Lamina Cribrosa Moves Anteriorly After Trabeculectomy in Myopic Eyes

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PURPOSE. The purpose of this study was to investigate changes in lamina cribrosa (LC) depth after trabeculectomy in myopic eyes using enhanced depth imaging (EDI) spectral-domain optical coherence tomography (SD-OCT).

METHODS. Serial horizontal B-scans of the optic nerve head of 41 myopic eyes with primary open-angle glaucoma (POAG) were obtained before and 3 months after trabeculectomy using EDI SD-OCT. LC depth, defined as the distance from the opening plane of Bruch's membrane to the level of the anterior LC surface, was measured before and 3 months after trabeculectomy at 7 locations spaced equidistantly across the vertical optic disc diameter on B-scan images. The mean of the measurements at these seven planes was defined as the average LC depth. Factors associated with changes in LC depth were identified by linear regression.

RESULTS. Intraocular pressure (IOP) decreased from 26.3 ± 9.3 millimeters of mercury (mm Hg) preoperatively to 10.6 ± 3.5 mm Hg 3 months after trabeculectomy. LC depth was significantly lower 3 months after trabeculectomy than preoperatively ($P < 0.001$, all planes). The magnitude of LC depth reduction was significantly associated with younger age, higher preoperative LC depth, and greater magnitude of IOP reduction (all $P \leq 0.016$).

CONCLUSIONS. LC depth reduction was observed after trabeculectomy in myopic eyes. The degree of LC depth reduction was not related to the degree of myopia.

Keywords: lamina cribrosa, trabeculectomy, myopia, lamina cribrosa depth

The morphologic change or remodeling of the lamina cribrosa (LC) is a principal part of the glaucomatous optic neuropathy.[1] An experimental study demonstrated posterior bowing of the LC in early glaucoma model generated by increasing intraocular pressure (IOP).[2] Conversely, the LC was shown to move anteriorly[3,4] and to become less curved[5] when IOP was reduced by trabeculectomy or IOP lowering medication. In addition, re-elevation of IOP in patients who underwent glaucoma surgery was shown to result in an increase in LC depth.[6] Taken together, these findings suggested that LC position and morphology depend on changes in IOP, with LC depth and curvature increasing in response to elevated IOP.

The LC is anchored within the parapapillary sclera at the scleral canal. Therefore, the biomechanical characteristics of the sclera would be closely intertwined with that of the LC.

Indeed, computational modeling studies have suggested that the LC change behavior upon IOP change may be different according to the relationship between the stiffness of the parapapillary sclera and the LC.[7–9] Sigal et al.[8] demonstrated that IOP-induced deformation of the LC and parapapillary sclera would be diverse depending on the coupling of a stiff or compliant sclera with a stiff or compliant LC.

The sclera in myopic eyes is thinner and weakened.[10–12] These characteristics suggest that myopic eyes may have relatively compliant sclera. This concept is supported by the finding that highly myopic eyes are more prone to develop hypotony maculopathy when the IOP became abnormally low after glaucoma surgery.[13] In addition, myopic eyes are structurally obliquely deformed, due to the scleral extension that occurs during axial elongation. Thereby, the Bruch's membrane and anterior scleral canal are often distorted
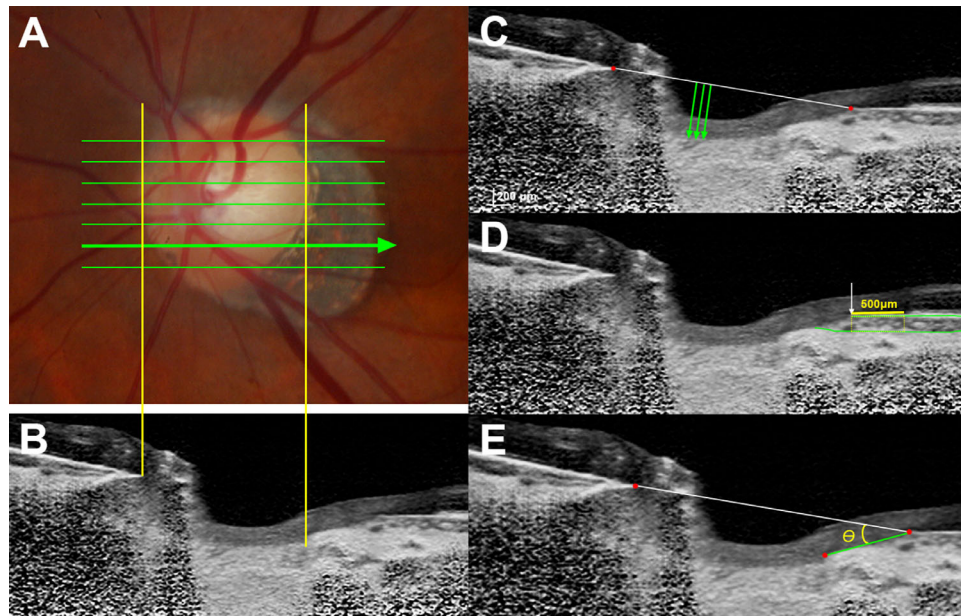
FIGURE 1. Measurement of lamina cribrosa (LC) depth, juxtapapillary choroidal thickness (JPCT), and Bruch's membrane opening (BMO) – border tissue angle (BBA). (**A**) Disc photograph showing seven horizontal *green solid lines*, indicating the locations at which the measurements were performed. (**B–E**) Spectral-domain optical coherence tomography (SD-OCT) B-scan images obtained in plane 6 from panel **A**. **B** B-scan image corresponds disc photograph. The *yellow lines* indicate the clinical boundary of the disc and were continued downward to meet the corresponding points on the SD-OCT B-scan image. **C** Measurement of LC depth, defined as the distance from the reference line connecting the two BMO points to the anterior surface of the LC. The LC depth was measured at three points, the maximally depressed point and two points 100 and 200 μm from the maximally depressed point in the temporal direction. The three measurements were averaged and defined as the LC depth on that B-scan. **D** Green sold lines indicate the upper and lower margins of the parapapillary choroid, represented by Bruch's membrane and the choroidoscleral interface, respectively. The area of the choroidal tissue within 500 μm from the border tissue of Elschnig (shown as a *yellow dotted line*) was measured using the built-in drawing tool of Spectralis viewer software (Heidelberg Engineering, Heidelberg, Germany). **D** Degree of horizontal disc tilt was measured from the BMO- BBA between the reference line connecting the two BMO points (*white line*) and border tissue line connecting temporal BMO point and ASCO point (*green line*).

asymmetrically.[14] In addition, myopic optic nerve head deformation is often accompanied by border tissue overhang, which was associated with glaucomatous visual field damage.[15,16] In this regard, it may be questioned whether LC change behavior according to change in IOP may differ in highly myopic eyes (i.e. anterior movement of the LC upon IOP elevation).

The purpose of the present study was to determine the changes in LC depth following trabeculectomy in myopic eyes, including highly myopic eyes.

METHODS

This investigation was based on an ongoing prospective Investigating Glaucoma Progression Study (IGPS)[17–19] that is being performed at the Seoul National University Bundang Hospital Glaucoma Clinic. Eyes diagnosed with primary open-angle glaucoma (POAG) were included. This study was approved by the Seoul National University Bundang Hospital Institutional Review Board and followed the tenets of the Declaration of Helsinki. All subjects provided written informed consent.

Study Subjects

All subjects enrolled in the IGPS received comprehensive ophthalmic examinations, including measurements of visual acuity, Goldmann applanation tonometry, refraction

tests, slit-lamp biomicroscopy, gonioscopy, dilated stereoscopic examination of the optic disc, and stereo disc photography (EOS D60 digital camera; Canon, Utsunomiyashi, Tochigiken, Japan). They also underwent spectraldomain optical coherence tomography (SD-OCT; Spectralis OCT, Heidelberg, Engineering, Heidelberg, Germany) and measurements of central corneal thickness (CCT; Orbscan II, Bausch & Lomb Surgical, Rochester, NY, USA), corneal curvature (KR-1800; Topcon, Tokyo, Japan), axial length (AXL; IOL Master version 5; Carl Zeiss Meditec, Dublin, CA, USA), and standard automated perimetry (Humphrey Field Analyzer II 750, 24-2 Swedish interactive threshold algorithm; Carl Zeiss Meditec).

Eyes included in the present study were required to have clinically apparent γ-zone parapapillary atrophy (PPA) with a width > 100 μm on at least one horizontal optical coherence tomography (OCT) scan image, as measured by the built-in caliper tool of the Spectralis OCT.[19] Eyes with poor image quality preventing clear delineation of the γ-zone on SD-OCT images were excluded. Eyes were also excluded when images did not allow clear delineation of the anterior border of the central LC.

Eyes included in the present study were required to have POAG, best-corrected visual acuity of at least 20/40, spherical refraction < -3.0 diopters (D) or an AXL > 24.0 mm, and cylinder correction within −3.0 to +3.0 D with a tilted appearance (defined as a Bruch's membrane opening [BMO]- border tissue angle [BBA] < 70°; Fig. 1). Subjects with a history of intraocular surgery other than cataract extrac-

tion, intraocular disease (e.g. diabetic retinopathy, retinal vein occlusion, or optic neuropathies), or neurologic disease (e.g. pituitary tumor) that could cause visual field loss were excluded. Eyes were also excluded when a good-quality image (i.e. quality score > 15) could not be obtained due to media opacity or lack of patient cooperation.

POAG was defined as the presence of glaucomatous optic nerve damage (i.e. focal thinning of the neuroretinal rim, notching, or a splinter hemorrhage) and associated visual field defect without ocular diseases or conditions that may result in elevated IOP. A glaucomatous visual field defect was defined as (1) outside the normal limits on glaucoma hemifield test; (2) three abnormal points with *P* values < 5% probability of being normal, including one with *P* values < 1% by pattern deviation; or (3) a pattern standard deviation < 5%, confirmed on two consecutive tests. Visual field measurements were considered reliable when false-positive/negative results were < 25% and fixation losses were < 20%.

Optic discs were examined by SD-OCT 1 day before surgery and 1–3 months after surgery. Pre- and postoperative IOPs were each defined as the average of at least two measurements on Goldmann applanation tonometry made within 2 weeks before surgery and at the time of follow-up SD-OCT scan, respectively. Indications for trabeculectomy were IOP deemed to be associated with a high risk for glaucomatous progression of the visual field or optic disc despite maximally tolerated medications.[3,5] If both eyes of a subject were eligible for the study, one eye was selected randomly.

Enhanced Depth Imaging OCT of the Optic Nerve Head

The optic nerve head was imaged using the enhanced-depth-imaging technique of the Spectralis OCT system. The details and advantages of this technology in evaluating the LC have been described.[20] In brief, imaging was performed through undilated pupils using a rectangle subtending 10° × 15° of the optic disc. This rectangle was scanned with approximately 75 B-scan section images, which were separated by 30 to 34 μm, with the scan line distance determined automatically by the machine. Approximately 42 SD-OCT frames were averaged for each section. Using Spectralis OCT, the images were obtained only when the quality score is higher than 15. This protocol provided the best trade-off between image quality and patient cooperation.[21] Corneal curvature was entered into the Spectralis OCT system before scanning to avoid potential magnification errors.

Quantification of Posterior Displacement of the LC

Before measurements, all images were postprocessed using adaptive compensation to enhance the visibility of the peripheral LC (Fig. 1).[22,23] To determine the degree of posterior LC displacement, LC depth was measured on pre- and postoperative B-scan images. A line connecting the edges of BMO was set as a reference plane (BMO reference line), and the distances from this reference line to the level of the anterior border of the LC were measured at 3 points, the maximally depressed point and points 100 and 200 μm from the maximally depressed point in a temporal direction (Fig. 1).[3,4,24,25] The mean of the three measurements obtained at the three points was considered the individual value at the selected B-scan. Each optic disc diameter

was vertically divided into eight equal parts, and seven B-scan images were obtained for each eye.[26,27] These seven B-scan lines (green lines) were defined as planes 1 to 7, from the superior to the inferior regions (Fig. 1), with plane 4 corresponding to the mid-horizontal plane, and planes 2 and 6 corresponding approximately to the superior and inferior mid-periphery, respectively. All measurements were performed using the manual calipers provided in the Spectralis viewer. LC depths were measured by two experienced observers (SHL and EJL), who were masked to the clinical information, with the measurements made by the two observers averaged for analysis. The average LC depth of each eye was calculated as the mean measurements at the seven points of the LC.

Measurement of Juxtapapillary Choroidal Thickness, Bruch's Membrane Opening Width and Bruch's Membrane Opening – Border Tissue Angle

Because the LC depth from the BMO is affected by choroidal thickness,[28] the juxtapapillary choroidal thickness (JPCT) was measured before and after the trabeculectomy. Briefly, JPCT was measured using the manual caliper and drawing tool of the Spectral OCT viewer.[19,29] The JPCT was calculated by dividing the measured choroidal area within 500 μm from the border tissue of Elschnig by 500 μm (Fig. 1).

The distance from the temporal to the nasal Bruch's membrane (BM) termination was defined as the width of BMO. Degree of horizontal disc tilt was measured from the BBA between the reference line connecting the two BMO points and border tissue line connecting temporal BMO point and anterior scleral canal opening (ASCO) point (Fig. 1).

The JPCT and BBA was measured at the mid-horizontal (plane 4) of horizontal B-scan images obtained by SD-OCT. Each measurement was performed twice by two masked observers (SHL and EJL), and the mean of these four measurements was used for analysis.

The distance from the temporal to the nasal BM termination was defined as the width of BMO. Each measurement was performed twice by two masked observers (SHL and EJL), and the mean of these four measurements was used for analysis.

Statistical Analysis

Interobserver agreement in the measurement of LC depth and JPCT was assessed using the Bland-Altman limits of agreement. The raw data for *t*-tests were subjected to Bonferroni's correction, based on the number of comparisons within each analysis. The association of clinical factors with the magnitude of LC depth reduction after trabeculectomy was assessed by liner regression analysis. Comparison of the LC depth reduction regarding to regional difference was performed using 1-way ANOVA with Scheffè's post hoc test. *P* values < 0.05 were regarded as statistically significant. All statistical analyses were performed using the Statistical Package for Social Sciences (version 22.0; SPSS, Chicago, IL, USA).

RESULTS

The present study initially included 49 eyes of 49 patients with POAG who underwent trabeculectomy. Of these, seven

TABLE 1. Demographic and Clinical Characteristics of Included Subjects ($n = 41$)

Variables	All Subjects ($n = 41$)
Age, y	46.6 ± 16.0
Male/female	21/20
Pre-operative IOP, mm Hg	26.3 ± 9.3
Post-operative IOP, mm Hg	10.6 ± 3.5
Spherical equivalent, diopters	-7.00 ± 3.43
Axial length, mm	26.69 ± 1.65
Central corneal thickness, μm	530.5 ± 43.6
Visual field MD, dB	-14.76 ± 10.27
Global RNFL thickness, μm	56.6 ± 16.6

IOP = intraocular pressure; MD = mean deviation; dB = decibel; RNFL = retinal nerve fiber layer.

Data are reported as mean ± standard deviation.

TABLE 2. Intraocular Pressure and Lamina Cribrosa Depth at Baseline and Follow-Up Optic Disc Examinations

	Pre-Operative	Post-Operative	P Value
IOP, mm Hg	26.3 ± 9.3	10.6 ± 3.5	**< 0.001**
Mean LC depth, μm	671.9 ± 183.5	544.7 ± 158.0	**< 0.001**
Plane 1[*]	676.2 ± 188.7	561.6 ± 162.3	**< 0.001**
Plane 2[*]	724.8 ± 204.8	592.7 ± 176.1	**< 0.001**
Plane 3[*]	707.5 ± 193.4	568.7 ± 171.6	**< 0.001**
Plane 4[*]	684.1 ± 196.8	547.9 ± 161.2	**< 0.001**
Plane 5[*]	665.6 ± 203.8	533.2 ± 168.8	**< 0.001**
Plane 6[*]	641.0 ± 178.4	518.3 ± 153.7	**< 0.001**
Plane 7[*]	603.9 ± 161.9	490.3 ± 147.5	**< 0.001**
JPCT, μm	106.8 ± 39.4	129.8 ± 34.1	**< 0.001**
BMO width, μm	1629.5 ± 266.7	1636.8 ± 257.1	0.577
BBA, °	33.1 ± 12.9	32.1 ± 12.1	0.208

IOP = intraocular pressure; LC = lamina cribrosa; JPCT = juxtapapillary choroidal thickness; BMO = Bruch's membrane opening; BBA = Bruch's membrane opening - border tissue angle.

Data are mean ± standard deviation.

[*] Values that were significant after Bonferroni correction ($P < 0.007$; 0.05/7) are shown in bold.
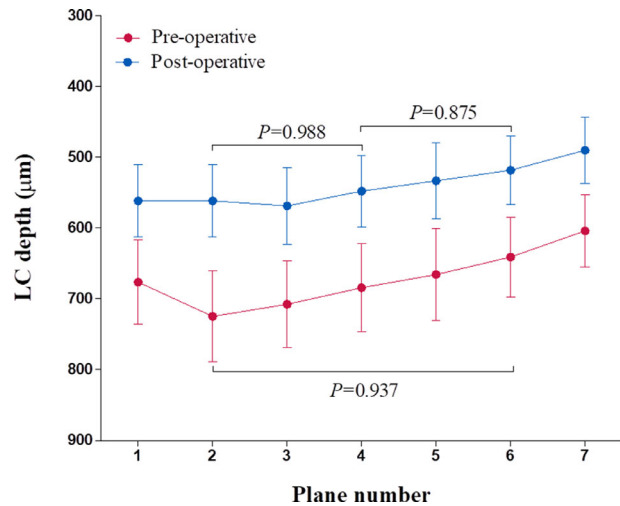

FIGURE 2. LC depth profile in horizontal SD-OCT scans of 7 planes, with planes 1 and 7 corresponding to the most superior and most inferior planes, respectively. Postoperative LC depth was significantly smaller than preoperative LC depth in all planes (all $P < 0.001$). The P values are for the comparison of the LC depth reduction regarding superior (plane 2), mid-horizontal (plane 4), and inferior (plane 6).

subjects were excluded due to poor image quality, which prevented clear visualization of the anterior LC surface in at least two of the seven horizontal B-scan disc images. In addition, one eye was excluded because of hypotony maculopathy due to an extremely low IOP (4 millimeters of mercury [mm Hg]) 3 months after trabeculectomy. Thus, 41 eyes of 41 subjects were analyzed.

Table 1 summarizes the demographic characteristics of the included subjects. The 41 subjects comprised 20 women (48.8%) and 21 men (51.2%), of mean age 46.6 ± 16.0 years. Their mean refractive error (spherical equivalent) was -7.00 ± 3.43 D (range, -16.00 to -2.50 D), and their visual field mean deviation was -14.76 ± 10.27 dB (range, -31.98 to -0.49 dB).

The IOP of the 41 eyes decreased markedly from 26.3 ± 9.3 mm Hg (range, 12–48 mm Hg) preoperatively to 10.6 ± 3.5 mm Hg (range, 6–22 mm Hg) 3 months after trabeculectomy (Table 2). All patients were being treated with ocular hypotensive medications before surgery, and 11 (26.8%) were receiving medical treatment at the time of postoperative OCT scan. The average LC depth in all seven planes was significantly lower after than before surgery (all $P < 0.001$; Table 2, Fig. 2), and the preoperative JPCT (106.8 ± 39.4 μm) was significantly thickened postoperatively (129.8 ± 34.1 μm; $P < 0.001$; Table 2). The decrease of LC depth was universal in each plane as well as on aver-

age (Fig. 3). There were no regional differences regarding the LC depth reduction in superior (plane 2), mid-horizontal (plane 4), and inferior (plane 6; Fig. 3).

The 95% Bland-Altman limits of agreement between the measurements of LC depth and JPCT by the 2 glaucoma specialists ranged from -19.71 μm to 21.43 μm and from -3.17 μm to $+2.91$ μm, respectively.

Factors Associated with Reduction of the LC depth

Univariate linear regression analysis showed that age, preoperative IOP, reduction of IOP, preoperative LC depth, and difference of JPCT were significantly associated with the mean reduction in LC depth ($P \leq 0.049$; Table 3). Multivariate analysis was performed using two models to avoid multicollinearity. In both models, reduction in LC depth showed statistically significant negative associations with age ($P \leq 0.007$) and significant positive correlations with reduction in IOP ($P = 0.006$) and preoperative LC depth ($P = 0.016$) (Table 3; Fig. 4). The association of younger age, higher preoperative IOP, larger reduction of IOP, and higher preoperative LC depth with the LC depth reduction were significant at all three planes (Table 4).

REPRESENTATIVE CASE

A representative case showing significant reductions in LC depth after trabeculectomy is presented in Figure 5.

DISCUSSION

The present study found that the LC depth in myopic eyes was significantly reduced in all planes after trabeculectomy. The degree of LC depth reduction was significantly associated with patient age, preoperative LC depth, and magnitude of IOP lowering, but not with axial length.

In the present study, LC depth was measured from the BMO level to evaluate LC position. This method has a limi-

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TABLE 3. Factors Associated With the Mean Reduction of Posterior Displacement of the Lamina Cribrosa

| | Univariate | | Multivariate | | | |
| | | | Model 1 | | Model 2 | |
Variables	Beta (95% CI)	P	Beta (95% CI)	P	Beta (95% CI)	P
Age, per 1-year older	−4.039 (−5.822 to −2.256)	**< 0.001**	**−2.918 (−4.974 to −0.861)**	**0.007**	**−3.134 (−5.045 to −1.223)**	**0.002**
Gender, female	25.891 (−43.670 to 95.453)	0.456				
Preoperative IOP, mm Hg	3.966 (0.385 to 7.547)	**0.031**	1.079 (−2.832 to 4.991)	0.577		
Reduction of IOP, mm Hg	5.387 (2.171 to 8.602)	**0.002**			**4.836 (1.454 to 8.219)**	**0.006**
Preoperative LC depth, μm	0.307 (0.142 to 0.473)	**0.001**	**0.232 (0.046 to 0.418)**	**0.016**	0.153 (−0.039 to 0.346)	0.115
Preoperative BMO width, μm	0.079 (−0.052 to 0.209)	0.229				
Preoperative BBA, °	−0.123 (−2.864 to 2.618)	0.928				
Difference of JPCT, μm	−1.736 (−3.462 to −0.009)	0.049	−1.231 (−2.744 to 0.283)	0.107	−1.124 (−2.592 to 0.345)	0.129
Border tissue overhang	−14.093 (−121.021 to 92.835)	0.791				
Axial length, mm	−5.336 (−27.016 to 16.344)	0.621				
Corneal central thickness, μm	−0.454 (−1.253 to 0.345)	0.253				
Global RNFL thickness, μm	−2.113 (−4.471 to 0.246)	0.077	−1.388 (−3.252 to 0.476)	0.139	−1.153 (−2.962 to 0.656)	0.203
Visual field MD, dB	−1.219 (−4.648 to 2.210)	0.477				
Visual field PSD, dB	0.664 (−8.303 to 9.631)	0.882				

CI = confidence interval; IOP = intraocular pressure; LC= lamina cribrosa; BMO = Bruch's membrane opening; BBA = BMO-border tissue angle; JPCT = juxtapapillary choroidal thickness; RNFL = retinal nerve fiber layer; MD = mean deviation; PSD = pattern standard deviation; dB = decibel.

Only variables with $P < 0.1$ on univariate analysis were included in the multivariate model.

Values with statistical significance are shown in boldface.

TABLE 4. Factors Associated With the Mean Reduction of Posterior Displacement of the Lamina Cribrosa in Different Regions

Variables	Superior-Midperiphery, Plane 2				Mid-Horizontal, Plane 4				Inferior-Midperiphery, Plane 6			
	Univariate		Multivariate		Univariate		Multivariate		Univariate		Multivariate	
	Beta	P	Beta	P	Beta	P	Beta	P	Beta	P	Beta	P
Age, per 1-year older	-4.610	**< 0.001**	-3.286	**0.001**	-4.378	**< 0.001**	-2.652	**0.005**	-3.854	**< 0.001**	-2.797	**0.001**
Gender, female	26.264	0.509			35.883	0.352			26.681	0.432		
Pre-operative IOP, mm Hg	4.828	**0.021**	-14.138	**0.001**	4.887	**0.016**	-14.138	**0.001**	3.145	0.083	-13.061	**< 0.001**
Reduction of IOP, mm Hg	6.390	**0.001**	15.728	**0.001**	6.436	**0.001**	15.948	**< 0.001**	4.521	**0.008**	13.075	**< 0.001**
Pre-operative LC depth, μm	0.338	**0.001**	0.215	**0.010**	0.377	**< 0.001**	0.293	**0.002**	0.309	**< 0.001**	0.230	**0.002**
Pre-operative BMO width, μm	0.079	0.296			0.070	0.339			0.075	0.243		
Pre-operative BBA, °	-0.105	0.947			0.093	0.951			-0.171	0.898		
Difference of JPCT, μm	-2.023	0.045	-0.139	0.194	-1.748	0.076	-0.104	0.298	-1.783	0.038	-0.146	0.174
Axial length, mm	-8.088	0.516			-8.017	0.500			-6.165	0.559		
Corneal central thickness, μm	-0.634	0.194			-0.427	0.329			-0.498	0.195		
Global RNFL thickness, μm	-2.018	0.143			-2.609	0.050	-0.349	0.693	-1.995	0.080		
Visual field MD, dB	-1.045	0.595			-1.096	0.565			-1.383	0.408		
Visual field PSD, dB	-0.127	0.980			0.346	0.944			2.286	0.600		

IOP = intraocular pressure; LC = lamina cribrosa; BMO = Bruch's membrane opening; BBA = Bruch's membrane opening - border tissue angle; JPCT = juxtapapillary choroidal thickness; RNFL = retinal nerve fiber layer; MD = mean deviation; PSD = pattern standard deviation; dB = decibel.

Only variables with $P < 0.1$ on univariate analysis were included in the multivariate model.

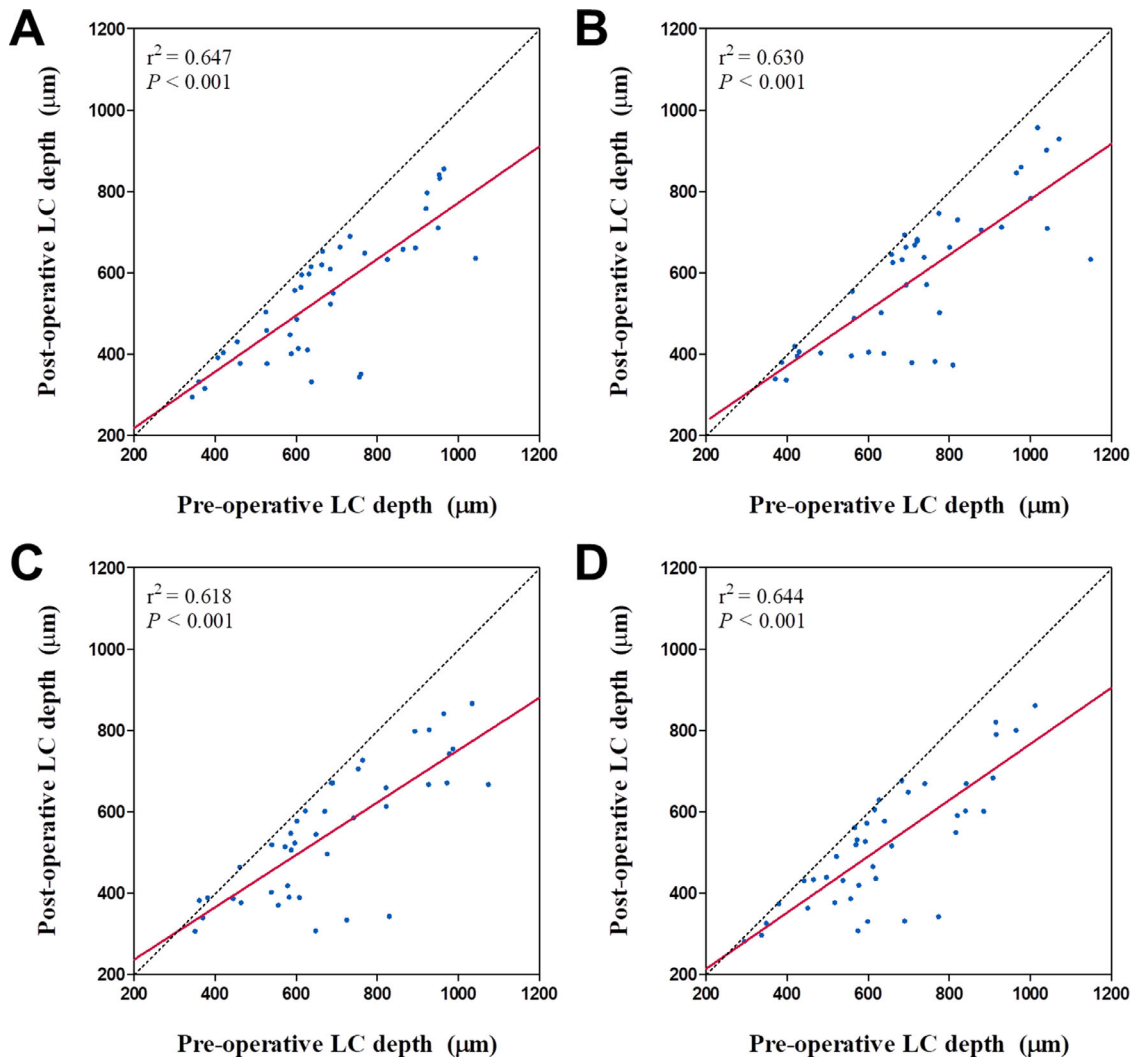Values with statistical significance are shown in boldface.

Figure 3. Scatterplots showing pre- and postoperative LC depths. (**A**) Average LC depth, (**B**) LC depth in the most superior plane (plane 2), (**C**) LC depth in the mid-horizontal plane (plane 4), and (**D**) LC depth in the most inferior plane (plane 6). *Red solid lines* indicate correlations between pre- and postoperative LC depths, and *black dotted lines* indicate 1:1 correllations between pre- and postoperative LC depths. Preoperative LC depth was greater than postoperative LC depth in almost all eyes. Note that change in LC depth pattern was not different according to the planes.
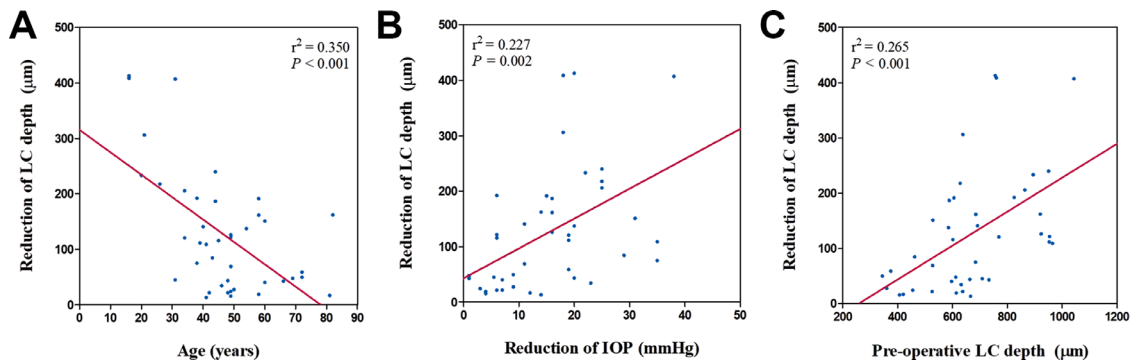

Figure 4. Scatterplots showing the relationships of postoperative reduction in LC depth with (**A**) age, (**B**) reduction in IOP, and (**C**) preoperative LC depth.
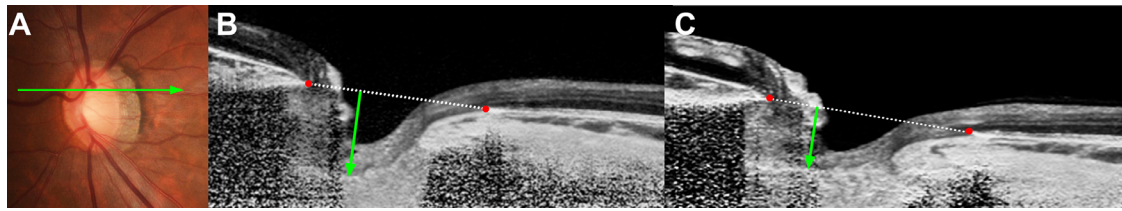
FIGURE 5. Optic disc photograph and B-scan images of the left eye of a 26-year-old male patient with myopic tilted disc. (**A**) Optic disc photograph image. (**B**) Pre-operative and (**C**) 3-month postoperative B-scan images of the plane indicated by the *green line* in the optic disc photograph **A**. Intraocular pressure decreased from 32 mm Hg before surgery to 7 mm Hg 3 months after surgery. LC depth was noticeably decreased after trabeculectomy.

tation in evaluating changes in LC position as it is affected by changes in choroidal thickness. This limitation may be overcome by measuring LC depth from the anterior scleral level or the LC curve as suggested. In our experience, however, the anterior scleral surface cannot be clearly detected in many patients. In addition, the LC curve is difficult to evaluate in myopic eyes because the nasal LC is often obscured by the overlying neuroretinal rim due to the tilted nature of the disc. Although we measured LC depth from the level of the BMO, we also measured choroidal thickness before and after surgery to overcome the limitation of this method. Consistent with previous observations,[30–32] we found that the choroid was thicker after than before surgery. Thickening of the choroid increases the distance between the BMO and the anterior LC surface, resulting in an overestimation of LC depth. Nevertheless, the present study found that LC depth was significantly lower postoperatively than preoperatively, clearly indicating that the LC surface had shifted anteriorly after trabeculectomy. In addition, the result of association between difference of JPCT and LC depth in the univariate analysis supports this notion.

Our previous studies found that posterior displacement of the LC in patients with POAG was reversed after IOP-lowering surgery and medical treatment.[3–5] However, the relationship between changes in LC position and changes in IOP in myopic eyes was not determined. Computational studies have suggested that properties of the peripapillary sclera may have a significant effect on LC change in response to IOP changes, in that, when the sclera is more compliant than the LC, the LC may move anteriorly upon IOP elevation and vice versa.[7–9,13,33] The sclera is thinner in myopic than in non-myopic eyes, suggesting that the sclera in myopic eyes may be more compliant to IOP induced stress. Based on this, it can be postulated that the LC change behavior may be different in eyes with myopia, at least in some eyes. However, the LC moved anteriorly upon IOP lowering in the present study, which is consistent with previous studies, which was not exclusively included myopic eyes.[3,4] Moreover, the anterior movement of the LC after trabeculectomy was universal in the present study. In other words, the LC moved anteriorly in all eyes after trabeculectomy with no exception.

Experimental studies have suggested that scleral canal expansion may have some influence on the LC movement. It would cause the LC taut so that the LC depth may decrease upon IOP elevation.[7–9] Although this can be theoretically plausible, no study has clearly demonstrated anterior movement of LC after IOP elevation. Some experimental studies[13,34–36] mentioned anterior movement of LC after IOP elevation, but the observed changes were not statically significant or found in a setting a bit away from real world

situation (i.e. comparison between IOP 0 and IOP 10 mm Hg).[33] In the current study, effect of scleral expansion could not be addressed because it was difficult to precisely detect the nasal anterior scleral canal opening in myopic tilted eyes. Further study with better imaging modality may be needed to investigate the relationship between scleral canal change and the LC depth change.

Our study found that younger age, greater IOP reduction, and greater preoperative LC depth were associated with a greater postoperative reduction in LC depth. This result is consistent with previous studies that included patients with non-myopic glaucoma, showing that LC depth was reduced after IOP lowering treatment.[3,4] Notably, however, we found no correlation between the magnitude of LC depth reduction and axial length and BBA, especially as the sclera is potentially thinner in eyes with longer axial length.[10] The BBA is an indicator of BMO shift showing the degree of oblique arrangement of BMO and ASCO during the axial elongation. It can be inferred that the reduction in LC depth after IOP lowering is not significantly affected scleral thinning and optic disc deformation caused by myopia.

The results of the current study have important clinical implications. Peripapillary scleral tension associated with axial elongation is considered to be an important pathogenic factor in myopic eyes,[37–39] along with IOP-induced stress. Reduction of LC depth after IOP lowering suggests that LC depth would increase upon IOP elevation. Therefore, the pathogenic mechanism in myopic eyes may be (partly) inferred based on the LC depth or morphology. IOP-induced stress may be a predominant mechanism in eyes with an LC that is deep or steeply curved posteriorly. If the LC is not deep or not highly curved posteriorly, then tangential stress arising from stretching of the peripapillary sclera may be considered to play a more predominant role. The classification of patients with myopic glaucoma based on the pathogenic mechanism is important because their clinical course of disease may differ. Disease progression was shown to be very slow or even halted in some patients with myopic glaucoma.[40–42] It has been suggested that tangential stress to the LC arising from axial elongation may be the predominant mechanism of damage in those patients. Because axial elongation is not a life-long process, such tangential stress may be less effective to develop further optic nerve damage at some point. Although further study is needed, those patients are more likely associated with relatively flat LC. Conservative management may be considered in those patients. On the contrary, in patients with steeply curved LC, which likely indicates that IOP-induced stress playing a significant role, IOP control would be important for slowing disease progression.

The current study has several limitations. First, patients were observed for only 3 months after trabeculectomy. However, we previously showed that reduction of LC displacement occurred largely during the first 3 months after surgery, suggesting that the follow-up period in the present study was sufficiently long to observe changes in LC associated with changes in IOP. Another limitation was that the optic nerve head was only scanned horizontally. To our experience, however, horizontal raster scan was superior to other scan protocols for imaging the LC at the same location on a longitudinal basis.

In conclusion, LC depth was reduced after trabeculectomy in myopic eyes, including highly myopic eyes. The degree of LC depth reduction was associated with age, magnitude of IOP reduction, and large preoperative LC depth, but not with degree of myopia.

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