Original Article

Retinal Sensitivity Around the Macula and Retinal Structure at 1 Year after Macular Hole Surgery

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ABSTRACT

Introduction: This study investigated retinal sensitivity around the macula using MP-3 microperimetry before and after macular hole (MH) surgery and assessed the correlation between retinal sensitivity and structural MH parameters measured by optical coherence tomography.

Methods: This retrospective study included 24 eyes with idiopathic MH (68 ± 6.73 years, 13 men) who underwent vitrectomy between April 2020 and November 2023. MP-3 examinations were conducted preoperatively and at 3 months (24 eyes) and 12 months (16 eyes) postoperatively. Forty-five points arranged at the fovea center and within an 8° diameter were divided into concentric circles with distances of 0.5°, 1°, 2°, 3°, and 4° from the fovea, labeled as S0, S0.5, S1, S2, S3, and S4, respectively. The MH minimum linear diameter (MD) and basal diameter (BD) were measured, and their correlation with the MP-3 results was evaluated.

Results: Sensitivity up to S3 was significantly improved from preoperatively to 3 months postoperatively (S0: 9.38 ± 8.41 to 22.63 ± 3.29 dB, $p < 0.0001$; S0.5: 11.07 ± 6.47 to 21.25 ± 3.86 dB, $p < 0.0001$; S1: 13.26 ± 5.62 to 21.19 ± 3.22 dB, $p < 0.0001$; S2: 19.66 ± 3.98 dB to 23.42 ± 2.66 dB, $p < 0.0002$; S3: 22.95 ± 3.31 to 25.01 ± 3.16 dB, $p = 0.0355$). No significant improvements were observed between 3 and 12 months.

The MH size was 286 ± 184.84 μm for MD and 685.79 ± 333.17 μm for BD; there was a significant correlation with S0.5-S4 preoperative retinal sensitivity.

Conclusions: In typical MHs, retinal sensitivity is impaired within a 3° range, with recovery observed at 3 months. The larger the hole, the greater the decrease in sensitivity at each point.

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KEYWORDS: macular hole, MP-3, microperimetry, spectral-domain optical coherence tomography, retinal sensitivity

Introduction

Macular hole (MH) is a common vitreomacular interface disorder that affects the posterior vitreous cortex, interposing the extracellular matrix and sensory retina.[1] Histopathological research suggests that MHs may originate from the avulsion of the Müller cell cone, which normally anchors photoreceptors in the fovea[2,3] and clinically leads

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to metamorphopsia (visual distortion) and poor central vision.

Despite successful surgery,[4–6] the prediction of postoperative visual function remains challenging.[7] Microperimetry is a rapid and noninvasive method that can determine retinal sensitivity. This approach establishes a direct link between retinal sensitivity and visual acuity, contrast sensitivity, and color vision during the postoperative assessment of macular function.[8, 9] MP-3 microperimetry (Nidek Co., Ltd., Aichi, Japan) is a widely used system that involves eye movement tracking and measures retinal sensitivity in specific subregions using fundus imaging.[10–12]

Advances in spectral-domain optical coherence tomography (SD-OCT) have facilitated the comprehensive assessment of the retinal microstructure layer-by-layer owing to its exceptional resolution and rapid scanning capabilities.[13, 14] The minimum hole width measured at the narrowest point in the mid-retina, roughly parallel to the retinal pigment epithelium (RPE), and the MH diameter, measured by OCT at the RPE level, appear to be prognostic factors for postoperative visual outcomes and anatomical success in MH surgery.[15–17]

This study aimed to investigate the retinal sensitivity profile around the macula using MP-3 preoperatively and postoperatively, and to assess the correlation between retinal sensitivity and MH structural parameters measured by OCT.

Methods

Ethics

This study was conducted in accordance with the Declaration of Helsinki and with the approval of the Ethics Committee of Toho University Omori Medical Center (Approval number: M23203). As this was a retrospective study, an opt-out approach was used, allowing patients to refuse the use of their data. Information about the study and the opt-out option was made available to the public via the hospital's website. Patients who did not want their data included in the study were provided with contact information to withdraw their data.

Patients

This single-center, retrospective, nonrandomized, comparative study included consecutive patients with MH who were admitted to the Toho University Omori Medical Center between April 2020 and November 2023. All patients had MH closure confirmed by OCT 1 month postoperatively.

All patients underwent basic ophthalmic examinations, including best-corrected visual acuity (BCVA), intraocular pressure, fundus examination, and SD-OCT, at each visit.

BCVA was obtained using Landolt C-charts. These values were subsequently converted to the logarithm of the minimum angle of resolution (logMAR) for statistical comparison.

The exclusion criteria were a history of any other retinal disease, the presence of a refractive error of more than ±6 diopters in the affected eye, severe cataracts, and glaucoma.

Surgical procedures

All patients underwent 25-gauge 3-port pars plana vitrectomy; for phakic eyes, phacoemulsification and aspiration were performed in combination, and an intraocular lens (NX-70, Advanced Vision Science, Inc., Goleta, CA, USA) was implanted by one of the authors (ST). The posterior hyaloid membrane was visualized by injecting preservative-free triamcinolone acetonide (MaQaid; Wakamoto Pharmaceutical Co., Ltd., Tokyo, Japan) suspended in 4 mL of balanced salt solution (BSS Plus; Alcon Japan, Tokyo, Japan) into the vitreous cavity during vitrectomy. After core vitrectomy, posterior vitreous detachment was surgically induced using a vitreous cutter with active aspiration over the optic disc or around the vitreous pocket, followed by gentle extension to the retinal equator. Brilliant Blue G was gently injected toward the posterior pole of the eye and immediately removed from the vitreous cavity via infusion and aspiration. The internal limiting membrane (ILM) was grasped using ILM forceps and peeled around the macula with a diameter of approximately two discs. For those with an MH base diameter >400 μm, the ILM was inverted. ILM exfoliation was performed at 4° around the macula in all cases where the MP-3 was examined. The air-fluid exchange was performed and approximately 1 mL pure sulfur hexafluoride was injected to achieve an intraocular concentration within 20% while considering intraocular pressure and axial length. Postoperatively, the patients were hospitalized and were maintained in the prone position for 3 days.

MP-3 microperimetry

MP-3 examination was conducted preoperatively and at 3 and 12 months postoperatively. Retinal sensitivity was evaluated in a dark room after pupil dilatation with 1% tropicamide. The stimulus size was Goldmann III (white, 200 ms), and the background luminance was 31.4 apostilbs. The stimulus luminance ranged from 0 to 34 dB and was

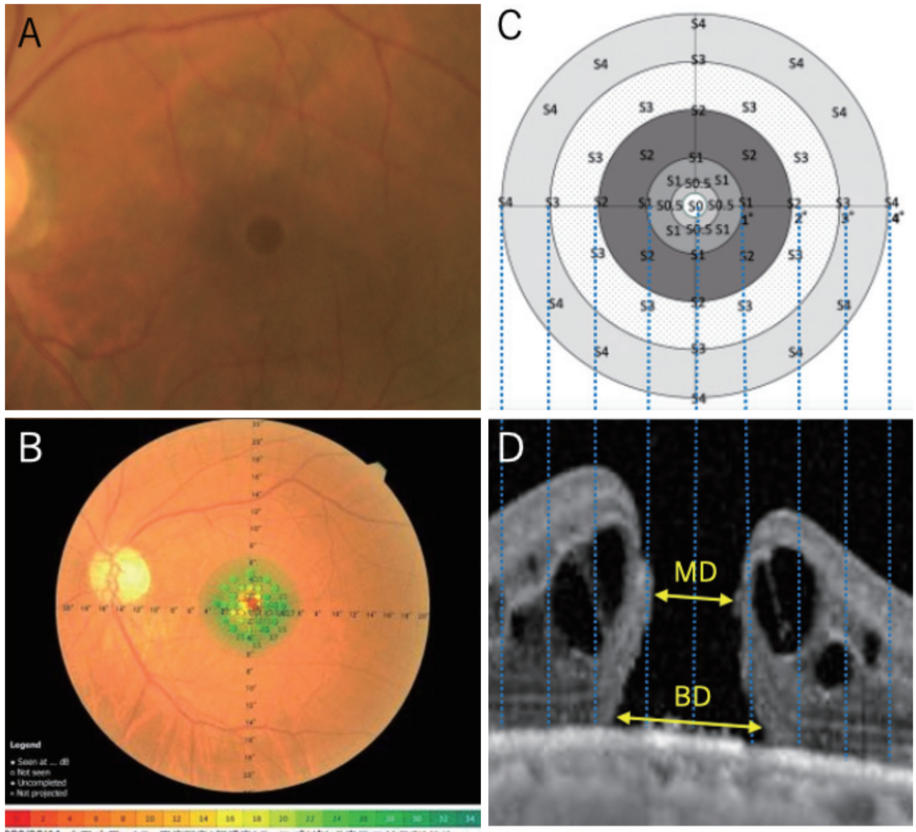

Fig. 1 A representative case of a macular hole (MH) in a 68-year-old man, classified as stage 3
(A) Color fundus photography showing an MH in the left eye. (B) Retinal sensitivity was evaluated in 45 points arranged within a 4° diameter. (C) The range was divided concentrically around the central fovea and at 0.5°, 1°, 2°, 3°, and 4°. The mean retinal sensitivity within each range was labeled as S0, S0.5, S1, S2, S3, and S4. (D) Optical coherence tomography of the MH. The minimum linear diameter (MD) and the basal diameter (BD) were measured using the internal limits.

evaluated using a 4-2 staircase method with 2-dB steps. This method is commonly used to determine visual sensitivity. An automatic fundus eye tracking system was used to ensure that the stimuli were projected at the same point each time to maintain consistency in the testing conditions. Fig. 1-A shows color fundus photography of MH and the measurement pattern comprised 45 points arranged in a 4° diameter range (Fig. 1-B). Points were classified on the basis of their distance from the fovea. The measured retinal sensitivities were divided into concentric ranges of the fovea, 0.5°, 1°, 2°, 3°, and 4° from the central fovea, and the average retinal sensitivities measured in these ranges were set as S0 (1 point), S0.5 (4 points), S1 (8 points), S2 (8 points), S3 (12 points), and S4 (12 points) (Fig. 1-C).

OCT measurements

The retinal structure was evaluated using SD-OCT (Spectralis; Heidelberg Engineering, Heidelberg, Germany) images acquired before treatment (i.e., at baseline) and 3 and 12 months after treatment.

The MH size was measured manually in the OCT images using a Spectralis SD-OCT software caliper. The minimum linear diameter (MD) was defined as the narrowest width of the hole at the center of the retina parallel to the RPE, whereas the basal diameter (BD) was defined as the diameter of the hole at the level of the RPE (Fig. 1-D). Both measurements were confirmed by two retina specialists to ensure accuracy and consistency. The correlation between retinal structure and sensitivity at each time point was evaluated.

Table 1 Baseline characteristics of patients

Eyes (n)	24
Age (years)	68 ± 6.73
Sex (male/female)	13/11
MH stage (eyes)	Stage 1: 0, stage 2: 12, stage 3: 9, and stage 4: 3
Lens status (phakic/IOL, eyes)	22/2
Axis length (mm)	23.97 ± 1.08
MD (μm)	286 ± 184.84
BD (μm)	685.79 ± 333.17
ILM (peeling/inverted)	17/7
Follow-up duration (3 months/12 months)	24/16

MH, macular hole; IOL, intraoperative lens; MD, minimum linear diameter; BD, basal diameter; ILM, internal limiting membrane.

Statistical analysis

All values are presented as means and standard deviations, unless otherwise specified. The Steel-Dwass test was used to compare changes in retinal sensitivity preoperatively and at 3 and 12 months postoperatively. Nonparametric Spearman's tests were used to detect correlations between the OCT parameters and preoperative retinal sensitivity, and simple linear regression analysis was used to establish possible linear relationships.

p-values <0.05 were considered statistically significant. Data were analyzed using JMP (version 16.0.0) statistical analysis software (SAS Institute, Inc., Cary, NC, USA).

Results

Baseline characteristics of patients

Table 1 presents the patients' demographic data. All 24 eyes of 24 patients (mean age 68 ± 6.73 years, 13 men and 11 women) were followed for 3 months postoperatively. Among them, 16 eyes of 16 patients (mean age 69.56 ± 4.45 years, 8 men and 8 women) were followed up to 12 months postoperatively. MHs were classified as stage 2, 3, and 4 in 12, 9, and 3 eyes, respectively, according to the Gass classification. Cataract surgery was performed in 22 eyes (91.7%), and 2 eyes (8.3%) were pseudophakic. The axial length was 23.97 ± 1.08 mm, with an MD of 286 ± 184.84 μm and BD of 685.79 ± 333.17 μm.

Changes in postoperative visual acuity and retinal sensitivity

The logMAR BCVA was 0.61 ± 0.35 preoperatively, 0.31 ± 0.31 at 3 months ($p = 0.0035$), and 0.21 ± 0.25 at 12 months ($p = 0.0011$), indicating significant improvement. No significant improvement was observed from 3 to 12 months after surgery ($p = 0.5770$).

The sensitivity measured up to S3 was significantly improved from preoperatively to 3 months postoperatively (S0: 9.38 ± 8.41 dB to 22.63 ± 3.29 dB, $p < 0.0001$; S0.5: 11.07 ± 6.47 dB to 21.25 ± 3.86 dB, $p < 0.0001$; S1: 13.26 ± 5.62 dB to 21.19 ± 3.22 dB, $p < 0.0001$; S2: 19.66 ± 3.98 dB to 23.42 ± 2.66 dB, $p < 0.0002$; S3: 22.95 ± 3.31 dB to 25.01 ± 3.16 dB, $p = 0.0355$). However, no significant difference was found at S4 (25.03 ± 2.23 dB to 25.26 ± 2.88 dB, $p = 0.6873$) from preoperatively to 3 months. Moreover, there were no significant improvements at 12 months compared with those at 3 months at any examination point (S0: 22.50 ± 5.14 dB, $p = 0.9241$; S0.5: 21.89 ± 3.31 dB, $p = 0.8148$; S1: 21.95 ± 3.08 dB, $p = 0.7524$; S2: 24.06 ± 2.03 dB, $p = 0.8787$; S3: 26.03 ± 1.89 dB, $p = 0.7025$; S4: 26.03 ± 1.43 dB, $p = 0.8855$) (Fig. 2).

Correlation between MH size and retinal sensitivity

Fig. 3 shows the correlation between MD, BD, and S0-S4 preoperative retinal sensitivity by the nonparametric Spearman test. MD showed a significant correlation with all measurement points (S0: $r = -0.48009$, $p = 0.0174$; S0.5: $r = -0.5130$, $p = 0.0104$; S1: $r = -0.6173$, $p = 0.0013$; S2: $r = -0.4990$, $p = 0.0131$; S3: $r = -0.4291$, $p = 0.0364$; S4: $r = -0.4238$, $p = 0.0390$). BD showed significant correlations in the S0.5-4 range (S0.5: $r = -0.5717$, $p = 0.0035$; S1: $r = -0.6543$, $p = 0.0005$; S2: $r = -0.5801$, $p = 0.0030$; S3: $r = -0.5805$, $p = 0.0070$; S4: $r = -0.5279$, $p = 0.0080$), but no significant correlation was found for S0 ($r = -0.3966$, $p = 0.0550$).

Discussion

Despite the high rate of anatomical closure,[4–6] it is not entirely clear how visual function improves postoperatively. Our results showed that retinal sensitivity around the fovea was significantly affected within the S3 measurement point at 3 months postoperatively.

Microperimetry can provide an accurate and reproduc-

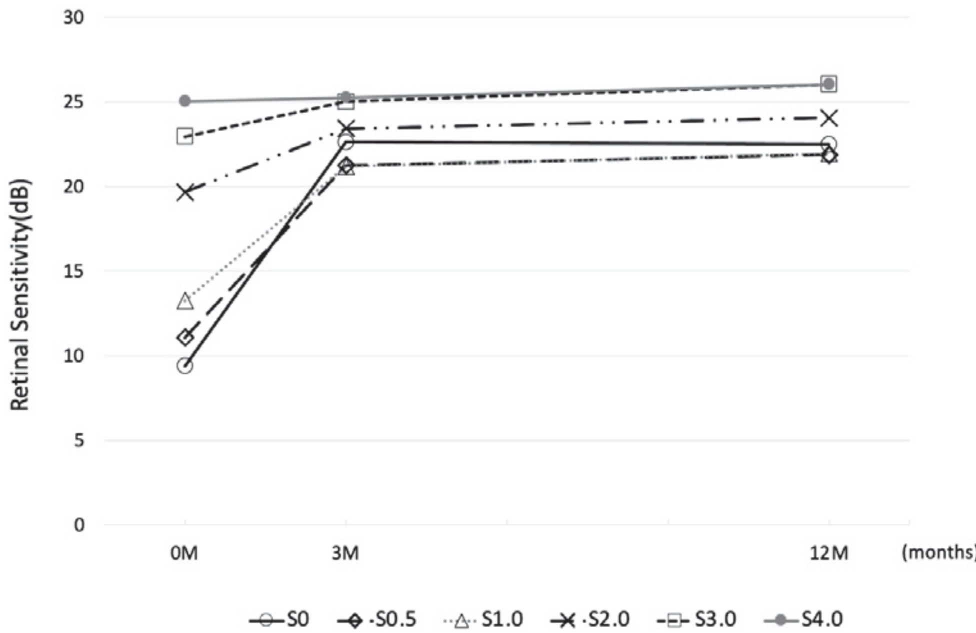

Fig. 2 Changes in retinal sensitivity after 3 and 12 months for each degree
Retinal sensitivity (S0–S4) was evaluated at baseline and at 3 and 12 months postoperatively. S0–S3 showed significant improvement at 3 and 12 months postoperatively compared with baseline ($p < 0.05$, Steel–Dwass test), whereas S4 showed no significant improvement. Across all ranges, no significant improvement was observed between 3 and 12 months postoperatively.

ible test of retinal sensitivity in areas with high cone concentrations and has been found to be more related to practical vision than to BCVA in patients with fundus diseases.[18]

Several studies have investigated retinal sensitivity in patients with MH using microperimetry.[8–12, 19, 20] Early studies often showed that the detection range for mean macular sensitivity was between 8° and 12°,[10, 19, 20] and considering that 1° on the fundus corresponds to a length of 250 μm, this range was much larger than the area actually damaged by the MH. Consequently, relatively normal retinal areas were included in the measurements, leading to an overestimation. Wang et al.[10] investigated the average within a 2° area around the macula and demonstrated, using multivariate stepwise linear analysis that this area was more sensitive than an 8° area. This highlights the importance of examining the region surrounding the structural damage caused by an MH. However, these studies were limited to a 2° area. In this study, even relatively small MHs were found to affect an area within a 3° range.

The mean retinal sensitivity significantly improved postoperatively, which was consistent with the improvement in BCVA. To the best of our knowledge, this is the first report showing the actual area affected by an MH. The examination of the extent of this damage enables a more detailed functional assessment and may be useful in surgical decision-making.

In this study, a difference in sensitivity was observed at 3 months but not at 12 months. This may be because the MD of the MHs in this study was relatively small, leading to early improvement in visual function. Previous studies on retinal sensitivity have reported improvements after comparing preoperative and 4-month measurements[10] and preoperative and 12-month data.[19] However, few studies have examined changes over time at multiple points. We considered it important to investigate retinal sensitivity changes over time. Although some patients showed improvement in visual function over time in the macular area, no significant changes were observed in this study due to the small number of patients.

MH formation begins with the detachment of Müller cell cones that anchor photoreceptors to the fovea.[1] As the hole develops, centrifugal traction toward the surrounding retina (hole edge) impairs central visual function.[2, 3] This tangential traction typically increases the incidence of idiopathic MHs over time. Therefore, the size measured at the RPE level by OCT, referred to as the BD, and the MD is considered to have better prognostic value, as they re-

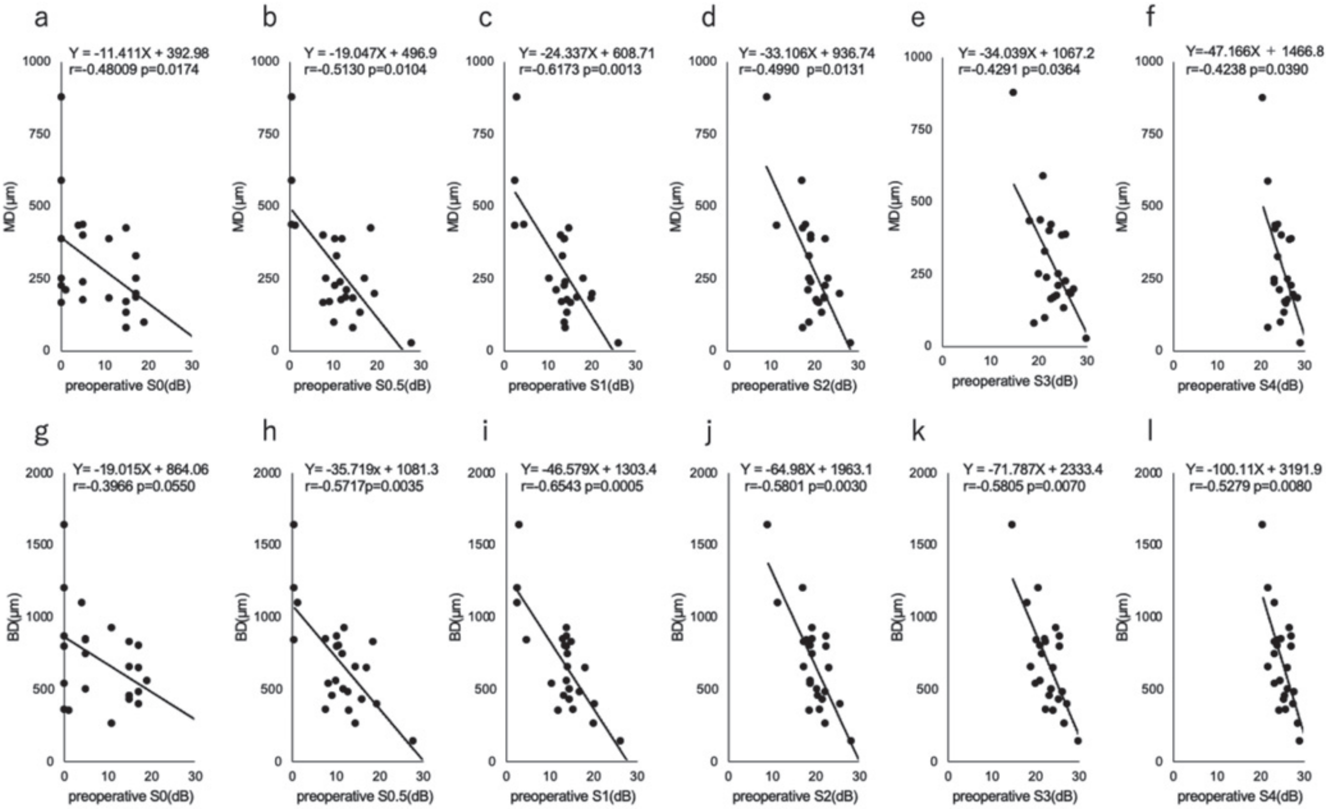

Fig. 3 Correlation between minimum linear diameter (MD), basal diameter (BD), and preoperative retinal sensitivity at S0–S4
a: Correlation between preoperative S0 and MD. b: Correlation between preoperative S0.5 and MD. c: Correlation between preoperative S1 and MD. d: Correlation between preoperative S2 and MD. e: Correlation between preoperative S3 and MD. f: Correlation between preoperative S4 and MD. g: Correlation between preoperative S0 and BD. h: Correlation between preoperative S0.5 and MD. i: Correlation between preoperative S1 and MD. j: Correlation between preoperative S2 and MD. k: Correlation between preoperative S3 and MD. l: Correlation between preoperative S4 and MD.

flect the actual size of the retinal lesion. It has been reported that small-diameter MHs are associated with better functional outcomes.[15–17)]

In our study, we observed that as the size of the MH increased, the affected area expanded. Interestingly, when comparing preoperative data, no significant difference was observed within the 4°. However, a significant correlation was found between sensitivity and hole size, even within the 4° range. The average MH size in our participants was 286 ± 184.84 μm, which is approximately 2° to 3° if considering that 1° on the fundus corresponds to a length of 250 μm; however, the surrounding edges of the hole were also affected. In MH, it has been reported that patients' visual fixation gradually shifts to the edge of the hole, leading to paracentral fixation.[8)] The ring-shaped area surrounding the full-thickness retinal defect shows a relative scotoma with reduced sensitivity, which is believed to reflect hole dysfunction and has been reported to affect visual acuity.[8, 21)] Furthermore, the stability of fixation and the proportion of fixation locations serve as indicators for evaluating gaze control and selection abilities,[21, 22)] making the function of hole edges an important evaluation target. SD-OCT development has enabled detailed layer-by-layer evaluation of the retinal microstructure, and fundus perimetry can depict the functional changes corresponding to these structural changes. Our results indicate that this comparison allows for a more detailed functional assessment of MHs.

This study has several limitations. The number of enrolled patients was small, and because this was a retrospective study, the findings were exploratory in nature. The participants included patients with and without cataract surgery, and those who underwent ILM peeling and those who used the inverted flap method. Therefore, further studies under more specific conditions are required.

In conclusion, MP-3 microperimetry is useful for evaluating retinal function in MHs, and a more detailed functional evaluation is possible by evaluating retinal sensitivity in thin concentric circles. In typical MH, preoperative retinal sensitivity is reduced to approximately 3°, and improvement in sensitivity is observed 3 months postoperatively. The larger the size of the hole, the greater the extent of impairment.

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Author's contribution: A.Y. and S.T. designed the study; A.Y., N.W., T.I., and K.S. analyzed the data; A.Y. and S.T. wrote the manuscript; N.W., T.I., K.S., and Y.H. reviewed the manuscript.

Ethics statement: This study was conducted in accordance with the Declaration of Helsinki and with the approval of the Ethics Committee of Toho University Omori Medical Center (Approval number: M23203). As this was a retrospective study, an opt-out approach was used, allowing patients to refuse the use of their data. Information about the study and the opt-out option were made available to the public via the hospital's website. Patients who did not want their data included in the study were provided with contact information to withdraw their data.

Consent for publication: All authors read and approved the final manuscript.

Conflicts of interest: None declared.

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