Pupil barycenter configuration in patients with myopia and hyperopia

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Abstract
Purpose To compare the apparent chord mu between hyperopia and myopia cases and investigate the usefulness of iris barycenter configurations as an alternative for performing kappa angle distance calculations.

Methods This prospective study evaluated 394 eyes of 197 patients classified into two groups according to their spherical equivalent values: the myopic (mean spherical equivalent refraction $\leq -0.50$ D) and the hyperopia group (mean spherical equivalent refraction $\geq +0.50$ D). The two groups were further subdivided according to severity (myopic group: mild, $\leq -0.50$ and $\leq -3.00$ D; moderate, $<-3.00$ and $\leq -6.00$ D; severe, $<-6.00$ D; hyperopic group: mild, $\geq +0.50$ and $\leq +2.00$ D; moderate, $>+2.00$ and $\leq +4.00$ D; severe, $>+4.00$ D). The pupil and iris barycenter distance measurements and other parameters were obtained through optical low-coherence reflectometry.

Results Of the 197 patients, 109 (55.3%) were female and 88 (44.7%) were male individuals; their ages ranged from 7 to 60 years (mean, 35.16±14.75 years). The average pupil barycenter distances were 0.38±0.15 and 0.21±0.11 mm in hyperopia and myopia patients, respectively ($p<0.01$). Corneal and lens thickness measurements were higher in hyperopia patients ($p<0.01$, $p<0.01$, respectively), whereas anterior chamber depth and pupil diameter measurements were higher in myopia patients ($p<0.01$, $p<0.01$, respectively). No significant difference in astigmatism or white-to-white measurements was observed between hyperopia and myopia patients ($p>0.05$).

Conclusion The measurements for the apparent chord mu of the pupil and iris barycenter origins were higher in hyperopic than in myopic cases.

Keywords Pupil barycenter · Iris barycenter · Kappa angle · Myopia · Hyperopia

Introduction
The kappa angle is generated by the intersection of the visual axis and the pupillary axis in the pupillary space. If the light reflex is on the nasal side, it is classified as positive; if it is on the temporal side, it is classified as negative [1–3]. The line perpendicular to the center of the corneal curvature at the entrance of the pupil is the pupillary axis, and the line joining the fixation point and the fovea is the visual axis [3]. Chord mu is considered to
be the new reference marker. It describes the displacement between the subject-fixated coaxially sighted corneal light reflex and the pupil center. The apparent chord mu is defined as the apparent distance between Purkinje–Sanson image 1 and the apparent pupillary center when viewed coaxially from the light source through the cornea [4]. The mean apparent chord mu was calculated to be 0.3 ± 0.15 mm. The values of actual chord mu range from 0.2 ± 0.11 mm [4].

The fovea is located somewhat temporally with respect to the point where the pupillary axis intersects the posterior pole of the globe. Therefore, the normal kappa angle is somewhat positive. Parallel to this, the corneal light reflex is somewhat on the nasal side, and the pupillary axis is more temporal [5, 6].

In refractive surgery cases, the kappa angle is a clinically important entity and may play a role in refractive results [7, 8]. A wide kappa angle (0.6 mm) may cause misalignment errors during photoablation in laser refractive surgery and lens decentralization after multifocal lens implantation, leading to irregular astigmatism, photic phenomena (glare and halo), and decreased best-corrected visual acuity [9].

Although different methods are used to measure the kappa angle, the corneal reflection method, using a synoptophore or major amblyoscope, is used to measure the true kappa angle [9]. Orbscan II (Bausch & Lomb, Rochester, NY, USA), Galilei (Ziemen Ophthalmic Systems, Port, Switzerland), and OPD Scan II (Nidek, Gamagori, Japan) are the newer devices used to determine the kappa angle [10].

The working principle of Lenstar LS 900 (Haag-Street AG, Koeniz, Switzerland) is based on optical low-coherence reflectometry using a wide-band light source with a central wavelength of 820 µm. Lenstar does not directly determine the kappa angle. Instead, it measures the pupil barycenter [3] by measuring the distance (x and y Cartesian values) between the corneal vertex and the pupillary center, from which the kappa angle can be determined according to the Pythagorean theorem [9].

In this work, we aimed to compare the apparent chord mu between hyperopia and myopia patients and investigate the usefulness of iris barycenter configurations as an alternative option for kappa angle distance calculations.

**Methods**

**Study design and patients**

This prospective study was performed at the Private Medipol University Faculty of Medicine and Kütahya Anadolu Hospital between September 2020 and January 2021. Patients with hyperopia or myopia > 0.50 D, normal slit-lamp and fundoscopy examination results, intraocular pressure levels < 21 mmHg, and with no history of systemic or ocular corticosteroid medication administration were included. In contrast, patients who were taking drugs that can affect pupil diameter (such as miotics, mydriatics, or other systemic drugs) or had corneal astigmatism values > 1.00 D, irregular astigmatism, dry-eye syndrome, pupillary abnormality, corneal disease, glaucoma or intraocular inflammation history, or previous ocular surgery history, were excluded. In total, 394 eyes (197 right and left eyes, respectively) from 197 patients were examined. Power analysis was performed (Confidence interval, 95%; power, 80%; 162 eyes per group). The patients included in the study were classified into two main groups according to their spherical equivalent values as follows: the myopic group (mean spherical equivalent refraction ≤ −0.50 D) and the hyperopia group (mean spherical equivalent refraction ≥ +0.50 D). The two groups were further subdivided according to severity (myopic group: mild, ≤ −0.50 and ≤ −3.00 D; moderate, < −3.00 and ≤ −6.00 D; severe, < −6.00 D; hyperopic group: mild, ≥ +0.50 and ≤ +2.00 D; moderate, > +2.00 and ≤ +4.00 D; severe, > +4.00 D).

The pupil and iris barycenter distance measurements and other parameters were obtained using Lenstar LS 900 optical low-coherence reflectometry. The corneal vertex was evaluated while the eye was focused on an object. Additionally, the distance (x and y Cartesian values) between the corneal vertex and the pupillary center was measured using Lenstar LS 900. After measuring the pupil barycenter (the x and y coordinates of the pupil—dx and dy, respectively), we used the Pythagorean theorem to calculate the apparent chord mu in terms of distance. The apparent chord mu was calculated diagonally (hypotenuse), that is, the square root of the sum of the squares of the pupil dx and pupil dy [8, 10]. Using the same theorem, we calculated the apparent chord mu formed based on the distance.
between the corneal vertex and the center of the iris over the iris barycenter values. All measurements were conducted by the same experienced observer (İ.C.).

Statistical analysis

The Number Cruncher Statistical System 2007 program (NCSS, Kaysville, UT, USA) was used for statistical analysis. Descriptive statistical methods (mean, standard deviation, median, frequency, percentage, minimum, and maximum) were used to evaluate the study data. The suitability of the quantitative data to normal distribution was tested using the Shapiro–Wilk test and graphical analysis. Student’s t test was used to compare normally distributed quantitative variables between the two groups, one-way analysis of variance was used for three-group evaluations, and the Bonferroni test was used for post hoc comparisons. The Mann–Whitney U test was used to compare quantitative variables that did not show normal distribution between the two groups. The Kruskal–Wallis test was used in three-group evaluations. Pearson’s $\chi^2$ test was used to evaluate categorical variables, and statistical significance was set at $p < 0.05$.

Results

Of the 197 patients, 55.3% ($n = 109$) were female and 44.7% ($n = 88$) were male. The ages of the patients ranged from 7 to 60 years (mean, 35.16 ± 14.75 years). The patients’ characteristics are presented according to groups in Table 1. The spherical equivalent values were significantly different between the hyperopic and myopic groups ($p < 0.05$). Similarly, the distributions of mild, moderate, and severe cases based on spherical equivalent values showed statistically significant differences between the hyperopic and myopic groups ($p < 0.05$) (Table 2). A statistically significant difference in corneal thickness was observed between the hyperopic and myopic groups ($p < 0.01$), with higher values observed in patients with hyperopia (Table 3). A statistically significant difference in anterior chamber measurements was found between the hyperopic and myopic groups ($p < 0.01$), with higher values observed in patients with myopia. A statistically significant difference in lens thickness was found between the hyperopic and myopic groups ($p < 0.01$), with thicker lens observed in patients with hyperopia. There were no statistically significant differences in astigmatism or white-to-white measurement between the hyperopic and myopic groups ($p > 0.05$). A statistically significant difference in iris barycenter measurements was observed between the hyperopic and myopic groups ($p < 0.01$), with higher values observed in patients with hyperopia (Fig. 1). Similarly, a statistically significant difference in pupil diameter was found between the hyperopic and myopic groups ($p < 0.01$), with higher pupil diameter observed in patients with myopia. A statistically significant difference in pupil barycenter measurements

### Table 1: Evaluation of descriptive characteristics according to groups

|                | Hyperopic ($n = 99$) | Myopic ($n = 98$) | $p$ value  |
|----------------|---------------------|------------------|------------|
| Age (years)    | 40.71 ± 15.86       | 29.55 ± 11.04    | 0.001***   |
| Sex            |                     |                  |            |
| Male           | 46 (46.5)           | 42 (42.9)        | 0.611b     |
| Female         | 53 (53.5)           | 56 (57.1)        |            |

*a Student’s t test  
bPearson’s $\chi^2$ test  
**$p < 0.01$

### Table 2: Evaluation of descriptive properties according to spherical equivalent

|                   | Hyperopic ($n = 198$) | Myopic ($n = 196$) | $p$ value  |
|-------------------|-----------------------|--------------------|------------|
| Spherical equivalent |    |                     |            |
| Min/max (median)   | 0.25/12.1 (2.1)       | −20.1/5.1 (−2.9)   | 0.001**    |
| Mean ± standard deviation | 2.81 ± 2.10           | −3.32 ± 2.72      |            |
| Mild              | 98 (49.5)             | 106 (54.1)        | 0.009b**   |
| Moderate          | 63 (31.8)             | 74 (37.8)         |            |
| Severe            | 37 (18.7)             | 16 (8.2)          |            |

*a Mann–Whitney U test  
bPearson’s $\chi^2$ test  
**$p < 0.01$
was found between the hyperopic and myopic groups ($p<0.01$), with higher pupil barycenter values observed in patients with hyperopia. In hyperopic cases, a statistically significant difference was found between iris barycenter measurements according to the spherical equivalent classification ($p<0.01$). Iris barycenter measurements were observed to be significantly lower in the mild than in the moderate and severe groups ($p=0.001$, $p=0.001$, and $p<0.01$) (Fig. 2). Moreover, the iris barycenter measurements of the moderate group were significantly lower than those of the severe group ($p=0.018$ and $p<0.05$). Although there was no statistically significant difference in pupil barycenter measurements between the groups according to the spherical equivalent classification ($p=0.093$ and $p>0.05$), the pupil barycenter

**Table 3** Evaluations by groups

|                         | Hyperopic | Myopic     | $p^a$   |
|-------------------------|-----------|------------|---------|
| **Axial length (mm)**   |           |            |         |
| Min–max (median)        | 19.4–25.3 (22.5) | 22.2–30.2 (24.5) | 0.001b** |
| Mean ± SD               | 22.37 ± 1.18 | 24.59 ± 1.27 |         |
| **Corneal thickness (µm)** |           |            |         |
| Min–max (median)        | 476–633 (548) | 412–614 (539.5) | 0.001** |
| Mean ± SD               | 547.93 ± 31.94 | 538.42 ± 32.47 |         |
| **Anterior chamber depth (mm)** |           |            |         |
| Min–max (median)        | 2.3–5 (3.2) | 2.4–4.9 (3.6) | 0.004** |
| Mean ± SD               | 3.19 ± 0.39 | 3.63 ± 0.34 |         |
| **Lens thickness (mm)** |           |            |         |
| Min–max (median)        | 3.1–5 (4) | 0.6–4.7 (3.7) | 0.001b** |
| Mean ± SD               | 4.04 ± 0.44 | 3.70 ± 0.42 |         |
| **Flat meridian (D)**   |           |            |         |
| Min–max (median)        | 37.7–47.4 (42.9) | 38.1–46.4 (43.3) | 0.009** |
| Mean ± SD               | 42.84 ± 1.80 | 43.28 ± 1.54 |         |
| **Steep meridian (D)**  |           |            |         |
| Min–max (median)        | 40.3–48.9 (44) | 39.1–54.8 (44.4) | 0.002** |
| Mean ± SD               | 44.05 ± 1.73 | 44.63 ± 2.00 |         |
| **Astigmatism (D)**     |           |            |         |
| Min–max (median)        | 0–4.5 (1) | 0–9.4 (1.1) | 0.074b |
| Mean ± SD               | 1.21 ± 0.97 | 1.35 ± 1.20 |         |
| **White-to-white (mm)** |           |            |         |
| Min–max (median)        | 10.9–13.6 (12) | 11.2–13.3 (12.1) | 0.064 |
| Mean ± SD               | 12.0 ± 0.48 | 12.08 ± 0.39 |         |
| **Iris barycenter**     |           |            |         |
| Min–max (median)        | 0.1–0.9 (0.5) | 0.1–1 (0.4) | 0.001** |
| Mean ± SD               | 0.50 ± 0.14 | 0.37 ± 0.13 |         |
| **Pupil diameter (mm)** |           |            |         |
| Min–max (median)        | 3–6.9 (4.7) | 3–8.1 (5.1) | 0.001** |
| Mean ± SD               | 4.69 ± 0.85 | 5.14 ± 0.94 |         |
| **Pupil barycenter**    |           |            |         |
| Min–max (median)        | 0–0.9 (0.4) | 0–0.7 (0.2) | 0.001** |
| Mean ± SD               | 0.38 ± 0.15 | 0.21 ± 0.11 |         |

$SD$ standard deviation  
$^a$Student’s $t$ test  
$^b$Mann–Whitney $U$ test  
$^{**p<0.01}$

**Fig. 1** Distribution of iris and pupil barycenter measurements by groups

**Fig. 2** Iris barycenter measurements according to the spherical equivalent groups
measurements were significantly lower in the severe group \((p=0.001\) and \(p<0.01\)), while those of the moderate group were significantly lower than those of the severe group \((p=0.002\) and \(p<0.01\)) (Fig. 3).

In patients with myopia, no statistically significant difference was found between the iris and pupil barycenter measurements, according to the spherical equivalent classification \((p>0.05)\) (Table 4).

### Discussion

This study compared the pupil barycenter configurations that can be used to calculate the apparent chord mu in terms of distance in patients with myopia and hyperopia. The results showed that the apparent chord mu over the pupil barycenter distance was higher in hyperopic than in myopic cases. In another study, higher positive kappa angle values were found in patients with hyperopia than in those with myopia and emmetropia [5]. A difference was observed between the mean kappa angle values of the right and left eyes [5]. The kappa angles of the left eyes of patients with emmetropia tend to be slightly increased [1, 5, 11]. In our study, the mean distance of the pupil and iris barycenter origins was higher in the right than in the left eye in both myopic and hyperopic cases.

Evidence showing the importance of the kappa angle in refractive surgery, whether in laser surgery or in multifocal lens treatment, is increasing [12–15]. Generally, hyperopic eyes have a wide kappa angle, and these eyes are prone to decentralized treatment during laser ablation [16]. The mean kappa angles were 5.46° and 5.22° in the studies by Hashemi et al. [2] and Basmak et al. [5], respectively. The insignificant difference between the angles is supposedly attributed to the age of the participants, which was between 14 and 81 years in the study by Hashemi et al. [2] and between 20 and 40 years in the study by Basmak et al. [5]. In this study, the participants’ ages ranged from 7 to 60 years, and the mean pupil barycenter distance was 0.30 mm.

In the study by Hashemi et al. [2], the mean kappa angles for patients with myopia, emmetropia, and hyperopia were 5.13° ± 1.50°, 5.72° ± 1.10°, and 5.52° ± 1.19°, respectively. A significant correlation was found between the refractive status of the patients and the kappa angle measurements, in line with the findings of Hashemi et al. [2]. In the study by Basmak et al. [5], the values, which were obtained using Orbscan II, for patients with myopia, emmetropia, and hyperopia were 4.51°, 5.55°, and 5.65°, respectively [5]. Qazi et al. [16] measured the preoperative kappa angles using Orbscan and reported values of 5.0° and 6.9° in myopic and hyperopic cases, respectively.

### Table 4

| Spherical equivalent | Iris barycenter | Pupil barycenter |
|----------------------|----------------|------------------|
|                      | Moderate       | Moderate         |
| Hyperopic Iris barycenter | Mild  | 98              | 0.44             | 0.12 | 0.001*** |
|                      | Moderate       | 63              | 0.53             | 0.12 |          |
|                      | Severe         | 37              | 0.60             | 0.14 |          |
| Pupil barycenter     | Mild  | 98              | 0.34             | 0.13 | 0.001*** |
|                      | Moderate       | 63              | 0.39             | 0.15 |          |
|                      | Severe         | 37              | 0.49             | 0.15 |          |
| Myopic Iris barycenter | Mild  | 106             | 0.38             | 0.14 | 0.672b   |
|                      | Moderate       | 74              | 0.36             | 0.12 |          |
|                      | Severe         | 16              | 0.38             | 0.14 |          |
| Pupil barycenter     | Mild  | 106             | 0.21             | 0.11 | 0.702b   |
|                      | Moderate       | 74              | 0.22             | 0.12 |          |
|                      | Severe         | 16              | 0.21             | 0.10 |          |

**SD** standard deviation

*a One-way analysis of variance

*b Kruskal–Wallis test

**p < 0.01
with an average spherical equivalent of 3.50 D. The average kappa angles were 4.66° in cases of myopia with refractive defects between −3.00 and −6.00 D, while they were 5.45° in cases of hyperopia with refractive defects between 2.00 and 4.00 D. In our study, the mean pupil barycenter origins of the apparent chord mu were 2.85 ± 1.12° (0.38 ± 0.15 and 0.21 ± 0.11 mm) in hyperopia and myopia cases, respectively. The mean distance of the pupil barycenter originating from the apparent chord mu was 1.65° (0.22 mm) in myopia cases with a refractive error between −3.00 and −6.00 D, and 2.92° (0.39 mm) in hyperopia cases with a refractive error between 2.00 and 4.00 D.

Kappa angle measurement may depend on the biometric, geometric, and optical properties of the cornea, globe, retina, crystalline lens, and anterior chamber depth. Depending on the corneal power, anterior chamber depth, and nodal point, we can expect that the optic axis and the entrance and exit of the pupil have specific localizations. The visual axis also depends on the geometric and anatomical features of the fovea, nodal point, and pupil entrance. Thus, there may be a relationship between the geometric, optical, and biometric properties of the eye when there are changes in the kappa angle [2].

A synoptophore measures the kappa angle using the corneal reflection method, which is the most widely used method in clinical practice [6]. Basmak et al. [5] used both Orbscan II corneal topography and synoptophore to measure the basin and arc kappa angle. According to their results, the kappa angles obtained with Orbscan II were higher than those obtained with synoptophore. Additionally, they reported higher kappa angles in patients with hyperopia than in those with emmetropia or myopia. Yeo et al. [17] used ultrasound biomicroscopy and corneal topography to measure the kappa angle and obtained reliable results. New instruments, such as Galilei (Ziemer Ophthalmic Systems) and OPD Scan II (Nidek), are currently being used to measure the kappa angle. If the kappa angle cannot be automatically and directly measured, the distance between the corneal vertex and the pupillary center (x and y Cartesian values) can be used to calculate the kappa angle [18]. The Lenstar LS 900 (Haag-Streit AG, Koniz, Switzerland) device can be used for this purpose. Although Lenstar LS 900 does not directly measure the kappa angle [9], we can apply the Pythagorean theorem to measure the pupil barycenter distances (x and y coordinates of the pupil center; dx and dy) and determine the apparent chord mu. Likewise, we evaluated the apparent chord mu using the iris barycenter distances (x and y coordinates of the iris center; dx and dy) and compared the pupil and iris barycenter origin of the apparent chord mu.

In our study, the apparent chord mu was higher in hyperopic cases when calculating it in both the pupil and iris barycenter origins. Although the corneal and lens thickness values were higher in the hyperopic cases included in our study, the anterior chamber depth and pupil diameter were similarly observed to be higher in myopic cases. Moreover, no significant differences were observed between hyperopic and myopic cases in terms of astigmatism and white-to-white measurements.

This study had several limitations. First, patients with emmetropia were not included in this study, and second, the study was not conducted according to age groups. More objective evaluations can be performed by including primarily hyperopic and myopic cases as well as emmetropic cases. If cases are categorized according to age groups, age-related changes in the kappa angle can equally be detected. The third limitation was that we did not automatically measure the kappa angle using automated instruments; rather, x and y cartesian values were used to estimate the kappa angle.

In conclusion, the apparent chord mu was found to be higher in hyperopic than in myopic cases. The measurements were higher in hyperopic cases when calculating the apparent chord mu of both the pupil and iris barycenter origins than in myopic cases. If there are no abnormalities, such as ectopic pupil or pupillary irregularity, iris barycenter configurations can be used instead of pupil barycenter configurations.

Author contributions Both authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by HK and FK. The first draft of the manuscript was written by HK, and both authors commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article.
Declarations

Conflict of interest  The authors have no relevant financial or nonfinancial interests to disclose.

Ethical approval  The study was conducted in accordance with the principles of the Helsinki Declaration. The study was reviewed and approved by the Private Istanbul Medipol University Ethics Committee (17/09/2020/699).

Consent to participate  All patients provided written informed consent.

Consent to publish  The participant has consented to the submission of the case report to the journal.

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