Macular Displacement After Vitrectomy in Eyes With Idiopathic Macular Hole Determined by Optical Coherence Tomography Angiography

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• PURPOSE: To determine whether the macula is displaced after vitrectomy with internal limiting membrane (ILM) peeling in eyes with an idiopathic macular hole.

• DESIGN: A retrospective, observational case series.

• METHODS: Optical coherence tomography angiography was used to obtain 3 mm × 3 mm en face images before and 2, 4, and 8 weeks after the vitrectomy with ILM peeling for 20 eyes of 20 patients with an idiopathic macular hole. The displacements of easily identifiable retinal vessel bifurcations were measured relative to the fovea and the optic disc.

• RESULTS: The distance between the optic disc and vessel bifurcations was significantly shorter in all 4 quadrants throughout the postoperative period ($P < .001$). This distance was significantly greater in the temporal quadrant ($P < .001$). The distance of the bifurcations was significantly correlated with the preoperative distance from the optic disc ($r = -0.579$, $P < .001$). A significantly greater downward displacement was observed in the superior quadrant ($P < .001$). The change in the angle of bifurcations was significantly correlated with the preoperative angle to the optic disc ($r = -0.632$, $P < .001$). The change in the distance in the inner region was significantly greater than that in the outer region in all quadrants. A significant reduction was observed in the mean foveal avascular zone area during the follow-up period.

• CONCLUSIONS: The retina in the macular region was displaced nasally, probably owing to movement of the retina toward the optic disc because of a contraction after the ILM removal. There is also a possibility of a rotation downward by buoyancy from gas tamponade, and centripetal contraction during the process of hole closure. (Am J Ophthalmol 2018;189:111–121. © 2018 Elsevier Inc. All rights reserved.)

AN IDIOPATHIC MACULAR HOLE (MH) CAN BE SUCCESSFULLY closed by vitrectomy and gas tamponade,[1–6] and the success rate can be significantly improved by peeling the internal limiting membrane (ILM) during the vitrectomy.[2–8] The compartment formed by the tamponading gas has been suggested to induce glial proliferation and centripetal movement of the retinal tissue, resulting in the MH closure.[7,9] However, it has also been reported that there is an asymmetrical contraction of the foveal tissue that has been detected by optical coherence tomography (OCT) after MH closure, and the asymmetrical changes were the cause of the postoperative metamorphopsia.[10] Analyses of preoperative and postoperative fundus photographs have shown that the fovea is displaced toward the optic disc, and the temporal vessels were shifted more than the nasal vessels.[11,12] Recently, analyses of en face images from optical coherence tomography angiography (OCTA) have provided more detailed information on the changes of the retina after a surgical closure of idiopathic MHs.[13] However, the exact asymmetrical displacements have still not been determined, and more detailed information on the displacements should provide information on the mechanisms causing the displacements.

The recent advances in OCT using split-spectrum amplitude-decorrelation angiography have enabled clinicians to investigate the retinal and choroidal vasculature in situ by OCTA.[14,15] This system is noninvasive and safe because it does not require an intravenous injection of a contrast dye. The discomfort of the patients is minimal, and it can be performed repeatedly at short intervals. New OCTA findings have been reported in a variety of fundus abnormalities, and they have provided detailed information on the retinal capillary networks in the macular area, including the changes in the size of the foveal avascular zone (FAZ).[16]

The purpose of this study was to determine whether the macular region of the retina is displaced after vitrectomy with ILM peeling in eyes with MH and to identify factors correlated with the displacements.

METHODS

• ETHICS STATEMENT: This was a retrospective, cross-sectional, single-center study, and the procedures used

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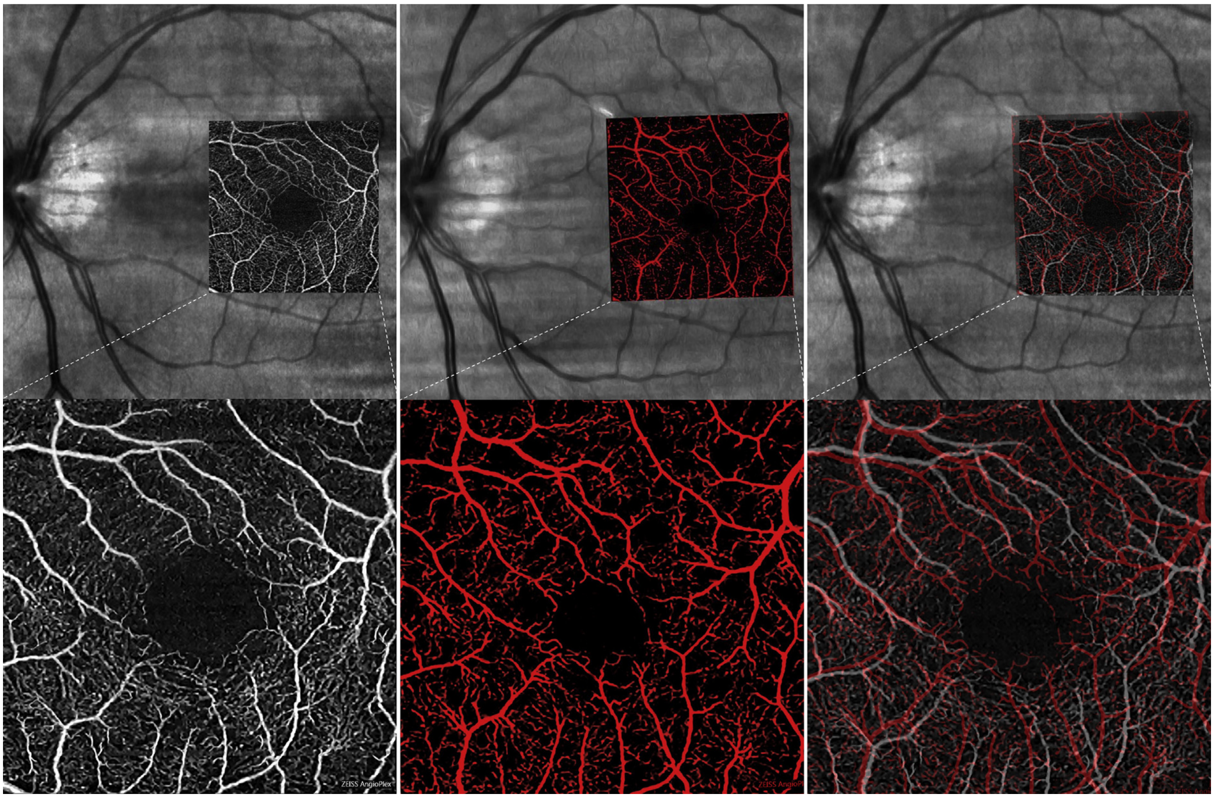

FIGURE 1. **Representative fundus photographs and superficial foveal retinal capillary plexuses observed by optical coherence tomography angiography (OCTA), from a 67-year-old man with a macular hole. Upper panels show fundus photographs and superimposed OCTA images of the superficial retinal capillary network; lower panels show magnified OCTA images. (Left) Preoperative images. The retinal vasculature is shown by white lines. (Middle) Postoperative fundus photograph with an OCTA image at week 2 after the vitrectomy. The retinal vasculature is shown as red lines. (Right) The preoperative (white) and postoperative (red) images are superimposed. The preoperative and postoperative images were adjusted by matching retinal vessels around the optic disc.**

were approved by the Ethics Committee of the Nagoya University Hospital, Nagoya, Japan. The study was performed at the Nagoya University Hospital, and the procedures used conformed to the tenets of the Declaration of Helsinki.

• **SUBJECTS:** We reviewed the medical records of patients who had undergone successful MH closure by vitrectomy and ILM peeling at the Nagoya University Hospital from August 23, 2016 to May 30, 2017. All of the patients had signed an informed consent form before the surgery. All of the patients had comprehensive ophthalmic examinations including measurements of the best-corrected visual acuity (BCVA), intraocular pressure (IOP), and the preoperative axial length. In addition, slit-lamp examinations, fundus photography, spectral-domain OCT (Spectralis; Heidelberg Engineering, Heidelberg, Germany), and OCTA were performed before and 2, 4, and 8 weeks after the vitrectomy.

The decimal visual acuities were converted to logarithm of the minimum angle of resolution (logMAR) units for the statistical analyses. The basal diameter and minimum diameter of the MH were measured in the cross-sectional spectral-domain OCT images. The size of the retina where the ILM was removed was measured in the videos recorded during the surgery. The area of FAZ was measured by the software embedded in the OCTA instrument.

• **EXCLUSION CRITERIA:** Eyes with macular diseases (diabetic retinopathy, age-related macular degeneration, myopic choroidal neovascularization), history of other ocular diseases (rhegmatogenous retinal detachment, epiretinal membrane), severe cataract, and high myopia > -5 diopters (D) were excluded.

• **OPTICAL COHERENCE TOMOGRAPHY ANGIOGRAPHY:** The Zeiss Cirrus 5000 HD-OCT (Zeiss Meditec, Inc, Jena, Germany) was used to obtain en face images of the microvasculature around the fovea. This device operates at a central wavelength of 840 nm and a speed of 68 000 A-scans/second. The optical microangiography complex algorithm analyzed the changes in both the intensity and phase contained in sequential B-scans performed at the same position.[17,18] The software then generates

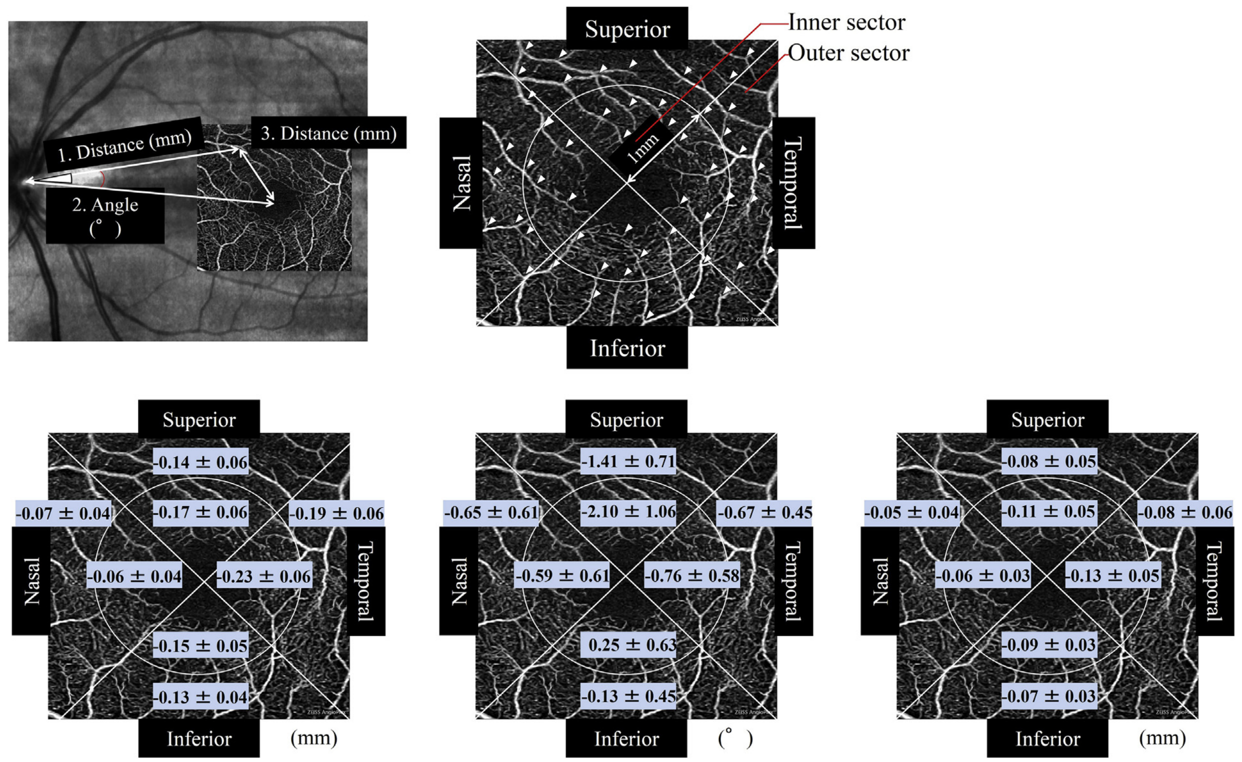

FIGURE 2. Displacement measurements using optical coherence tomography angiography (OCTA) images and the results in the quadrants. (Top left) Plot of distances between the center of the optic disc and a bifurcation of retinal vessels. Image shows how the angle made by a line between the center of the optic disc and the retinal vessel bifurcation and line extending from the optic disc to the preoperative fovea is used to measure the angle of the bifurcation point. (Top middle) The OCTA images are divided into 4 sectors by drawing a line from the retinal vessel bifurcations to the fovea. Then a line was drawn perpendicular to the original line. This divided the retina into 4 quadrants: temporal, superior, nasal, and inferior. In addition, each quadrant was subdivided into an inner region and an outer region. The inner sector was defined as the region within a distance of 1 mm from the fovea and the outer sector was outside the 1 mm region. (Bottom row) Changes in distance from the optic disc and the retinal vessel or bifurcations (Bottom left), in angle from the optic disc and the retinal vessel bifurcation (Bottom middle), and in distance between the fovea and the retinal vessel bifurcation (Bottom right) between preoperative and week 2 in each sector is shown.

$3 \times 3\text{-mm}^2$ en face images of the microvascular network centered on the fovea. The $3 \times 3\text{-mm}^2$ scan pattern is composed of 245 A-scans and 245 B-scans. The vascular image of the superficial capillary network layer, which is 1 of the 4 slabs provided automatically determined by the embedded software in the instrument, was used for the displacement measurements and the measurements of the FAZ (Figure 1). The superficial capillary network was determined to be between the ILM and the inner plexiform layer. After all scans were reviewed by the 2 graders (T.A. and T.I.), the low-quality OCT angiographic images and images with severe artifacts owing to poor fixation or failure of automatic layer segmentation were excluded from the analysis. These 2 authors measured the vascular displacements independently. Agreements between the 2 observers for quantitative analysis of the vascular displacements were determined by intraclass correlation coefficient (ICC).

• **DISPLACEMENT MEASUREMENTS USING OPTICAL COHERENCE TOMOGRAPHY ANGIOGRAPHIC IMAGES:** The OCTA images were analyzed with ImageJ software (ImageJ version 1.47; NIH, Bethesda, Maryland, USA), and the changes between the preoperative and postoperative images were adjusted by matching the retinal vessels around the optic disc (Figure 1, Right).

We determined the displacements of the retina relative to the fovea and optic disc. To do this, we measured the distance between the center of the optic disc and an easily identifiable bifurcation of the retinal vessels (Figure 2, Top left, numbered "1"), and the angle made by a line between the center of the optic disc and the bifurcation point and a line extending to the center of the fovea (Figure 2, Top left, numbered "2"). The angle was 0 degrees in the foveal direction and increased in a counterclockwise direction in the left eye and a clockwise direction in the right eye. We also measured the distance between the fovea

TABLE 1. Clinical Characteristics of Subjects (20 Patients/20 Eyes)

Characteristics	Results
Age, y	65.9 ± 9.7
Male:female	7:13
Right eyes:left eyes	10:10
Preoperative BCVA (logMAR)	0.58 ± 0.27
Postoperative BCVA (logMAR)	0.29 ± 0.20
Axial length (mm)	24.0 ± 1.6
FAZ size (mm^2)	0.39 ± 0.11
MH stage 2:3:4 (eyes)	6:8:6
Basal MH size (μm)	707 ± 329
Minimum MH size (μm)	347 ± 187
PPV + PEA + IOL/PPV (eyes)	15:5
ILM peeling size (DD)	3.62 ± 0.46
Gas tamponade (C_3F_8:SF_6)	4:16

BCVA = best-corrected visual acuity; C_3F_8 = octafluoropropane; DD = disc diameter; FAZ = foveal avascular zone; ILM = internal limiting membrane; IOL = intraocular lens; logMAR = logarithm of minimum angle of resolution; MH = macular hole; PEA = phacoemulsification and aspiration; PPV = pars plana vitrectomy; SF_6 = sulfur hexafluoride.

Values are presented as numbers or as means ± standard deviations.

and the bifurcation of easily identifiable retinal vessels (Figure 2, Top left, numbered "3").

The bifurcations in the vessels in the OCTA en face images were used to divide the retina into 4 quadrants: temporal, superior, nasal, and inferior (Figure 2, Top middle). In addition, each quadrant was divided into an inner and outer region. The inner region was defined as the area within a distance of 1 mm from the fovea and the outer region was more than 1 mm peripheral to the fovea. The average of the changes in the distance and the angle in each quadrant and region was determined.

• **SURGICAL TECHNIQUE:** Standard 3-port pars plana vitrectomy (PPV) was performed with 25 gauge instruments under 2.5 mL of 2% lidocaine and 2.5 mL of 0.5% bupivacaine retrobulbar anesthesia. Cataract surgery was performed on all 15 phakic eyes. To begin the PPV procedure, a trocar was inserted at an approximate angle of 30 degrees to the limbus. Once the trocar was past the trocar sleeve, the angle was changed to be perpendicular to the retinal surface. After creation of the 3 ports, PPV was performed using the Alcon Constellation system (Alcon Laboratories, Inc, Fort Worth, Texas, USA).

After completion of the core vitrectomy, a posterior vitreous detachment was created if one was not present by active aspiration. Then the ILM was peeled from the retina using ILM-peeling forceps (25 gauge Grieshaber Revolution DSP ILM forceps; Alcon Laboratories, Inc) assisted by triamcinolone acetonide (TA). Fluid-air exchange was performed, then 20% sulfur hexafluoride (SF_6) or 12% perfluoropropane (C_3F_8) was injected into the vitreous fluid upon completion of the PPV. After the IOP was adjusted to normal levels, the cannulas were withdrawn, and the sclera was pressed and massaged with an indenter or sutured with 8–0 vicryl to close the wound. The patients were instructed to maintain a prone position until a closure of the MH was confirmed.

To begin the cataract surgery, a 2.4-mm-wide self-sealing superior sclerocorneal tunnel was created at 12 o'clock, and a continuous curvilinear capsulorrhexis was performed. The lens nucleus was removed, and the residual cortex was aspirated with an irrigation/aspiration tip. Then, a foldable acrylic IOL was implanted into the capsular bag.

• **STATISTICAL ANALYSES:** The values are presented as the means ± standard deviations. One-way analysis of variance (ANOVA) was used to evaluate differences of the chronological data and used to compare 4 quadrants. Dependent *t* tests were used to compare inner region and outer region. The Pearson correlation coefficient test was used to determine the significance of the associations between the changes in the displacement or angle of each bifurcation and the preoperative distance or angle. All statistical analyses were performed using the Statistical Package for Social Sciences for Windows 21.0 (SPSS Inc, Chicago, Illinois, USA).

RESULTS

• **PATIENT DEMOGRAPHICS AND SURGICAL CHARACTERISTICS:** Thirty-four eyes of 34 patients with an MH underwent vitrectomy with ILM peeling between September 2016 and May 2017. Of these, 14 eyes were excluded: 1 for macular degeneration, 2 for prior vitrectomy, 8 for high myopia, and 3 for severe cataract that prevented obtaining high-quality OCTA images. In the end, 20 eyes of 20 patients (mean age, 65.9 ± 9.7 years) were studied. The MH was closed in all eyes after the initial surgery. The demographics and surgical procedures are shown in Table 1. The size of the ILM peeled area was 3.62 ± 0.46 disc diameter (DD). The repeatability of the measurements between the graders was excellent, with an ICC of 0.99 for the changes in distance from optic disc and retinal vessel bifurcations, 0.99 for the changes of angle of retinal vessel bifurcations, and 0.99 for the changes in distance between fovea and retinal vessel bifurcations.

• **CHANGES IN DISTANCE FROM OPTIC DISC TO RETINAL VESSEL BIFURCATIONS:** The mean number of measured retinal vessel bifurcations for each eye was 51.5 ± 8.1. The distance between the center of the optic disc and retinal vessel bifurcations was significantly shorter after the vitrectomy than before in all 4 quadrants and throughout the postoperative period ($P < .001$; Table 2).

TABLE 2. Change in Distance and Angle Between Bifurcations and the Optic Disc

	Quadrant	Region	Week 2	Week 4	Week 8	*P* Value
Change in distance (mm)	Temporal	All	−0.20 ± 0.06	−0.20 ± 0.08	−0.22 ± 0.08	<.001
		Inner	−0.23 ± 0.06	−0.23 ± 0.08	−0.24 ± 0.08	<.001
		Outer	−0.19 ± 0.06	−0.19 ± 0.08	−0.20 ± 0.08	<.001
	Superior	All	−0.15 ± 0.05	−0.16 ± 0.07	−0.18 ± 0.07	<.001
		Inner	−0.17 ± 0.06	−0.17 ± 0.07	−0.19 ± 0.08	<.001
		Outer	−0.14 ± 0.06	−0.15 ± 0.08	−0.17 ± 0.07	<.001
	Nasal	All	−0.06 ± 0.04	−0.07 ± 0.05	−0.08 ± 0.05	<.001
		Inner	−0.06 ± 0.04	−0.07 ± 0.06	−0.08 ± 0.05	<.001
		Outer	−0.07 ± 0.04	−0.07 ± 0.05	−0.08 ± 0.04	<.001
	Inferior	All	−0.14 ± 0.04	−0.15 ± 0.06	−0.16 ± 0.06	<.001
		Inner	−0.15 ± 0.05	−0.16 ± 0.06	−0.18 ± 0.05	<.001
		Outer	−0.13 ± 0.04	−0.13 ± 0.06	−0.15 ± 0.07	<.001
Change in angle (degree)	Temporal	All	−0.70 ± 0.50	−0.63 ± 0.65	−0.52 ± 0.68	<.001
		Inner	−0.76 ± 0.58	−0.69 ± 0.73	−0.56 ± 0.78	<.001
		Outer	−0.67 ± 0.45	−0.58 ± 0.60	−0.47 ± 0.62	<.001
	Superior	All	−1.68 ± 0.82	−1.54 ± 1.02	−1.34 ±1.08	<.001
		Inner	−2.10 ± 1.06	−1.85 ± 1.18	−1.74 ± 1.31	<.001
		Outer	−1.41 ± 0.71	−1.33 ± 0.87	−1.10 ± 0.96	<.001
	Nasal	All	−0.63 ± 0.57	−0.46 ± 0.87	−0.39 ± 0.91	<.001
		Inner	−0.59 ± 0.61	−0.41 ± 0.91	−0.39 ± 0.88	<.01
		Outer	−0.65 ± 0.61	−0.48 ± 0.90	−0.39 ± 0.96	<.001
	Inferior	All	−0.08 ± 0.52	−0.13 ± 0.77	0.20 ± 0.68	.680
		Inner	0.25 ± 0.63	0.31 ± 0.89	0.37 ± 0.76	.210
		Outer	−0.13 ± 0.45	−0.14 ± 0.65	−0.04 ± 0.65	.390

There were no significant differences in the distances among postoperative periods in all of the quadrants (Figure 3, Top left). Thus, the change in the distance between the center of the optic disc and the retinal vessel bifurcations at week 2 was selected to compare the alterations in the 4 quadrants. The change in the distance in the temporal quadrant was significantly greater than that in the other quadrants ($P < .001$), and it was significantly shorter in the nasal quadrant than the other quadrants ($P < .001$; Figure 3, Top right).

The degree of the displacement of each vessel bifurcation at week 2 was significantly correlated with its preoperative distance from the optic disc ($r = -0.579$, $P < .001$) (Figure 4, Top left). A comparison between the values of the inner and the outer regions showed that the distance change was significantly greater in the inner region than in the outer region at the temporal, superior, and inferior quadrants (Figure 3, Top left).

• **CHANGES OF ANGLE OF RETINAL VESSEL BIFURCATIONS AFTER VITRECTOMY:** The mean changes in the angle made by a line from the center of the optic disc to the center of the fovea and a line connecting the optic disc to the bifurcations are shown in Figure 3 (Bottom left). The angle was significantly rotated downward in the temporal, superior, and nasal quadrants 2 weeks after the surgery ($P < .01$). However, there was no significant difference between the angles thereafter in all 4 quadrants. The change in the angle at week 2 was selected to compare among the quadrants. A significantly greater downward displacement was observed in the superior quadrant ($P < .001$), and the displacement was significantly smaller in the inferior quadrant ($P < .001$; Figure 3, Bottom right).

The change in the angle at each bifurcation at week 2 was significantly correlated with the preoperative angle to the optic disc ($r = -0.632$, $P < .001$; Figure 4, Top right). The change in the angle was significantly greater at the bifurcations located in the inner region than in the outer region in the superior quadrant ($P < .001$; Figure 3, Bottom left). The changes were significantly different in the regions at the inferior quadrant, with upward rotation in the inner region and downward rotation in the outer region.

• **CHANGES IN DISTANCE BETWEEN FOVEA AND RETINAL VESSEL BIFURCATIONS:** The changes in the distance between the fovea and the retinal vessel bifurcations are shown in Figure 5. The change in the distance was significantly smaller in the nasal quadrant than in the temporal and superior quadrants ($P < .05$), and the changes in the distance in the inner region were significantly greater than in the outer region in all of the quadrants ($P < .05$). The changes in the distance between the fovea and each bifurcation at week 2 were significantly correlated with the preoperative distance to the fovea ($r = 0.216$, $P < .001$; Figure 4, Bottom left).

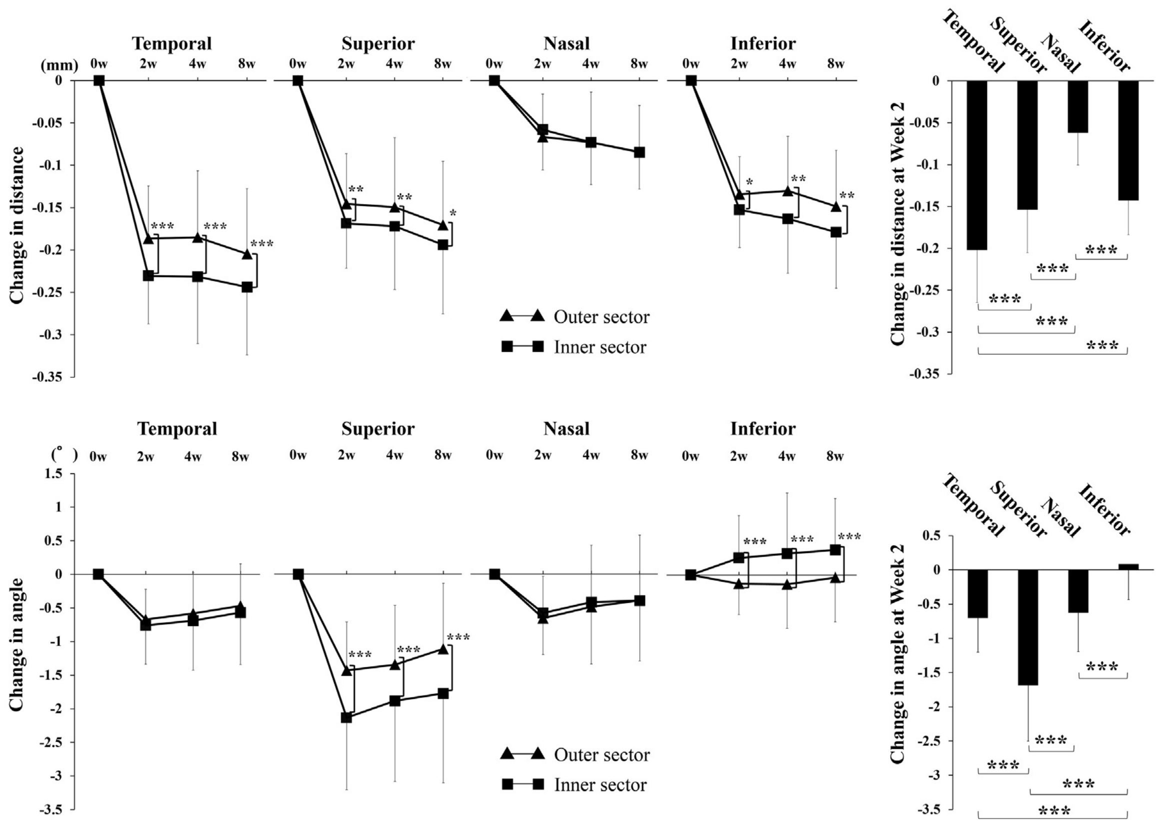

FIGURE 3. Displacement in the quadrants after surgery and comparisons among the quadrants. (Top left) Distance from the center of the optic disc and retinal vessel bifurcations was significantly shorter in all of the quadrants throughout the postoperative period following surgery ($P < .001$). However, there were no significant differences in the distance after week 2. (Top right). Comparisons of the changes in the distance in the 4 quadrants at week 2. (Bottom left) Angle from the optic disc and the retinal vessel bifurcations was rotated significantly downward in the temporal, superior, and inferior quadrants at week 2 ($P < .01$), but there was no significant difference in the distance after week 2. (Bottom right) Comparisons of the changes in the angle in the 4 quadrants at week 2. Each point represents the mean ± standard deviation. *$P < .05$, **$P < .01$, ***$P < .001$ between 2 comparisons.

• **CHANGES OF FOVEAL AVASCULAR ZONE AREA:** The mean preoperative FAZ area was 0.39 ± 0.11 mm^2 in eyes with an MH, which was larger than that in the fellow eye before the surgery, at 0.32 ± 0.11 mm^2 ($P = .005$; Figure 6, Top left). A significant reduction was observed in the mean FAZ during the follow-up period ($P = .034$). The change in FAZ was significantly and positively correlated with the minimum MH size ($r = 0.48$, $P < .001$; Figure 6, Bottom left) and the basal MH size ($r = 0.49$, $P < .001$; Figure 6, Bottom right).

• **CHANGES OF FOVEAL POSITION:** The changes in the distance and the angle between the fovea and the optic disc were −0.10 ± 0.05 mm and −0.69 ± 0.63 degrees, respectively.

• **RELATIONSHIPS BETWEEN DISPLACEMENTS AND OTHER FACTORS:** Single linear regression analysis showed that the changes in distance between the optic disc and the bifurcations and the changes in the angle to the optic disc were not significantly correlated with parameters including the size of the MH, the size of ILM peeled area, the axial length, improvement of BCVA, the type of gas tamponade, the surgeon, or the type of surgery. The changes in the distance between the fovea and bifurcation in the temporal inner region were significantly correlated with only the basal MH size ($r = -0.554$, $P = .011$).

DISCUSSION

ONE OF THE ADVANTAGES OF USING THE OCTA IMAGES TO measure the displacements in the retina after vitrectomy is the ability to measure many points in a short time. In earlier reports, fundus photographs and cross-sectional OCT images were used to measure the displacement of the retina. We measured a much larger number of points, an average of 51.5 points, for each eye in the OCTA images.

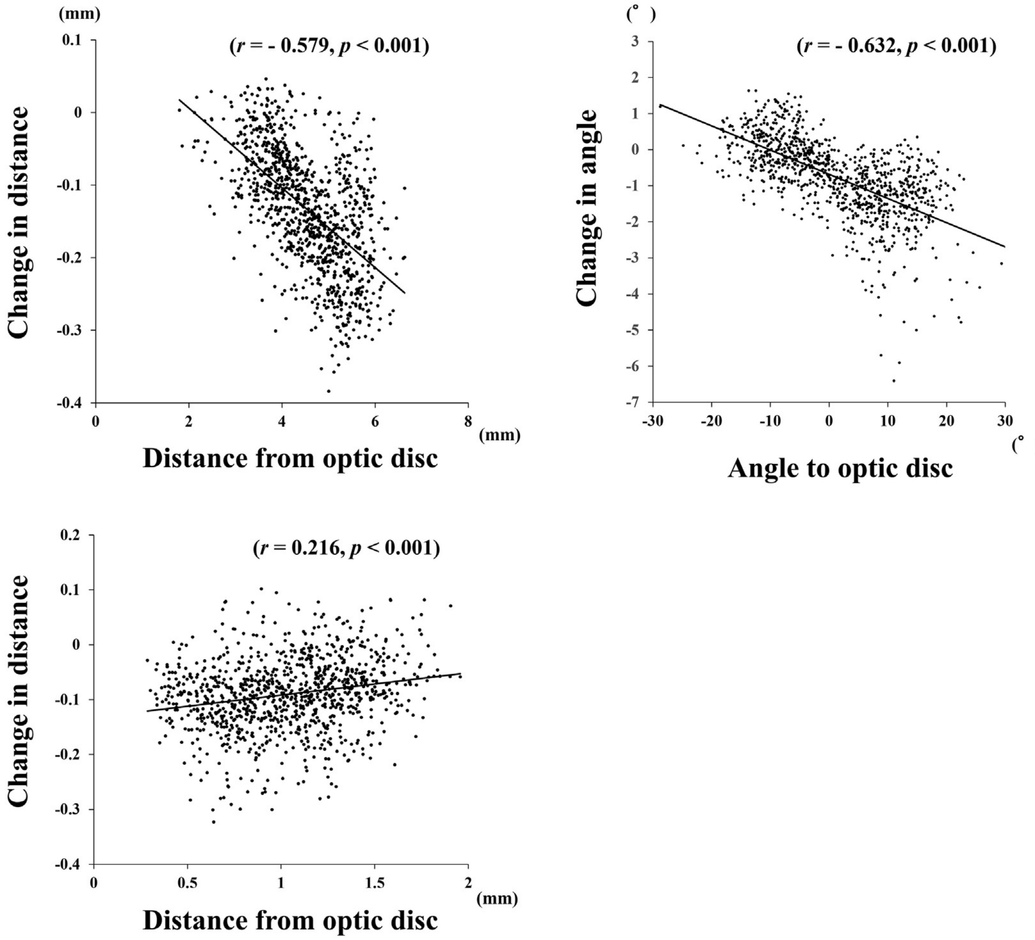

FIGURE 4. Relationship between changes in the distance from the optic disc to the retinal vessel bifurcations, changes in the angle and the angle from the optic disc to retinal vessel bifurcations, and changes in the distance from the fovea to the retinal vessel bifurcations. (Top left) Plot of displacements at 2 weeks after surgery. The changes in distance were significantly correlated with the preoperative distance from the optic disc ($r = -0.579, P < .001$). (Top right) Plot of the changes in the angle at 2 weeks after surgery. The changes in angle were significantly correlated with the preoperative angle made by the line through the center of the optic disc to the fovea and the optic disc to the bifurcations ($r = -0.632, P < .001$). (Bottom) Plot of displacements at 2 weeks after surgery. The changes in distance were significantly correlated with the preoperative distance from the fovea ($r = 0.216, P < .001$).

There have been several reports on the directions of the macular displacements in eyes after successful closure of the MH with ILM peeling.[11–13] However, it is difficult to determine the displacement of the fovea accurately because the fovea is also displaced after the surgery. Thus, we measured the displacements of the bifurcations of the retinal vessels relative not only to the fovea but also to the optic disc. With the optic disc as the fixed point, the displacements were significantly correlated with their distance from the optic disc, and the changes in the angles were significantly correlated with the angle made by the line from the optic disc to the fovea. These findings indicate that there was a nasal and inferior displacement of that specific point after the surgery. Using the fovea as the fixed point, there were centripetal displacements of the vessel bifurcations.

In the measurements of the retinal displacements using the center of the fovea as the fixed point, our results showed that the distance from the center of the fovea to the retinal vessel bifurcations was shorter postoperatively in all of the quadrants. In addition, the displacement in the inner ring was significantly greater than that in the outer ring in all quadrants, and the displacements were negatively correlated with their distance from the fovea. The displacement in the inner temporal ring was correlated with the basal MH size. Furthermore, the area of the superficial FAZ measured by OCTA was significantly smaller after the closure of the MHs. These findings clearly indicate a centripetal movement of the retina after a successful MH closure. The surgical procedures, including ILM peeling, may have induced glial cell proliferation, resulting in the closure of the macular hole by the proliferating cells.[19]

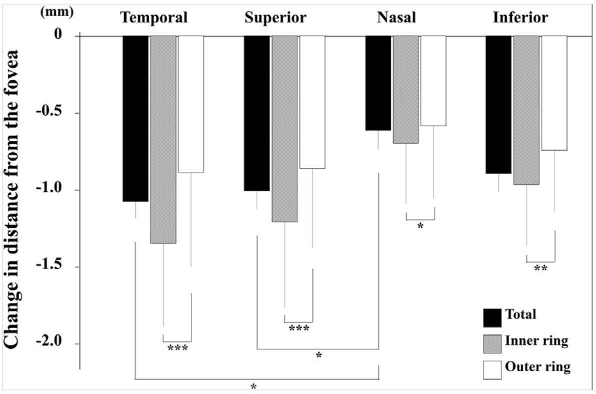

FIGURE 5. Changes in the distance between the fovea and the retinal vessel bifurcations at week 2. The changes in the distances were significantly greater in the inner ring than the outer ring in all quadrants. The changes in the distances were significantly smaller in the nasal quadrants than those in the temporal and the superior quadrants. *$P < .05$, **$P < .01$, ***$P < .001$.

Glial cell proliferation is known to occur at the MH, and the edge of the MH is displaced to the center of the fovea, and the area closer to the MH should be displaced more than the peripheral areas.

Pak and associates reported that the size of ILM removed was an independent variable that was significantly related to the macular displacement,[13] which differs from our results. This may be because of differences in the measurement methods and our smaller measurement area of 3×3 mm^2. In their study, the ILM peeled over a much wider area than where the OCTA images were obtained, suggesting that the ILM was peeled in an area where the OCTA images were analyzed.

Baba and associates reported that there was a significant reduction in the superficial FAZ area after a successful MH closure, and also a significant negative correlation between the area of the postoperative superficial FAZ and the postoperative central foveal thickness.[16] The central foveal thickness and small superficial FAZ area suggest a movement of foveal tissue toward the central fovea, a centripetal movement, when the MH is closed. Not surprisingly, the preoperative superficial FAZ area in eyes with MH is larger than that in normal subjects[20,21] because the preoperative FAZ included the area of the MH. In addition, the tissues around the fovea are displaced centrally to close the MH, leading to a smaller FAZ.

The change in the FAZ area was significantly correlated with the maximum and the basal diameter of the MH. These changes are reasonable because the retinal tissue around the fovea moves toward the fovea in eyes with larger MHs after a successful closure.

In the displacement measurements using the center of the optic disc as the fixed point, the displacements of the vessel bifurcations were positively and significantly correlated with the preoperative distance between the optic disc and the bifurcations. Thus, the farther the bifurcation was from the optic disc, the greater was the displacement; and the closer the bifurcation was from the optic disc, the smaller was the displacement after the vitrectomy. The vessels temporal to the fovea were displaced toward the optic disc more than the nasal vessels after the ILM peeling. In addition, the superior and inferior quadrants were displaced toward the horizontal raphe. These results clearly indicate that the macular region including the fovea was displaced toward the optic disc after vitrectomy with ILM peeling, and these observations corroborate previous reports.[11–13]

Our findings are in general agreement with those of Yoshikawa and associates, who reported that the papillofoveal distance was shorter in ILM peeled eyes than ILM nonpeeled eyes in eyes with diabetic macular edema.[22]

Peeling the ILM has been reported to improve the anatomic and functional outcomes after vitrectomy on eyes with an MH.[3,23] The exact mechanisms causing the displacement of the macular region after vitrectomy with ILM peeling have not been determined, but some evidence can be obtained from our results and the results of earlier studies. The ILM is the basement membrane of the Müller cells, and the removal of the ILM leads to a loss of the structural support of the retina and the retinal nerve fiber layer (RNFL). This enables the retina to be displaced because the ILM is a relatively anchored tissue that contributes to the strength of the retina[24] and contributes less to retinal elasticity.[22,25] It has been reported that nerve fibers consist mainly of microtubules, and depolymerization of microtubules may cause neuronal contractions.[26] Because the optic nerve fibers are tethered to the lamina cribrosa,[27] the nerve fibers in the retina would move toward the optic disc after contraction of the fibers. Accordingly, the place farther from the optic disc would be displaced more if the RNFL contracts evenly, because the RNFL is anchored at the optic disc. Therefore, if ILM peeling promotes the nerve fibers to shrink where the ILM was peeled, this may be one of the reasons why the displacement was correlated with the distance from the optic disc.

It has been suggested that the centripetal contraction is in the same direction as the RNFL contraction in the temporal quadrant of the MH.[13] In contrast, the directions of the 2 forces are opposite in the nasal quadrant. The differences in the summation of the contractile force vectors may result in an asymmetrical displacement, which results in the asymmetric movement (ie, the displacement is more in the temporal quadrant). However, the displacement was positively correlated with the distance from the optic disc in our results. This suggests that the displacement is greater at distances farther from the optic disc (ie, temporal quadrant).

The displacement from the center of the optic disc in the inner ring was also significantly larger than that in the outer

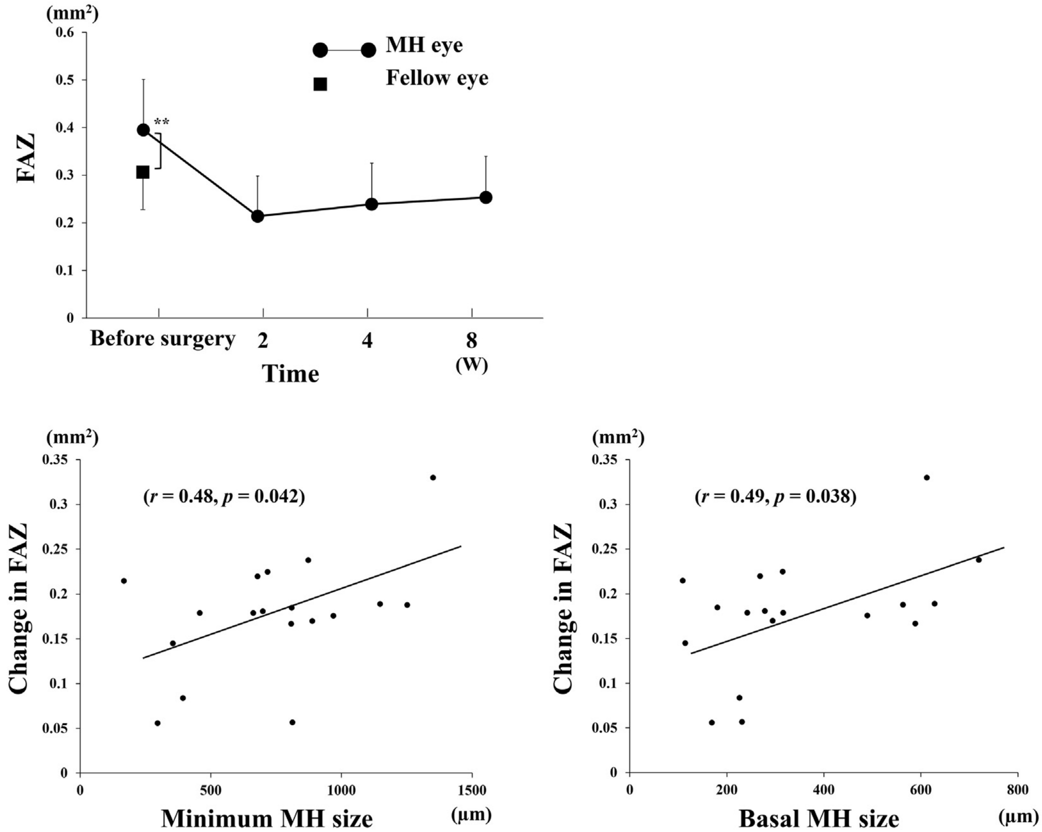

FIGURE 6. Change in foveal avascular zone (FAZ) area and the correlation between the foveal avascular zone area and the size of the macular hole. (Top) The mean FAZ area was larger in the operated eye than in the fellow eye before the vitrectomy ($P = .005$). A significant reduction was observed in the mean FAZ during the follow-up period ($P = .034$). (Bottom left) Change in the FAZ area at week 2 was significantly and positively correlated with the minimum MH size ($r = 0.48$, $P < .001$). (Bottom right) Change in the FAZ area is significantly and positively correlated with the basal MH size ($r = 0.49$, $P < .001$). **$P < .01$.

ring in the temporal, superior, and inferior quadrants. These changes may be associated with the displacement of the fovea toward the optic disc.

The angle made by the line between the center of the optic disc and the retinal vessel bifurcation and a line extending from the optic disc to the center of the preoperative fovea was rotated significantly downward in the following order: superior, temporal, nasal, and inferior quadrants.

There are 2 forces acting on the macula after vitrectomy with ILM peeling: 1 force is toward the optic disc owing to the ILM peeling and the second is toward the center of the fovea owing to the macular hole closure after the surgery. However, it is not possible to explain the displacement downward by those 2 forces. Accordingly, we suggest that another force may be causing this displacement. Several reports have mentioned this downward displacement after MH closure.[11,13] Pak and associates suggested that gravity displaces the macula inferiorly.[13] However, the displacement downward was observed from week 2 and the tamponade gas was still in the vitreous cavity, and the patients were instructed to maintain a prone position for 2 weeks after surgery. This means that the retina should not be affected by the gravity. In addition, the changes in the angle were significantly correlated with the preoperative angle of the bifurcation point to the optic disc. Furthermore, the displacement downward slightly recovered in all quadrants after week 2, although the changes were not significant. Consequently, it is difficult to explain this downward displacement by gravity. It is more likely that another force may be the cause of the downward displacement at 2 weeks after the surgery.

The gas in the vitreous cavity has 2 major effects.[28] One is its buoyancy, which would have the greatest effect on the upper quadrant. The other effect is surface tension, which has an even force at the contact area between the gas and the retina. Leitritz and associates have reported on the head position of a patient who was instructed to maintain a prone position after MH surgery.[29] They reported that the average angle of the head position was −6.7 degrees, and they reported that patients take the prone position of −45 degrees or more only 18% of the 24 hours. Therefore, the force of buoyancy on the retina by the intraocular gas is most likely larger on the superior retina around the arcade vessels and not the fovea. The downward force generated by the gas tamponade would be greatest in the superior quadrant. Taken together, it is likely that buoyancy and the prone positioning would cause a downward displacement within 2 weeks after surgery, and the downward displacement should have recovered after week 2 because the gas had been absorbed.

In the inferior quadrant, the change in the angle, which was different between the inner and outer rings (viz, an upward rotation in the inner region and a downward rotation in the outer region), can be assumed to be because there are 2 opposite directional forces (ie, centripetal and downward forces). As mentioned, the centripetal force is greater in the inner ring, and the downward force is not great and should not differ greatly between the rings in the inferior quadrant. The summation of the stronger centripetal force and weak downward force should result in an upward rotation in the inner ring and that of the weak centripetal force and weak downward force should result in a downward rotation in the outer ring.

Our results showed that the displacement of the fovea did not change significantly after week 2, which is consistent with a previous report.[12] The MH was closed within 2 weeks after surgery, which would be associated with no change in the displacement after week 2. The displacement after vitrectomy with ILM peeling should be completed in the very early postoperative period, probably during the closure of the MH.

There are limitations to this study. First, the number of eyes examined was relatively small, and this was a retrospective study. Second, the distances between the optic disc and retinal vessel bifurcations were measured manually. Third, the type of gas used for the tamponade and the period of prone position were not uniform. These differences may have affected the results, although the differences were not observed between the kinds of gas. Fourth, the OCTA images were first taken at week 2 after the surgery because the tamponade gas still remained in the vitreous cavity. There were no significant differences in the displacement after week 2. The results suggest that the displacement occurred very early in the postoperative period after the vitrectomy with ILM peeling. Fifth, we did not examine the metamorphopsia by any methods (eg, the M Chart), and the findings may have helped explain the association between the displacement and the functional outcome. In addition, there would be a possibility that another force, other than centripetal, nasal, and inferior, can affect the displacement of the macula. Further prospective studies using a larger number of subjects, and analyses of the deep vascular layer in addition to superficial layer vascularity from earlier postoperative periods, will be necessary for clarification of the mechanism of the displacement.

In conclusion, the results show that the retina in the macular region was displaced nasally, probably owing to movement of the retina toward the optic disc because of a contraction after the ILM was removed. There is also a possibility of a rotation downward caused by buoyancy from gas tamponade, and centripetal contraction during the process of hole closure.

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