Heliyon 7 (2021) e08059

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Asymmetric extent of distortion measured using the Watzke-Allen Test in patients with macular hole

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ARTICLE INFO

Keywords:
Macular hole
Optical coherence tomography
Photoreceptors
Watzke-Allen test

ABSTRACT

Visual dysfunction in patients with macular hole is believed to occur because of cone cell displacement, often measured by the Watzke-Allen test (WAT). However, it is unknown if the horizontal and vertical measurements recorded by WAT reflect the true extent of photoreceptor displacement. This study aimed to measure the extent of photoreceptor displacement in patients with macular hole using WAT and compare the displacement value with the hole diameter measured by optical coherence tomography (OCT). This prospective, observational study at a single tertiary referral center included 43 patients with macular hole. WAT thresholds were assessed for their ability to detect macular hole. The slit was presented vertically and horizontally, and the brightness of the monitor screen was 180 cd/m^2. Horizontal and vertical WAT thresholds for distortion were measured. Correlations and performance evaluations were assessed by Pearson's correlation analysis and Wilcoxon rank-sum test, respectively, between WAT threshold values and hole diameters. Horizontal and vertical WAT thresholds and diameters were compared using paired *t*-tests. The mean vertical WAT threshold (1.95° ± 0.87°) was significantly higher than the mean horizontal threshold (1.71° ± 0.73°; $P < 0.0001$). The mean minimum horizontal hole diameter (303.42 ± 111.16 mm; visual angle, 1.01°) was significantly greater than the mean minimum vertical diameter (264.12 ± 107.88 mm; visual angle, 0.88°; $P = 0.0149$). The minimum vertical and horizontal macular hole diameters were positively correlated with the vertical and horizontal WAT threshold values ($r = 0.514$, $P < 0.01$; $r = 0.447$, $P < 0.01$, respectively). The WAT threshold values were greater than the respective minimum macular hole diameters, indicative of cone cells displacement over an area larger than that of the hole. The difference in the extent of vertical and horizontal distortions suggests asymmetric hole formation. Hence, WAT threshold values may help evaluate visual function in patients with macular hole.

1. Introduction

Distorted vision, where faces appear to be misshapen and straight lines appear to be bent, is a typical symptom in patients with macular disease, including age-related macular disease, central serous chorioretinopathy, vitreomacular traction syndrome, reattached retinal detachment, epiretinal membrane, and macular hole (de Wit and Muraki, 2006; Enoch et al., 1995; Krøyer et al., 2005). Pathologically, these disorders are believed to occur when photoreceptors are displaced from their original position (la Cour and Friis, 2002). A macular hole develops as a result of centrifugal displacement of photoreceptors in the central area because of tangential retinal traction exerted by the vitreous body (Gass, 1988, 1995). However, to our knowledge, there is no method that can directly measure the photoreceptor displacement that causes this distortion.

Jensen and Larsen (1998) and Hikichi et al. (2002) measured displacement of photoreceptor cells using a binocular perimetry technique. Krøyer et al. (2008) modified the aniseikonia test to quantify the distortion caused by a macular hole and investigated the correlation between this distortion and the hole diameter to estimate the extent of photoreceptor displacement. However, because these measurement methods require testing of both eyes, their results may be affected by perceptual filling-in (Burke, 1999; Drasdo and Fowler, 1974; Wittich et al., 2006).

In the present study, we measured the extent of distortion using the Watzke-Allen test (WAT; Figure 1), which can be performed in one eye. The WAT is a subjective test based on photoreceptor displacement and is used in the diagnosis of macular hole (Watzke and Allen, 1969). Previous clinical studies have confirmed the usefulness of this test (Martinez et al., 1994; Tanner and Williamson, 2000; Tujikawa et al., 1997). Our

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https://doi.org/10.1016/j.heliyon.2021.e08059
Received 7 June 2019; Received in revised form 5 May 2021; Accepted 20 September 2021

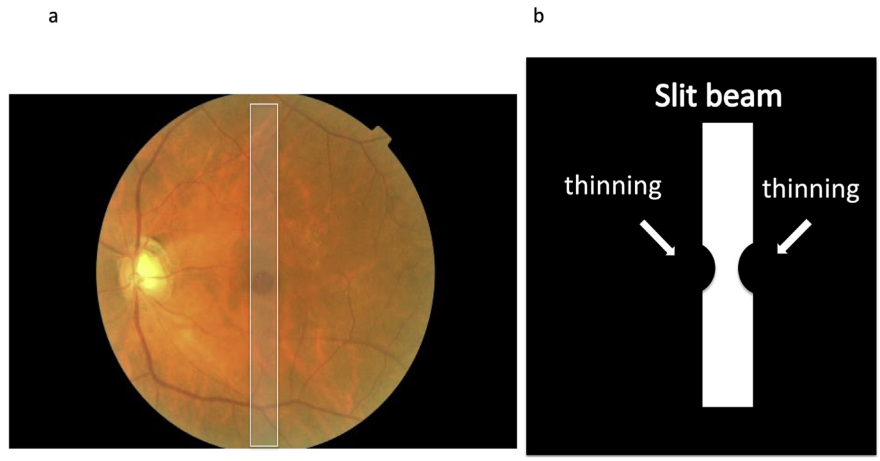

Figure 1. Image of Watzke-Allen test. Slit lamp beam on the macular hole (a) and beam perception (b). A thin slit of light (i.e., slit beam) is projected onto the suspected hole. Narrowing of the slit beam (i.e. thinning) is a positive indicator of this condition, and patients who perceive this narrowing may have a macular hole.

Table 1. Mean horizontal and vertical values of WAT thresholds, minimum diameter of macular hole (MH), and basal diameter of MH of study subjects.

	Horizontal	Vertical	P value*
WAT threshold (degrees)	1.71 ± 0.73	1.95 ± 0.87	0.014
Minimum diameter of MH (μm)	303.42 ± 111.16	264.12 ± 107.88	<0.001
Basal diameter of MH (μm)	659.20 ± 284.12	559.19 ± 230.31	<0.001

WAT, Watzke-Allen Test; MH, macular hole; *P value of paired t-test.

objective was to measure the horizontal and vertical extent of distortion in patients with macular hole and to compare the distortion with the diameter of the hole measured by optical coherence tomography (OCT).

2. Results

The 43 study subjects comprised 19 men and 24 women with a mean age of 67.02 ± 7.30 (range 53–88) years. Median corrected visual acuity was 0.23 (range 0.08–1.0). The mean logarithm of the minimum angle of resolution (logMAR) visual acuity was 0.64 ± 0.26 (range 0–1.10). The macular hole was in the right eye in 22 cases and in the left eye in 21 cases.

The mean horizontal WAT threshold was 1.71° ± 0.73°, while the mean vertical threshold was 1.95 ± 0.87°. The mean minimum horizontal hole diameter was 303.42 ± 111.16 μm, while the mean minimum vertical hole diameter was 264.12 ± 107.88 μm. The mean basal horizontal hole diameter was 659.20 ± 284.12 μm, while the mean basal vertical hole diameter was 559.19 ± 230.31 μm (Table 1).

The mean horizontal WAT threshold was significantly lower than the mean vertical threshold ($P = 0.014$). The mean minimum horizontal hole diameter was significantly greater than the mean minimum vertical hole diameter ($P < 0.001$). The mean basal horizontal hole diameter was significantly greater than the mean basal vertical hole diameter ($P < 0.001$) (Table 1). We compared the WAT thresholds, which indicate the extent of distortion, with the hole diameters measured by OCT using an approximation formula to convert the hole diameter measurements from micrometers to degrees of visual angle (Burke, 1999). We found a

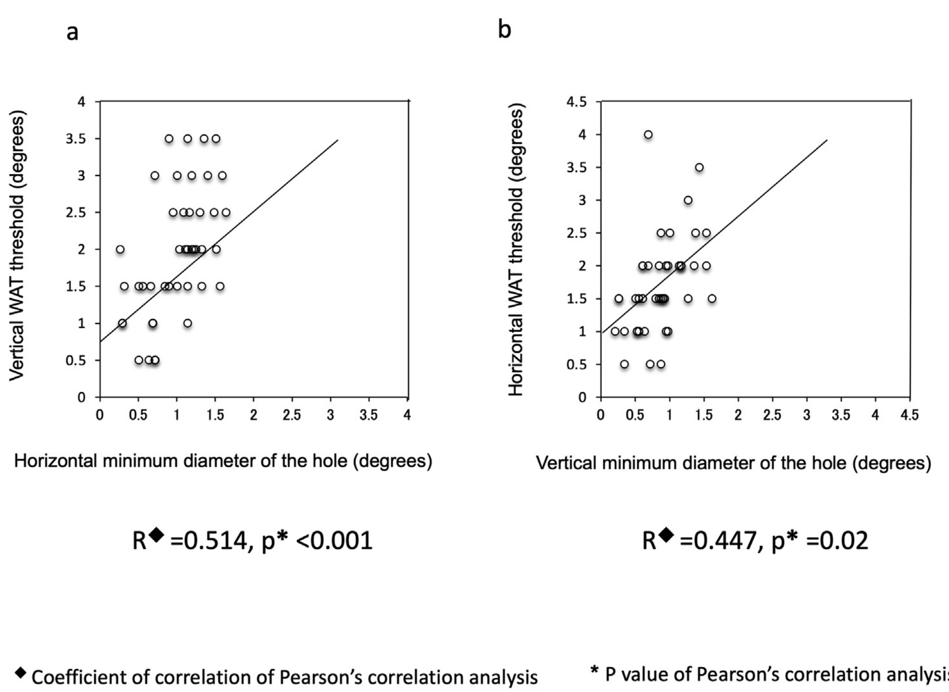

Figure 2. Correlation of horizontal (a) and vertical (b) minimum macular hole diameters to Watzke-Allen Test (WAT) thresholds.

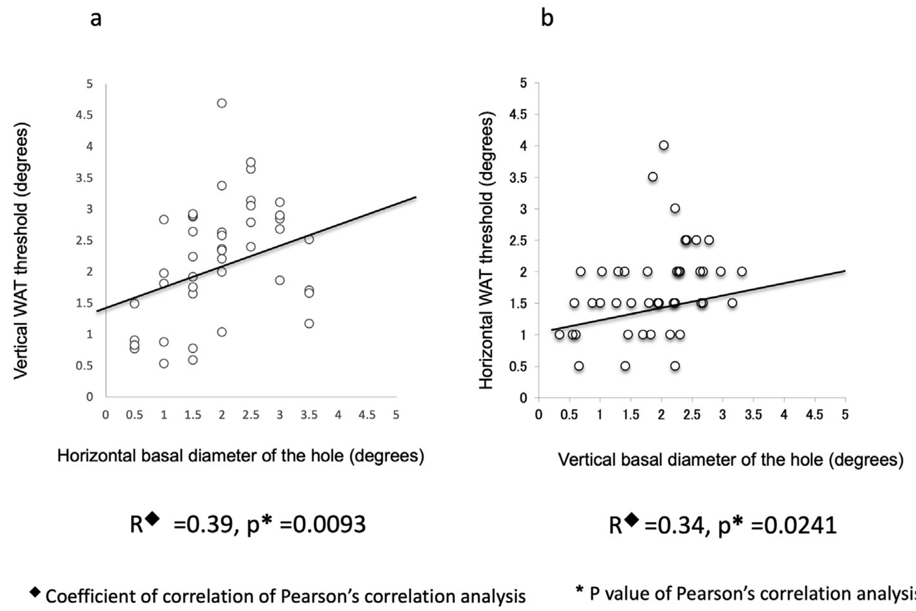

Figure 3. Correlation of horizontal (a) and vertical (b) basal macular hole diameters to Watzke-Allen test (WAT) thresholds.

positive correlation between horizontal minimum macular hole diameter and the extent of distortion ($r = 0.514$, $P < 0.001$; Figure 2a). There was also a positive correlation between vertical minimum macular hole diameter and the extent of distortion ($r = 0.447$, $P = 0.02$; Figure 2b). In both orientations, the larger the hole diameter, the greater the degree of distortion. There were few positive correlations between basal macular hole diameter in both orientation and extent of distortion (horizontal: $r = 0.39$, $P = 0.0093$, vertical: $r = 0.34$, $P = 0.02$; Figures 3a, 3b).

We then compared the relative magnitudes of extent of distortion and hole diameters. The mean horizontal WAT threshold, indicating vertical extent of distortion, was significantly greater than the mean minimum vertical macular hole diameter (1.71° ± 0.73° vs 0.88° ± 0.36°; $P < 0.001$).

The mean vertical WAT threshold, indicating horizontal extent of distortion, was significantly greater than the mean minimum horizontal macular hole diameter (1.95° ± 0.87° vs 1.01° ± 0.37°; $P < 0.001$). The extent of distortion was thus significantly greater than the minimum diameter of the macular hole in both the vertical and horizontal orientations.

The mean horizontal WAT threshold, indicating the vertical extent of distortion, was not significantly smaller than the mean basal vertical macular hole diameter (1.71° ± 0.73° vs 1.86° ± 0.77°; $P = 0.2454$). The mean vertical WAT threshold, indicating the horizontal extent of distortion, was not significantly smaller than the mean basal horizontal macular hole diameter (1.95° ± 0.87° vs 2.20° ± 0.95°, $P < 0.001$).

Next, we compared the horizontal and vertical WAT thresholds and hole diameters. The mean vertical WAT threshold was significantly greater than the mean horizontal threshold (1.95° ± 0.87° vs 1.71 ± 0.73°, $P = 0.015$). This indicated that the extent of distortion in the horizontal direction was greater than that in the vertical direction. The mean minimum horizontal diameter of the macular hole was significantly greater than the mean minimum vertical diameter (303.42 ± 111.16 μm vs 264.12 ± 107.88 μm, $P < 0.001$). The mean basal

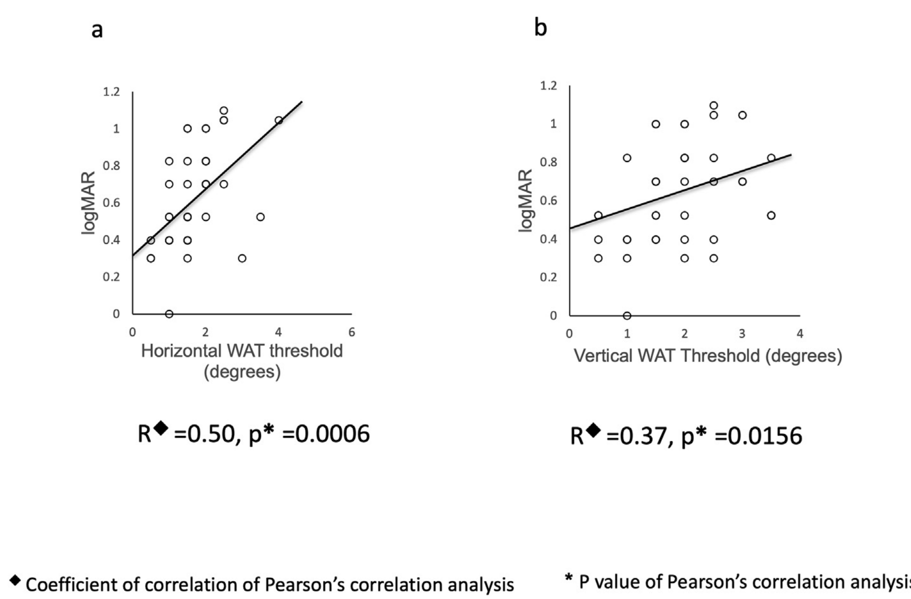

Figure 4. Correlation of horizontal (a) and vertical (b) Watzke-Allen test (WAT) thresholds to visual acuity (logMAR).

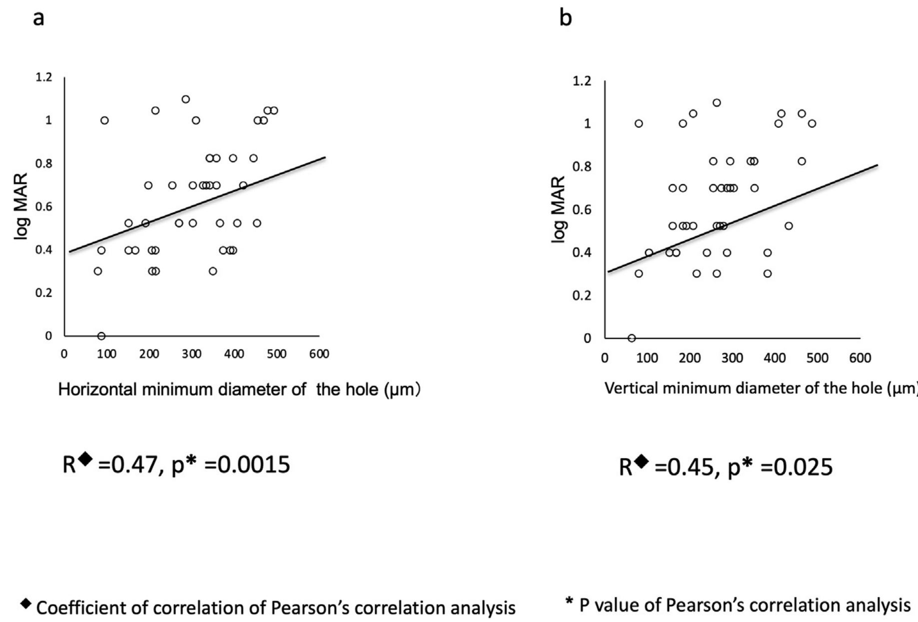

Figure 5. Correlation of horizontal (a) and vertical (b) minimum diameter of macular hole to visual acuity (logMAR).

horizontal diameter of the macular hole was significantly greater than the mean basal vertical diameter (659.2 ± 284.1 μm vs 559.2 ± 230.3 μm, $P < 0.001$).

First, we investigated the correlation between visual acuity and WAT and compared log MAR and WAT thresholds (Figures 4a, 4b). There were positive correlations between log MAR and WAT threshold in either direction (horizontal: $r = 0.50$, $P = 0.0006$, vertical: $r = 0.37$, $P = 0.0156$; Figures 4a, 4b). Next, we compared logMAR and minimum and basal diameter of the macular hole. There were positve correlations between log MAR and the minimum diameter of the macular hole in both directions (horizontal: r =0.47, P = 0.0015, vertical: r = 0.45, P = 0.025; Figure 5a, 5b). There were positve correlations between log MAR and the basal diameter of the macular hole in both directions (horizontal: r = 0.47, P = 0.0014, vertical: r = 0.37, P = 0.0104; Figure 6a, 6b).

3. Discussion

3.1. Asymmetry of the macular hole

The vertical WAT threshold was higher than the horizontal WAT threshold, indicating that the extent of distortion in the horizontal direction was greater than that in the vertical direction. OCT revealed that the minimum and basal diameter of the macular hole was greater horizontally than vertically. These results suggest that the macular hole is oval. Kim et al. (2012) observed the postoperative morphology of macular holes using spectral-domain OCT (SD-OCT) and found that the foveal tissue defect was asymmetric, i.e., extending further in the horizontal direction than in the vertical direction. A previous study also compared the horizontal and vertical results of regular WAT using a slit beam from a slit lamp and revealed

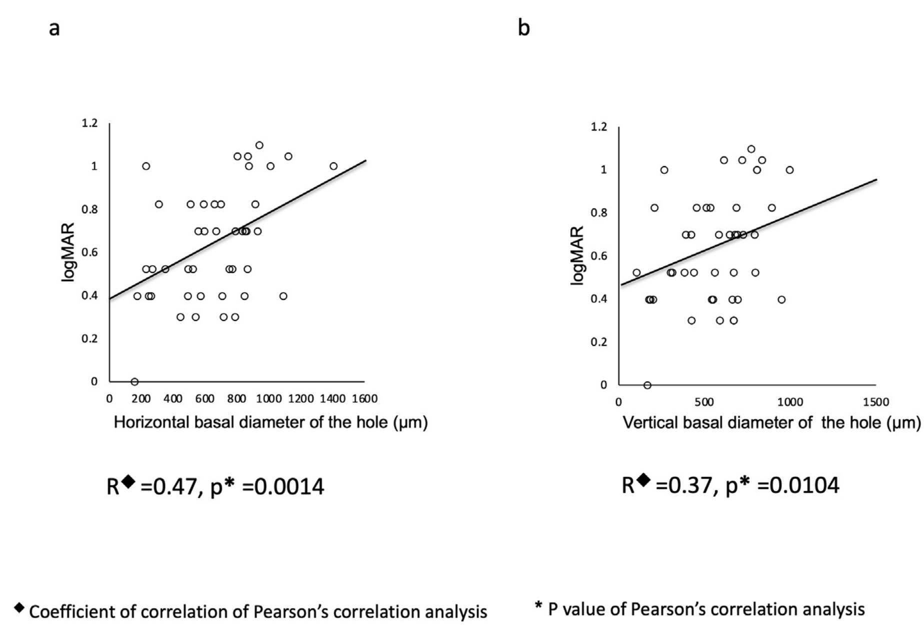

Figure 6. Correlation of horizontal (a) and vertical (b) basal diameter of macular hole to visual acuity (logMAR).

inconsistencies in the shape of the slit beam thinning sign in the vertical and horizontal orientations in 25% of patients with a macular hole (Tanner and Williamson, 2000). The results of these studies and the present study suggest that the shape of the hole can be asymmetric.

3.2. Correlation between extent of distortion and diameter of the macular hole

We found that the extent of distortion was positively correlated with the diameter of the macular hole. The WAT reflects the centrifugal displacement of photoreceptors that are located at the edge of the slit and projected onto the retina. Therefore, it is unaffected by central scotoma, and as a result, the WAT threshold is positively correlated with the diameter of the macular hole. Arimura et al. (2007) found that for macular holes <500 μm in diameter, the extent of distortion was correlated with the fluid cuff diameter, but for holes ≥500 μm in diameter no such correlation was evident. On the basis of these findings, we did not include holes >500 μm in diameter. Although the diameter may indicate centrifugal displacement, the fluid cuff mainly induces anterior photoreceptor displacement, so the discrepancy between our results and those of Arimura et al. cannot be clearly explained.

3.3. Binocular perimetry technique and the WAT threshold

Jensen and Larsen (1998) developed the binocular perimetry technique to estimate the extent of photoreceptor displacement in patients with unilateral macular hole. They found that, in most cases, the extent of photoreceptor displacement was greater than the diameter of the hole and corresponded to the fluid cuff. On the basis of these findings, they hypothesized that some degree of remodeling of higher perceptual mechanisms had occurred; however, no evidence is available to support the existence of a central mechanism for correction of irregular transformations.

In the present study, we found that both the vertical and horizontal WAT thresholds were greater than the minimum diameter of the macular hole, which is consistent with the findings of the study by Jensen and Larsen (1998). Krøyer et al. (2008) improved the aniseikonia test to estimate the extent of photoreceptor displacement and found that the extent of displacement was correlated with the hole diameter and that it was smaller than the minimum diameter of the hole. They hypothesized that the extent of photoreceptor displacement was less than the minimum hole diameter because although visuospatial distortion in the macular hole is the result of the centrifugal displacement of radial photoreceptors, the results could have been affected by perceptual filling-in (Burke, 1999; Drasdo and Fowler, 1974; Wittich et al., 2006), which is a characteristic of perception in the cerebral cortex.

3.4. Relationship between diameter of the hole and WAT threshold

The displacement of the photoreceptor was three-dimensional. However, WAT only measured the tangential displacement of the photoreceptor. Since there were various shapes such as a fluid cuff and cyst of the macular hole, WAT, which did not have much of a linear correlation, was larger than the minimum, but tended to be smaller than the basal diameter of the hole and was not significant. Theoretically, the photoreceptor displacement is (It fell within that range.) This result is confirmed.

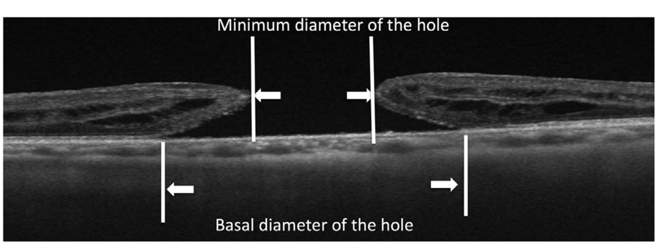

Figure 7. Diameter of the macular hole measured by optical coherence tomography.

3.5. Correlation between visual acuity and WAT threshold

Since the visual acuity of patients with macular holes is affected by fixation, the measured visual acuity may not reflect the true visual function (Horiguchi, 2001). Therefore, visual acuity was strongly correlated with neither macular hole diameter nor the WAT threshold (Figures 4,5, and 6).

3.6. Limitations of the WAT used in this study

In this study, the initial width of the slit was a 0.5° visual angle, and this was increased in 0.5° increments to measure the amount of distortion. The minimum width of the slit, i.e., 0.5°, was approximately 150 μm above the retina. Thus, if the extent of photoreceptor displacement was £150 μm, theoretically no slit thinning would have been perceived, and a WAT threshold value of <0.5° could not be detected. According to the theory proposed by Gass et al. (1988, 1995), the extent of photoreceptor displacement in the macular hole is greater than the minimum hole diameter. The variability of WAT threshold is large at 1.0 and 1.5°, which is probably caused by variability of morphology of the hole. Fluid cuff, cystoid edema, and vitreous traction were not constant in subjects. Unlike the aniseikonia test, which is performed in both eyes, our method tested only the affected eye, and expanding the width of the indicator after central fixation may have reduced the influence of perceptual filling-in.

4. Conclusions

We used the WAT to calculate quantitative thresholds in patients with macular hole, compared these values with the diameter of the macular hole, and estimated the extent of distortion relative to the hole diameter. The extent of distortion was greater than the minimum diameter of the macular hole and was greater in the horizontal direction than in the vertical direction. On OCT, the horizontal minimum diameter of the macular hole was greater than its vertical diameter. The macular holes were vertically and horizontally asymmetric, both morphologically and functionally. Calculation of the WAT threshold for distortion may be useful for assessment of macular holes.

4.1. Materials and methods

This is a prospective study. All subjects underwent a complete preoperative assessment, including measurement of corrected visual acuity, slit-lamp examination of the anterior chamber of the eye, and mydriatic

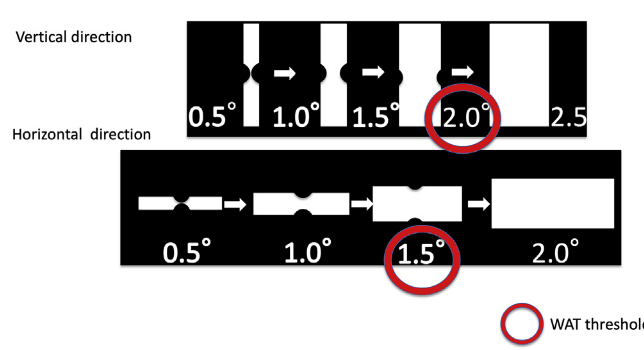

Figure 8. Methods for determining the vertical and horizontal distortion thresholds using Watzke-Allen test (WAT). The initial width of the slit was a 0.5° visual angle, and this was increased in 0.5° increments until thinning was no longer observed. The final width at which thinning was reported was taken to be the threshold value. The slit was displayed both vertically and horizontally, and the thresholds for each orientation were measured. The red circles indicate the thresholds in each of the horizontal and vertical directions.

funduscopy with a 90-diopter lens and a monocular indirect ophthalmoscope (BS III LED®, NEITZ, Tokyo, Japan). Horizontal and vertical SD-OCT (3D-OCT 2000®, Topcon, Tokyo, Japan) of the macular region was performed. The SD-OCT images were acquired using the 1:1 μm horizontal to vertical ratio setting in the preinstalled software, with measurements made manually by a single technician. The minimum and basal horizontal and vertical macular hole diameters were measured (Figure 7), and the diameters were measured on 7 vertical (7 × 6.0 mm scan, resolution 1024, step 0.25 mm) and 32 horizontal (6.0 × 6.0 mm scan, resolution 512 × 32).

We devised a method for determining the WAT threshold for distortion, which indicates the extent of distrosion displacement of photoreceptors. The WAT was performed with the slit displayed on a monitor screen and patients wearing their usual glasses to enable them to focus on the screen. To enable accurate visual fixation by eyes with a macular hole, which are incapable of central fixation, a cross with a diameter of 0.5° was displayed on the screen, and patients were instructed to fix their gaze on the intersection of the lines. This technique of fixation has been used for multifocal electroretinogram recording in patients with macular hole and provides reliable data (Kondo et al., 1995; Si et al., 1999). The initial width of the slit was a 0.5° visual angle, and this was increased in 0.5° increments until thinning was no longer observed. The final width at which thinning was reported was taken to be the threshold value. The slit was displayed both vertically and horizontally, and the thresholds for each orientation were measured (Figure 8). Using this method, the vertical threshold indicates the extent of horizontal displacement of photoreceptors and the horizontal threshold indicates the extent of vertical displacement The brightness of the monitor screen was 180 cd/m^2. The OCT and WAT were performed by different technicians.

4.2. Subjects

The study included 43 eyes of 43 patients who underwent surgery for idiopathic macular hole at Fujita Health University Hospital between July 2018 and December 2019. All patients provided written informed consent for this study. The study was approved by the ethics committee of Fujita Health University Hospital (HM18-044). Patients with a macular hole <500 μm in diameter were included, in accordance with the findings of Arimura et al. (2007) If a patient had a macular hole in both eyes, the first eye to undergo surgery was included in the study. The exclusion criteria were as follows: traumatic macular hole, uveitis or other intraocular inflammation, severe cataract, unclear OCT images, and other ophthalmic disorders that might affect visual acuity or macular morphology, such as glaucoma or epimacular membrane.

Of 73 cases screened, 30 were excluded because of the presence of other ophthalmic disorders (such as glaucoma or epimacular membrane; n = 20) or a macular hole <500 μm in diameter (n = 10), leaving data for 43 eyes available for analysis. All 43 patients perceived thinning at 0.5° slit.

4.3. Statistical analysis

The statistical analysis was performed using JMP version 9.0® (SAS Institute Inc., Tokyo, Japan). Pearson's correlation analysis and the Wilcoxon rank-sum test were used to evaluate correlations and to perform comparisons, respectively, between WAT threshold values and macular hole diameters. Horizontal and vertical WAT thresholds and diameters were compared using paired *t*-tests. A p-value < 0.05 was considered statistically significant. Hypothesis tests were 2-sided.

Declarations

Author contribution statement

Masayuki Horiguchi: Conceived and designed the experiments.
Ryouta Sakurai: Performed the experiments.
Tadashi Mizuguchi: Analyzed and interpreted the data.
Atsuhiro Tanikawa: Analyzed and interpreted the data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

The clinical trial described in this paper was registered at The University Hospital Medical Information Network Center under the registration number UMIN000033005.

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