ARTICLE

Application of Purkinje images for pinhole pupilloplasty and relevance to chord length mu

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Purpose: To evaluate the results of pinhole pupilloplasty in cases with high astigmatism and higher-order aberrations (HOAs).

Setting: Dr. Agarwal's Eye Hospital & Research Centre, Chennai.

Design: Case series.

Methods: Pinhole pupilloplasty was performed based on the Purkinje 1 (P1) images formed from the light source of a Lumera surgical microscope; the images served as a reference marker for centration. A single-pass 4-throw technique was used to achieve a pinhole pupil. The preoperative and postoperative pupil diameter, uncorrected (UDVA) and corrected (CDVA) distance visual acuities, simulated keratometry (K), and chord length mu (μ) were assessed, the latter using a Pentacam rotating Scheimpflug camera.

Results: Pinhole pupilloplasty was performed in 8 eyes (8 patients). There was a statistically significant reduction in the mean horizontal and vertical pupil diameters and in the mean pupil diameter from preoperatively to postoperatively (both $P < .001$). Although the improvement in UDVA was statistically significant ($P < .001$), the change in CDVA was not. The mean simulated K and mean chord length μ values were significantly lower postoperatively ($P = .024$ and $P < .001$, respectively). The reduction in pupil size was more apparent than the reduction in chord length μ. The correlation between the change in chord length μ and the change in pupil size was not significant ($r = -0.067$, $P = .874$). The pupil was well centered on the P1 images. No major adverse events or complications occurred postoperatively.

Conclusion: Postoperative results showed a correlation between the improvement in visual acuity and the decrease in pupil size and chord length μ.

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Online Video

Eyes with high corneal astigmatism have higher-order aberrations (HOAs) that can cause significant visual problems. Thus, a surgical technique that can counteract the negative effects of these aberrations would be useful.

Kappa has been defined as the angle formed between the visual axis and pupillary axis[1] and is important for the proper placement of multifocal intraocular lenses (IOLs).[2,3] The pupillary axis is a line perpendicular to the cornea that passes through the center of pupil. It can be determined by locating the source from which the reflected image of the light source (viewed from the source), which is the first Purkinje image (P1), is centered over the pupil center. Recently, a more appropriate term, *chord length mu* (μ), has been suggested. Chord length μ denotes the 2-dimensional displacement of the pupillary center from the subject-fixated coaxially sighted corneal light reflex that references the distance between 2 points rather than the angles.[4,5] Several corneal topographers measure chord length μ, which is defined as the distance from the pupil center (line of sight) to the light reflex.[6]

We previously published a technique, pinhole pupilloplasty, to improve vision in eyes with HOAs.[1] This surgical technique channels the central and paracentral rays of light through a pinhole and bars the peripheral rays, thereby decreasing the overall aberrations in the eye and improving

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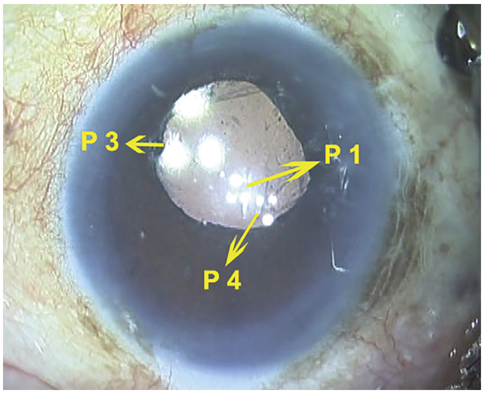

Figure 1. Purkinje images P1, P3, and P4 in a pseudophakic eye scheduled for pinhole pupilloplasty (P = Purkinje image).

the visual and image quality. The P1 images formed from the light source of the surgical microscope function as a reference marker; after this marker is identified, the rotating Scheimpflug camera is used to analyze chord length μ. We present the results in a case series in which the pinhole pupilloplasty technique was used.

PATIENTS AND METHODS

The study adhered to the tenets of the Declaration of Helsinki, and all patients provided informed consent before participating in the study. The local ethical committee approved the study protocol. All the surgeries were performed under peribulbar anesthesia of 4.0 mL lidocaine hydrochloride (Xylocaine 2.0%) and 2.0 mL bupivacaine hydrochloride 0.5% (Sensorcaine) under monitored care.

Purkinje Images

After reflection of the light source is obtained, 4 Purkinje images (P1, P2, P3, and P4) are formed, although only 3 (P1, P3, and P4) are appreciated clinically (Figure 1). The P1 reflex is formed from the anterior surface of cornea and is bright and upright, whereas the P2 image is formed from the posterior surface of cornea and is an erect image; it is overlapped by the P1 image. The P3 and P4 images are formed from the anterior surface and posterior surface of the lens–IOL and forms an erect image and inverted image, respectively. The P1 and P4 images are relatively close compared with the P3 image (Figure 1). The Lumera operating microscope (Carl Zeiss Meditec AG) used in this study projects 3 lights; therefore, each Purkinje image is a cluster of 3 lights. The triad of P1 image seen on the cornea comprises the main illumination light (*center*) and 2 coaxial lights (*at the bottom*) that emerge from the ocular side tube. The P1 image is considered the main reference marker for assessing centration intraoperatively. In all cases, the P1 image was assessed intraoperatively under peribulbar block, and the pinhole pupilloplasty was centered on it. This negates the need for patient fixation to achieve intraoperative centration.

Patient Assessment

The eyes were assessed with the rotating Scheimpflug camera preoperatively and postoperatively. Chord length μ was determined with a mathematical calculation using the x and y coordinates of the pupillary axis. The chord length was obtained using the Pythagoras formula, wherein the square root of sum of the squares of the x and y coordinates [$C = \sqrt{(x^2 + y^2)}$] denotes the value of chord length μ (C). The mean apparent chord length μ at the corneal plane, as defined by Chang and Waring,[4] is 0.30 mm ± 0.15 (SD). Thus, apparent values greater than 0.60 mm occur in fewer than 2.5% of eyes, and these eyes are at risk for glare and halos if a premium IOL is implanted. The mean actual distance from the pupil center to the visual axis at the iris plane measured with the rotating Scheimpflug camera is 0.20 ± 0.11 mm. Thus, actual values greater than 0.42 occur in fewer than 2.5% of eyes, and these eyes are also at risk for glare and halos if a premium IOL is implanted. The preoperative and postoperative pupil diameters were documented by anterior segment optical coherence tomography (Visante, Carl Zeiss Meditec AG). The uncorrected (UDVA) and corrected (CDVA) distance visual acuities were recorded in logarithm of the minimal angle of resolution (logMAR) notation using the Snellen visual acuity chart.

Surgical Technique

The technique of pinhole pupilloplasty has been described.[7] In brief, pinhole pupilloplasty was performed with a single-pass 4-throw technique[8] using a multiple quadrant approach. The pinhole pupilloplasty was centered and the center of pupil aligned

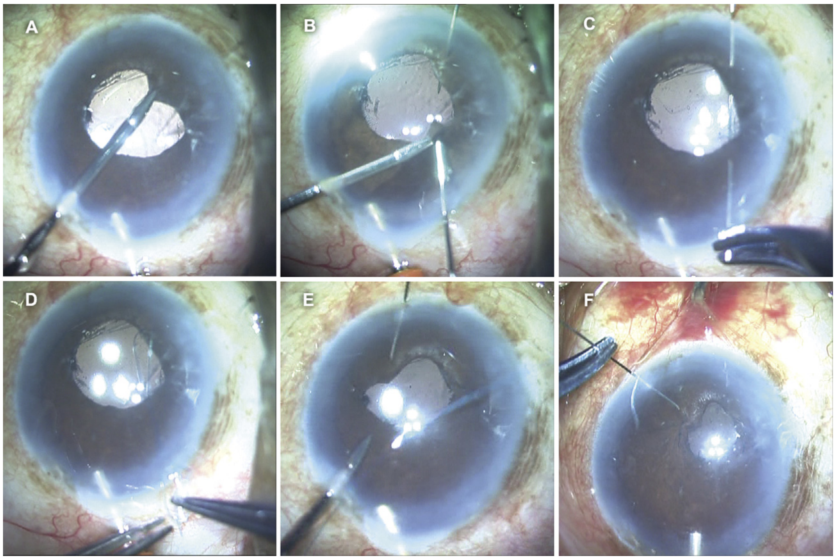

Figure 2. Clinical image of the single-pass 4-throw technique to achieve a pinhole pupil. *A*: The proximal portion of iris through which the 10-0 suture will pass is held with an end-opening forceps. *B*: The single-pass 4-throw is performed. The 10-0 needle engages the proximal iris tissue, and a 26-gauge needle, introduced from the paracentesis in the opposite direction, engages the distal iris tissue. *C*: The 10-0 needle is pulled out of the eye. *D*: The suture loop is withdrawn with a Sinskey hook, and the suture end is passed through the loop 4 times. *E*: The single-pass 4-throw is performed in the second quadrant. *F*: The single-pass 4-throw is then performed in the third quadrant.

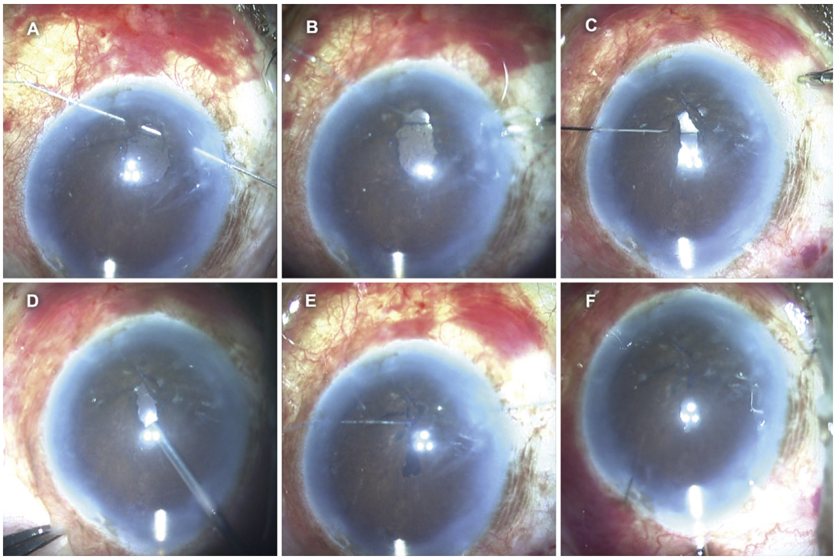

Figure 3. Clinical image of the single-pass 4-throw technique to achieve a pinhole pupil. *A* to *C*: The single-pass 4-throw is performed in the superior quadrant. *D*: The pinhole pupilloplasty is not centered with the P1 light reflex. The iris tissue overlapping the P1 image is cut with a vitrector probe. *E*: The superior portion of the pupil margin is sutured. *F*: A pinhole pupil, which envelopes the P1 reflex in its center, is achieved (P1 = Purkinje image 1).

with the lights of the Lumera operating microscope. The central pupil was created based on how the P1 image of the operating microscope fell within the pupil center (Figures 2 and 3). If the pupil was a bit eccentric and the P1 image fell on iris tissue, a vitrectomy probe was used to cut the iris tissue to ensure proper alignment (Figure 3, *D*) (Video 1, available at http://jcrsjournal.org).

Statistical Analysis

Data were entered into Excel software (Microsoft Corp.) and analyzed using Stata software (version 14.0, StataCorp LLC). Continuous variables were expressed as the mean ± SD, and categorical variables were expressed as individual counts. After the data were tested for normality of distribution, the statistical tests were allotted. Normality of data was checked using the Shapiro-Wilk normality test, and the data were found to have normal distribution. Preoperative and postoperative parameters were compared with the paired-sample *t* test. Pearson correlation analysis was used to calculate correlation coefficients. The nonparametric Wilcoxon signed-rank test was used to compare the preoperative and postoperative simulated keratometry (K) values. Differences were considered statistically significant when the *P* value was less than 0.05.

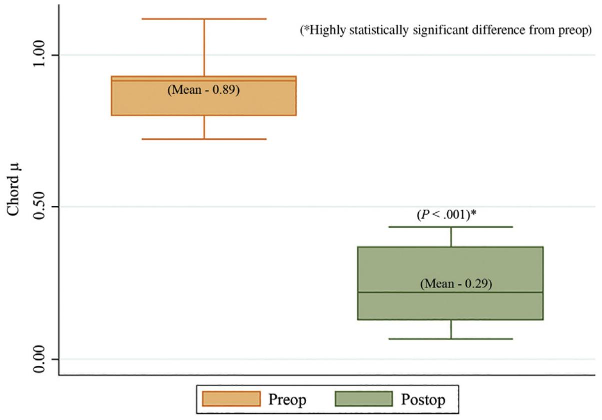

Figure 4. Change in chord length mu (Chord μ) from before to after pupilloplasty.

RESULTS

Pinhole pupilloplasty was performed in 8 eyes of 8 patients. Table 1 shows the preoperative and postoperative details. The preoperative indications for pupilloplasty were decreased vision resulting from cornea HOAs (7 cases) or glare (1 case). Seven eyes had implantation of a posterior chamber IOL, and 1 eye had grade 2 nuclear sclerosis. Isolated pinhole pupilloplasty (using the single-pass 4-throw technique) was performed in 7 eyes and combined phacoemulsification with IOL implantation and pinhole pupilloplasty was performed in 1 eye.

Table 2 shows the mean patient age as well as the preoperative and postoperative pupil diameters, logMAR UDVA, logMAR CDVA, simulated K, and chord length μ. There was a statistically significant reduction in the mean horizontal and vertical pupil diameters and in the mean in the pupil diameter from preoperatively to postoperatively (both $P < .001$). The improvement in UDVA was also statistically significant ($P < .001$); however, the change in CDVA was not statistically significant in any case. The mean simulated K and mean chord length μ were statistically significantly lower after surgery ($P = .024$ and $P < .001$, respectively) (Figure 4).

Table 3 shows the change in pupil size, logMAR UDVA, and chord length μ from preoperatively to postoperatively in each case. Overall, the mean change was 3.80 ± 1.49 mm for pupil size, 0.68 ± 0.24 logMAR UDVA, and 0.60 ± 0.26 mm for chord length μ. Figure 5 shows the correlation between the change in UDVA and the change in mean pupil size ($r = -0.477$, $P = .232$) and between the change in UDVA and the change in chord length μ ($r = -0.323$, $P = .435$). The reduction in pupil size was more apparent than the reduction in chord length μ. The correlation between the change in chord length μ and the change in mean pupil size was not significant ($r = -0.067$, $P = .874$).

The pupil was well centered on the P1 images (Figure 6). No major adverse events or complications occurred postoperatively.

Table 1. Demographics and clinical data.

Sex/Eye	Surgery	Lens Status	Cornea	Pupil Diameter (mm) Preoperative H	V	Mean	Postoperative H	V	Mean
M/OD	PPP	PC IOL	Post patch graft	4.93	4.70	4.82	1.47	1.38	1.43
M/OD	PPP	PC IOL	Clear	2.45	4.20	3.33	1.39	1.37	1.38
M/OS	PPP + phaco + IOL	Cataract	Post PKP	5.84	5.01	5.43	1.04	1.39	1.22
M/OD	PPP	PC IOL	Clear	5.40	4.80	5.10	1.84	1.52	1.68
M/OS	PPP	PC IOL	Post PKP	6.20	5.70	5.95	1.61	1.22	1.42
F/OS	PPP	PC IOL	Post PDEK	3.32	3.82	3.57	1.52	0.85	1.19
M/OS	PPP	PC IOL	Post PKP	5.87	4.49	5.18	1.40	1.6	1.50
F/OS	PPP	PC IOL	Post PKP	7.90	8.20	8.05	1.20	1.3	1.25

CDVA = corrected distance visual acuity; H = horizontal; IOL = intraocular lens implantation; logMAR = logarithm of the minimum angle of resolution; PDEK = pre Descemet endothelial keratoplasty; PKP = penetrating keratoplasty; SimK = simulated keratometry; UDVA = uncorrected distance visual acuity; V = vertical.

DISCUSSION

Purkinje images are considered to be ideal markers for IOL centration because they are an appropriate reference marker from an anatomic and clinical aspect. Because reflections from noncoaxial light sources project peripherally, the use of a coaxial light source is important. The coaxially sighted corneal light reflex is the P1 image from the light source, which is coaxial to the surgeon's view. It is essential to create regular and reproducible alignment for pinhole pupilloplasty, and we believe that P1 images are crucial to achieving this alignment.

Table 2. Preoperative and postoperative parameters.

Variable	Mean ± SD	Range	*P* Value
Age	61.8 ± 4.71	54.0, 67.0	—
Pupil diameter (mm)			
Horizontal			<.001*
Preop	5.24 ± 1.70	2.45, 7.90	
Postop	1.43 ± 0.24	1.04, 1.84	
Vertical			<.001*
Preop	5.12 ± 1.37	3.82, 8.20	
Postop	1.33 ± 0.23	0.85, 1.60	
UDVA (logMAR)			<.001*
Preop	1.13 ± 0.15	1.00, 1.30	
Postop	0.44 ± 0.31	0.00, 0.78	
CDVA (logMAR)			
Postop	0.33 ± 0.30	0.00, 0.78	—
Simulated K (D)			.024†
Preop	11.68 ± 8.71	4.2, 26.6	
Postop	9.30 ± 9.30	2.8, 20.3	
Chord length mu (mm)			<.001*
Preop	0.89 ± 0.12	0.72, 1.12	
Postop	0.29 ± 0.24	0.07, 0.79	

CDVA = corrected distance visual acuity; H = horizontal; logMAR = logarithm of the minimum angle of resolution; K = keratometry; UDVA = uncorrected distance visual acuity; V = vertical.
*Statistically significant at 0.1% level ($P < .001$).
†Statistically significant at 5% level ($P < .05$).

Because the surgery in our cases was performed under peribulbar block, the subject-fixated coaxially sighted corneal light reflex, which is easily reproducible and identified, could not be assessed. Rather a coaxially sighted corneal light reflex concept was used to align and center the pinhole pupilloplasty. The triad of P1 images formed with the Lumera operating microscope serves as a perfect marker for achieving alignment and centration. Some operating microscopes might have a reflection of 1 or 2 lights that can be used as a reference marker tool, and the Purkinje images can be coordinated accordingly. Intraoperatively, when the patient fixates on the coaxial light source, it reproduces the position of P1 as visualized in the slitlamp examination of the coaxial image of an undilated pupil in the preoperative period.

When pinhole pupilloplasty is performed, the coaxially sighted corneal light reflex axis and the line of sight converge at the fixation point. Therefore, chord length μ decreases as the frame of reference moves anteriorly toward the observer and fixation point (Figure 7). In clinical practice, the change in chord length μ between the lens and the IOL plane (real chord length μ) and the corneal plane (apparent chord length μ) is typically not significant. The apparent chord length μ as seen through the cornea[9] and the actual chord length μ measured by the rotating Scheimpflug camera are different, as described in the Patients and Methods section.

The mean angle κ values are reported to be 3.0 ± 0.13 degrees, and values greater than 3.26 degrees are considered abnormally high.[10,11] In cases with high astigmatism and hyperopia, these values are often 10.0 degrees or more. The chord length values are reported in millimeters or microns, and a standard conversion formula of 1.0 mm to 7.5 degrees can be applied when measured along the surface of the cornea.[12] In our study, the mean preoperative chord length μ levels were 0.89 ± 0.12 mm (range 1.12 to 0.72 mm) and all cases had high astigmatism. With the postoperative decrease in the pupillary aperture, the chord length μ level decreased significantly to 0.29 ± 0.12 mm

Table 1. (Cont.)

UDVA (LogMAR)		CDVA (LogMAR)	SimK Astig (D)		Actual Chord Length Mu					
					Preoperative			Postoperative		
Pre	Post	Post	Pre	Post	X	Y	Value	X	Y	Value
1.10	0.60	0.30	24.2	20.2	−0.13	−0.92	0.93	0.10	0.09	0.13
1.00	0.00	0.00	4.4	2.8	−0.18	0.70	0.72	0.03	0.06	0.07
1.30	0.48	0.30	26.6	20.3	0.80	−0.46	0.92	0.58	−0.54	0.79
1.00	0.00	0.00	4.2	4.0	0.75	0.36	0.83	−0.21	0.22	0.30
1.30	0.78	0.78	8.2	8.0	0.15	0.75	0.76	0.40	−0.17	0.43
1.00	0.30	0.20	8.2	6.9	−0.70	−0.61	0.93	0.01	−0.12	0.12
1.00	0.60	0.30	9.9	5.1	0.90	0.12	0.91	−0.03	0.15	0.15
1.30	0.78	0.78	7.7	7.1	0.35	1.06	1.12	0.28	0.07	0.29

(0.79 to 0.07 mm), with a significant improvement in vision (Figure 8). We therefore theorize that the chord length decreases as pinhole pupilloplasty is performed and the patient effectively visualizes the object through the central opening of pinhole pupilloplasty, which is approximately 1.5 mm in diameter. The Pentacam rotating Scheimpflug camera reports the distance from the pupil center to the vertex normal, which is considered the center of the x and y coordinates. A negative x-axis value in the right eye and a positive value in the left eye indicate that the pupil is temporal to the light reflex. Similarly, negative values along the y-axis denote an inferior location of the pupil center (Figure 8).

Several factors affect the quality of vision. Centration of the IOL between the visual axis (P1) and pupillary center is considered the ideal position. When the apparent chord length μ is greater than 0.60 mm (actual chord length μ is greater than 0.44 mm on the Pentacam rotating Scheimpflug camera), placing the IOL halfway between P1 and the pupillary center is not close enough for diffractive IOLs to perform well optically; in addition, the incidence of halos and glare increases significantly. Pupil size also affects visual acuity, with better acuity reported with a pinhole pupil. In addition, the amount of tilt and decentration of the IOL from the visual axis also plays a role because IOL tilt induces coma and other HOAs and reduces the visual quality. Placing P1 between P3 and P4 ensures that the IOL is not decentered relative to the visual axis (Figure 1). Therefore, we believe the main reason for the improved UDVA in our study was a reduction in pupil size followed by proper centration of the IOL. Moving the small pupil to the visual axis might reduce the quality of vision if the IOL is decentered and tilted relative to P1.

Improvement in visual outcomes after pinhole pupilloplasty has been reported.[7] In the current study, there was also a decrease in chord length μ levels when the coaxially sighted corneal light reflex was used and pinhole pupilloplasty was performed enveloping the P1 reflex emanating from the ocular coaxial tube of the Lumera operating microscope on the surface of the cornea. The importance of chord length μ cannot be ignored in eyes having multifocal IOL implantation and keratorefractive procedures because deviating from the norm can result in high patient dissatisfaction. In pinhole pupilloplasty, the chord length decreases and the patient sees through the pinhole; patient satisfaction level is high because the pinhole effect negates the effect of corneal HOAs. In case 3 in our study, the decrease in chord length was not significant, although there was a

Table 3. Preoperative and postoperative values and change in values.

Case	Mean Pupil Size (mm)			UDVA (LogMAR)			Chord Length Mu		
	Preop	Postop	Δ	Preop	Postop	Δ	Preop	Postop	Δ
1	4.82	1.43	3.39	1.10	0.60	0.49	0.93	0.13	0.79
2	3.33	1.38	1.95	1.00	0.00	1.00	0.72	0.07	0.66
3	5.43	1.22	4.21	1.30	0.48	0.82	0.92	0.79	0.13
4	5.10	1.68	3.42	1.00	0.00	1.00	0.83	0.30	0.53
5	5.95	1.42	4.54	1.30	0.78	0.52	0.76	0.43	0.33
6	3.57	1.19	2.39	1.00	0.30	0.70	0.93	0.12	0.81
7	5.18	1.50	3.68	1.00	0.60	0.40	0.91	0.15	0.75
8	8.05	1.25	6.80	1.30	0.78	0.52	1.12	0.29	0.83

Δ = change; logMAR = logarithm of the minimum angle of resolution; UDVA = uncorrected distance visual acuity.

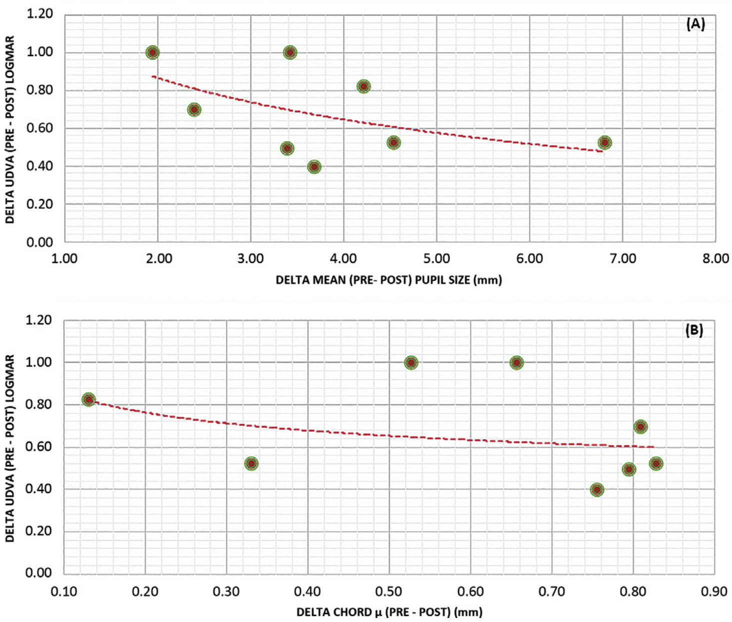

Figure 5. Correlation between the change in variables. *A*: Relationship between the change in UDVA and the change in mean pupil size. *B*: Relationship between the change in UDVA and the change in chord length mu (CHORD μ = chord length mu; DELTA = change from preoperatively to postoperatively; LOGMAR = logarithm of the minimal angle of resolution; UDVA = uncorrected distance visual acuity).

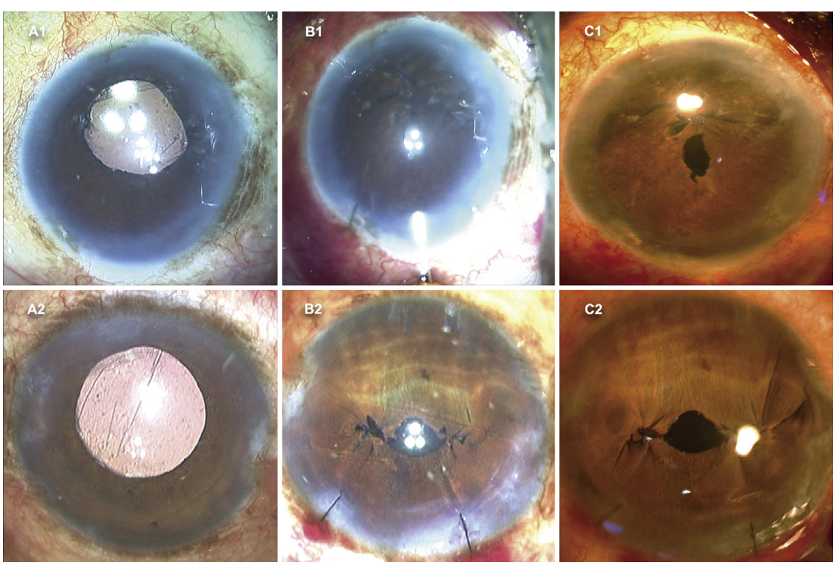

Figure 6. Clinical images of pinhole pupilloplasty in 2 cases. *A1* and *A2*: Images before pinhole pupilloplasty in a pseudophakic eye showing Purkinje images. *B1* and *B2*: Intraoperative images show a well-centered pinhole pupilloplasty with the P1 reflex engulfed by the pupillary margin. *C1* and *C2*: Postoperative images from slitlamp examination (P1 = Purkinje image 1).

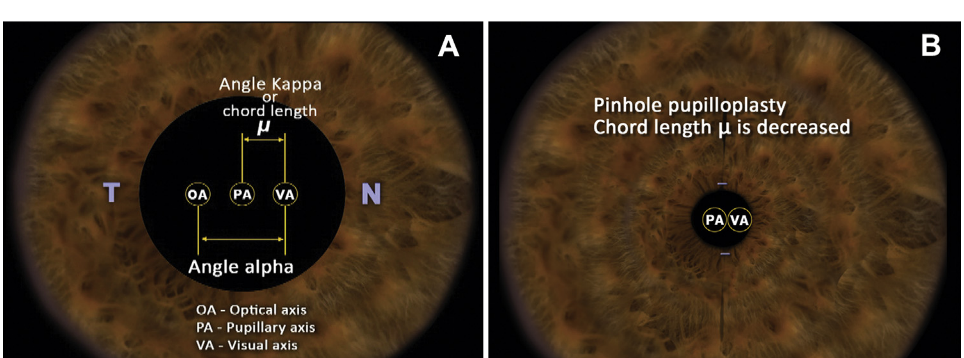

Figure 7. *A*: Preoperative image of optical axis, pupillary axis, visual axis, chord length mu (μ), and angle α in a normal case. *B*: After pinhole pupilloplasty, the chord length μ is decreased because the pupillary axis and visual axis almost coincide.

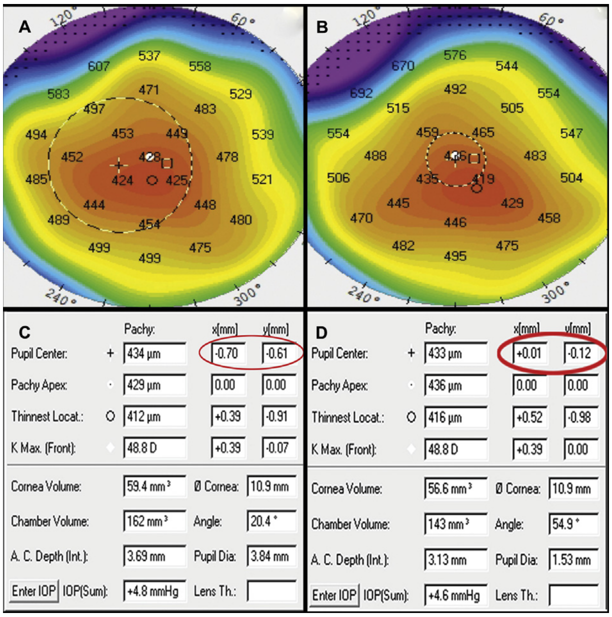

Figure 8. Preoperative and postoperative rotating Scheimpflug camera images. *A*: The pupillary center (*crosshair*) and visual axis (*white circle*) are apart in the pupillary area (*dotted circle*). The square shows the optical axis. *B*: The pupillary center and visual axis are overlapping each other. *C*: The distance between the pupillary center and the visual axis is shown by the *x* and *y* coordinates. *D*: The distance between the *x* and *y* coordinates is decreased, indicating a decrease in chord length mu values.

significant improvement in UDVA postoperatively. A reason could be improper centration of the pupil with regard to the visual axis. The change in the simulated K values postoperatively could be related to the creation of a paracentesis during pupilloplasty because in many cases, it took more than 3 attempts to resize the pupil centrally to the P1 image.

After pupilloplasty with the single-pass 4-throw procedure, significant pharmacologic mydriasis occurs, which helps the surgeon visualize the fundus.[13] In cases in which mydriasis is deemed insufficient, ultrasound biomicroscopy can be performed and, if necessary, the suture can be removed.

There are several limitations to this study. First, intraoperative P1 images were taken into consideration when performing pinhole pupilloplasty. Because the surgery was performed under peribulbar block, accurately locating the visual axis would have been difficult and an error could have occurred. A method to mark the visual axis preoperatively and then confirm and align it with the P1 reflex intraoperatively would help eliminate this error. Second, we believe that the improvement in vision was a result of the decrease in the chord length. However, other reasons and factors could have played an important role in attaining good vision. Nevertheless, a correlation was seen between the improvement in visual acuity and the decrease in the mean pupil size and in chord length μ; studies with a larger number of cases would help validate the relationship.

WHAT WAS KNOWN

- Purkinje images are formed as a result of the reflection of light in the eye.
- The Purkinje image 1 (P1) formed on the anterior surface of the cornea is considered to be the main reference marker.
- Chord length mu (μ) is the new clinical reference marker that denotes the distance between the pupillary center and the subject-fixated coaxially sighted corneal light reflex.

WHAT THIS PAPER ADDS

- Use of Purkinje images helped locate and create a central pupil.
- The triad of P1 images formed using a surgical microscope helped size the pupil to 1.5 mm.
- After pinhole pupilloplasty, the chord length μ decreased significantly.

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