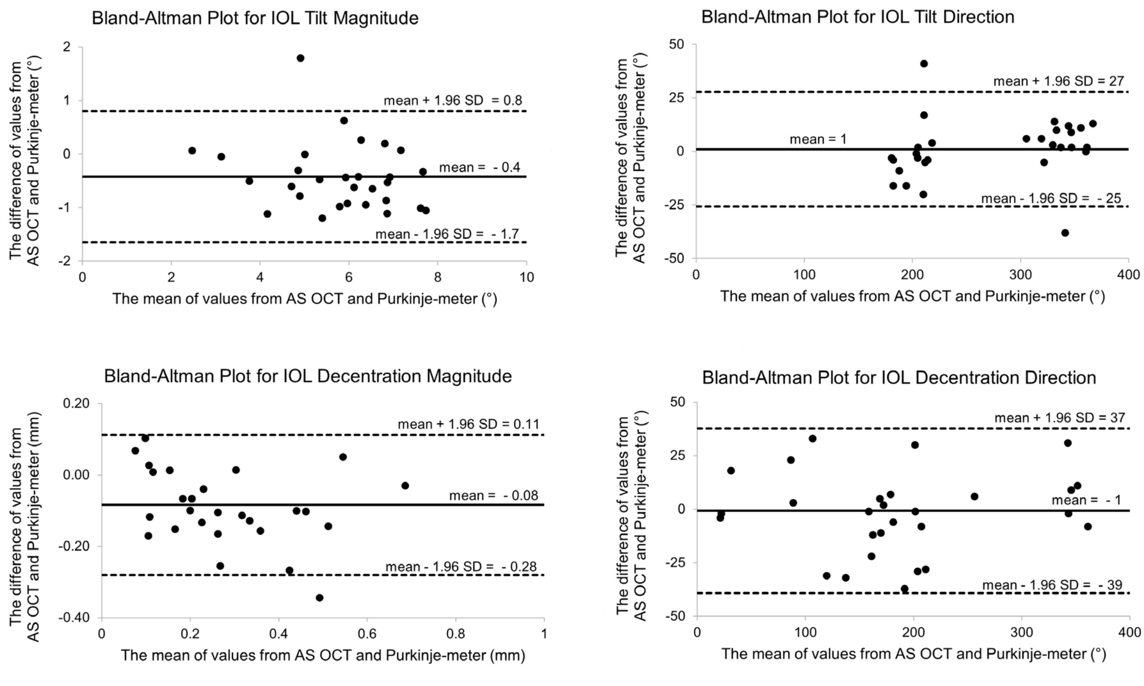

Fig. 7. Bland-Altman plots for all measured parameters: IOL tilt magnitude, IOL tilt direction, IOL decentration magnitude and IOL decentration direction.

and left eyes. A certain degree of axial symmetry can also be observed in the direction of IOL decentration (Fig. 6), but the tendency is not as clear as in the case of the tilt direction. Similar results were obtained by the authors of the recent study[30], which was also performed on the same AS OCT device – here the average IOL tilt was 205° for the right eye and 291° for the left eye, and at the same time there was no clear trend in the direction of decentration. Mirror symmetry in the change of IOL position was also noted in several other studies[13,15,31,32], regardless to the type of studied IOL (spheric or aspheric, C-loop or plate haptic). The mirror symmetry was measured also in phakic eyes[19].

In cases, where the discrepancy in the IOL decentration and tilt magnitude measured by the two methods was extreme (0.20 mm and more and 1.1° and more, respectively), the video documentation of the Purkinje-meter measurements was observed. It was noticed that these patients had poorer cooperation during the examination (relatively narrow eye slit, blinking, turning away from the fixation stimulus or small horizontal movements of the eyes) or there was a poorer quality of the video recording (photo contrast).

However, the mentioned problems with the patient's cooperation during the examination and their impact on the accuracy of the measured data do not apply only to measurements on the dynamic Purkinje-meter but they could also affect the measurements on AS OCT. When measuring on the AS OCT, the examiner cannot assess the correctness of the fixation. During an examination with the Purkinje-meter, the patient's fixation on the computer monitor can be checked thanks to the Purkinje images and the examiner can thus correct the patient's gaze direction, which is an advantage.

It has been already mentioned that the comparability of methods to measure the IOL displacement is questionable, as there has been no universal reference axis or point among the available studies[5]. Many of the studies, especially those using Purkinje-meters, set the pupil center or the pupillary axis as the reference[16,17,19,20,33-35]. Swept-source OCT biometer (i.e., IOLMaster 700) makes whole-eye OCT scans and can determine lens tilt with reference to the fovea, which lies on the visual axis[36]. Keratometric or topographic axis is used for alignment in keratometers and corneal topographers; this axis contains the center of curvature of the anterior surface of the cornea and is also called the *corneal vertex normal*, as it intercepts the anterior surface of cornea at the point called *corneal vertex*[23]. The corneal vertex is defined as the intersection of the cornea with the line connecting the fixation point and the 1st Purkinje image[24]. Vertex normal is used as a reference axis in anterior segment OCT, which was the point of interest of this study. It has been proven that the *corneal vertex* is the closest point on the cornea to the intersection of the ideal visual axis with the cornea[24-26]. So, for that reason, the values of IOL tilt and decentration obtained from AS OCT (with vertex normal as reference) and from our Purkinje-meter (with visual axis as reference) are comparable.

Also, an expression format of obtained IOL tilt and decentration differs across the studies and it is not always easy to compare the published results. The data are often presented as the coordinates of the IOL position relative to the reference structure, from which the exact value of the angle can be calculated, or only an approximate direction of the IOL tilt or decentration is given.

The resulting values of IOL tilt and decentration magnitude of this study were compared with some other published results, given in the same format and supplemented by reference structure and measurement method. Xiao et al.[30] (AS OCT, corneal topographic axis) measured values of tilt 5.6° ± 1.6° and decentration 0.18 mm ± 0.12 mm similar to the values from AS OCT in our study. Other published results of IOL position (presented in the same format) are given relative to the pupillary axis or pupil center, and thus the comparison with our results is questionable: tilt 2.9° ± 0.9° and decentration 0.56 mm ± 0.31 mm (Wang et al.[37], AS OCT Visante, pupillary plane), tilt 3.7° ± 1.2° and decentration 0.21 mm ± 0.17 mm (Fus et al.[38], custom software, pupil center), tilt less than 2.4° and decentration less than 0.4 mm (de Castro et al.[32], Pentacam Scheimpflug imaging, pupillary axis), tilt 1.5° and decentration 0.21 mm (Rosales et al.[31], Pentacam Scheimpflug imaging, pupillary axis), tilt 4.4° ± 2.5° (T) and 9.20° ± 6.96° (S) and decentration 0.44 mm ± 0.19 mm (T) and 0.74 mm ± 0.91 mm (S) (Maedel et al.[39], Tabernero's (T)[17] and Schaeffel's (S)[19] Purkinje-meters, pupillary axis). All the mentioned IOL tilt values are smaller than those from our study (both AS OCT and dynamic Purkinje-meter), apart from the Schaeffel's Purkinje-meter values which are higher (9.2° ± 7.0°) and are given relative to the fixation axis as the only ones. The values of IOL decentration vary considerably across the studies, even if the reference structure is limited to the pupil only – the range of mean values is from 0.17 mm to 0.74 mm[30-32,37-39]. We assume that different decentrations may depend primarily on different types of intraocular lenses.

Table 3. Characteristics of experimental Purkinje-meters.

Purkinje-meter	Used in this study	Tabernero et al.[17]	Schaeffel[19]
Arrangement	dynamic	static	static
Fixation target	1 LED, movable	9 fixed LEDs (9 directions)	1 fixed LED
Light source	12 IR LEDs, (semi)circle	7 IR LEDs, semicircle	1 IR LED
Detector	CMOS camera	CCD camera	analog CCD camera
Reference structure	visual axis	pupillary axis	pupil center (decentration), fixation axis (tilt)
Image processing	custom software	Zemax software	custom software
Dilated pupil	not necessary	necessary	not necessary

Table 3 summarizes the main characteristics of the dynamic Purkinje-meter used in this study and of the static Purkinje-meters designed and used for IOL position measurement by Tabernero et al. and Schaeffel[17,19].

All three mentioned Purkinje-meters use IR LEDs as a light source, but they differ in their number and arrangement. The Schaeffel's Purkinje-meter differs the most with its point light source, which brings certain disadvantages: it is more difficult to estimate the optimal focus of point reflexes[39], which are small and symmetrical, and thus the individual Purkinje images are often undistinguishable, especially when they are overlapped. Identifying Purkinje images is easier with a semicircular source due to its asymmetric geometry – especially for determining P4, which is inverted. In addition, thanks to the width of the source, even the Purkinje images which are partially obscured by the iris can be localized. With the dynamic Purkinje-meter, also a circular shape of the source is needed due to the necessary superposition of P3+P4.

The design of the light source and the device arrangement determine the necessity of a pupil dilation for measuring the IOL position. Schaeffel states that even with a pupil with a diameter of only 2.5 mm, the IOL position was measured by their system without problems[19]. This statement is questionable as both a point source and a narrow pupil make the examination challenging: even with a relatively small degree of IOL decentration or IOL tilt, the shift of P3 and P4 relative to P1 (during on-axis fixation) can be significant and the reflexes induced by the point light source can be hidden behind the iris. With the same rate of IOL decentration or IOL tilt and with the same pupil diameter, a circular or semi-circular light source would produce larger Purkinje images, which would be partially hidden behind the pupil, but thanks to their shape, it would be possible to assess the missing part of the reflex and thus to estimate the reflex position. On the contrary, with Tabernero's system, a good pupil dilation (at least 6 mm) is a prerequisite for capturing quality images with three clear Purkinje images[16]. But even with this system, which has a semi-circular light source, the visibility of the exact relative position of Purkinje images (in the dilated pupil) is influenced by the design of the IOL. In on-axis fixation, IOLs with a large curvature of the anterior (or posterior) surface produce the third (or fourth) Purkinje image which is too large and only its part is visible during the examination, or it is not visible at all – and this complication is caused by a static arrangement of the Purkinje-meter.

From our experience, it is difficult even to obtain a reliable static image, especially in patients who are less cooperative. The dynamic Purkinje-meter combines the construction of static Purkinje-meters with a dynamic examination of the IOL position according to the optical axis of the IOL, presented by Guyton et al.[20]. The advantage of the dynamic arrangement is primarily the possibility of a defined change in the position of the fixation stimulus associated with a dynamic evaluation of the relative position of the Purkinje images. The method thus makes it possible to exclude mistakes of a "random" static image and measure a large range of changes in the IOL position even with a relatively narrow pupil.

CONCLUSION

The values of IOL tilt and decentration direction are similar for both devices and show a mirror symmetry. The values of IOL tilt and decentration magnitude measured by Purkinje-meter are higher than those from AS OCT, but overall, they correspond to the values presented in other published studies. For that reason, the experimental dynamic Purkinje-meter could serve as a reliable tool for assessing the IOL tilt and decentration.

ABBREVIATIONS

AS OCT, Anterior segment optical coherence tomography; CCD camera, Camera with a "charge-coupled device" sensor; IOL, Intraocular lens; IR, Infrared; LED, Light emitting diode; OD/OS, Right/left eye; P1/P2/P3/P4, 1st/2nd/3rd/4th Purkinje image; UBM, Ultrasound biomicroscopy.

Acknowledgments: This work was supported by the Grant Agency of the Czech Technical University in Prague (grant No. SGS18/096/OHK4/1T/17). The authors acknowledge the Center of Eye Microsurgery Ofta (Pilsen, Czech Republic), where all the cataract surgeries and postoperative measurements were taken, and also the research was financially supported by this workplace. The authors also acknowledge Ondrej Hatle for the creation of custom software and Vaclav Petrak for the help with the statistical analysis.

Author contributions: EP: manuscript writing, investigation; JC, JN: manuscript editing; JC: supervision; EP, JC: concept; EP, JC, JN: literature search, methodology.

Conflict of interest statement: The authors state that there are no conflicts of interest regarding the publication of this article.

Ethics approval and informed consent: The study was approved by the Ethics Committee for Multi-Centric Clinical Trials of the University Hospital Motol and Second Faculty of Medicine, Charles University in Prague, Czech Republic (reference No. EK – 1019/23). All participants signed an informed consent to participate in this study.

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