BMJ Open Ophthalmology

Analysing the translatability of macular hole size measurements between high-density horizontal and radial OCT scan patterns

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To cite: Johannigmann-Malek N, Coulibaly L, Groselli S, *et al*. Analysing the translatability of macular hole size measurements between high-density horizontal and radial OCT scan patterns. *BMJ Open Ophthalmology* 2025;**10**:e002131. doi:10.1136/bmjophth-2024-002131

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bmjophth-2024-002131).

Received 30 December 2024
Accepted 22 April 2025

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ABSTRACT

Objective To assess the interchangeability of minimum linear diameter (MLD) macular hole (MH) size measurements in high-density horizontal and radial scan modes in optical coherence tomography (OCT).

Methods and analysis 60 patients with a MH had repeat high-density OCT volume scans in a horizontal (30 µm interscan-spacing) and a radial (angular 3.75° interscan-spacing) mode, and the MLD was measured by five raters.

Results There were no significant differences in the MLD measurements within the horizontal and the radial modes across repeat measurements of each rater in volume scan 1 (all p≥0.14 and p≥0.28, respectively), between volume scans 1 and 2 (all p≥0.14 and p≥0.69), among the raters (p=0.70 and p=0.60), and using all MLD measurements obtained in this study between primary and repeat measurements in volume scan 1 (p=0.10 and p=0.74) and between measurements obtained in volume scan 1 and 2 (p=0.21 and p=0.90).

There was a statistically significant difference of −10.05 µm between the mean MLD of all measurements in the horizontal (n=900) and in the radial (n=900) mode (427.91 (±187.01) vs 437.97 (±184.93) µm; p<0.001). However, the variability of these differences around the mean MLD was large (95% limits of agreement −77.31 to 57.21 µm). The mean difference between all horizontal and all radial MLD measurements in a MH was for MHs that had their widest MLD within 15° of the horizontal, vertical and diagonal meridians 0.77 (±13.88) µm, −34.43 (±55.22) µm and −10.39 (± 34.62) µm, respectively.

Conclusions Horizontal scans systematically underestimate the maximum MLD if located vertically or diagonally; however, they have less intra-rater and inter-rater and inter-scan variability in MLD measurements as compared with radial scans. Therefore, the two scan modes are not interchangeable but rather complement each other. These results may be limited to the MLD range analysed (125–924 µm).

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Previous studies have demonstrated that the mean minimum linear diameter (MLD) obtained from optical coherence tomography (OCT) scans is significantly smaller when a horizontal rather than a radial scan pattern was used. This observation implies a potential underestimation of MLD measurements when utilizing horizontal scanning patterns.

⇒ Considering that MLD measurements in previous studies were obtained using scan patterns with only low- or medium-density spacing intervals, it raises the question of whether a difference in MLD measurements between horizontal and radial scans persists when high-density OCT volume scans in both modes are used.

WHAT THIS STUDY ADDS

⇒ Both high-density horizontal (145 B-scans with 30 µm inter-scan spacing) and radial (48 B-scans with an angular 3.75° inter-scan spacing) OCT scanning modes contribute to the accuracy of MLD size measurements of a MH: While horizontal scans demonstrate less intra-rater and inter-rater as well as inter-scan variability in MLD measurements, because accurate centration of the scanning raster on the center of the MH is not as crucial as in radial scans, they systematically underestimate the size of a MH whose widest MLD is located in the vertical or oblique axis.

⇒ If the high-density radial raster could be perfectly centered at the center of a MH during scan acquisition, then the use of a horizontal raster would be redundant.

INTRODUCTION

The size of full-thickness macular holes (MHs), defined by their minimum linear diameter (MLD) on optical coherence tomography (OCT) scans, is the critical factor for treatment selection. Based on their MLD, MHs can be classified into small (<250 µm), medium (250–400 µm) and large (>400 µm).[1] While less invasive treatment options such as enzymatic or pneumatic vitreolysis are available for small to medium-sized MHs,[2 3] pars plana vitrectomy (PPV) is the main surgical approach to treat MHs of all sizes since significant ocular complications have been reported with ocriplasmin and pneumatic

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- ⇒ There is a need for standardisation of OCT scan patterns and inter-scan spacing to enhance the precision of MLD measurements in MHs and increase their comparability between studies assessing MLD-associated parameters such as the success rates of different treatment strategies. Our results highlight the importance of the use of high-density volume scans in both the horizontal and radial mode.
- ⇒ There is a need for software applications that automatically detect and track the centre of a MH during scan acquisition, and that provide automated MLD measurements.

vitreolysis.[1 2 4] Based on the size of the MH, some surgeons decide to perform the PPV with or without internal limiting membrane (ILM) peeling and with or without an inverted ILM-flap.[5–8] Therefore, accurate measurement of the MLD is essential for determining the appropriate management strategy in patients with aMH.

However, MLD measurements are not automatically provided by current OCT devices but need to be determined manually by clinicians using a calliper tool integrated in the OCT device software. Even though these measurements are obtained according to set guidelines,[1] they are subjective and prone to intra-observer and inter-observer variations. Furthermore, the morphology of a MH is not uniform, exhibiting variability in the location of the largest diameter along the horizontal, vertical or oblique axes.[9 10] As a result, horizontal OCT scans potentially underestimate the largest MLD in MHs with vertical or diagonal orientation, potentially resulting in misclassification of the MH size. For instance, MLD measurements using horizontal volume scans with an approximately 240 µm distance between scans underestimated the MH size by approximately 13% and resulted in a different MH classification in 22% when compared with radial scans with a 7.5° interval.[11] Moussa *et al* found that high-density horizontal scans with a Triton inter-scan spacing of 50 µm yield lower variability and a reduced discrepancy in MLD measurements for smaller MHs compared with low-density scans with a Spectralis inter-scan spacing of 124 µm.[12] Schneider *et al* demonstrated that the largest MLD detected with 24-line radial scanning was significantly greater than that obtained with 6-line radial patterns, with a clinically relevant rate of missed MHs associated with the lower radial density.[13]

High-density horizontal and radial scan patterns (narrow inter-scan spacing) provide a more accurate assessment of the true MLD of a MH and may potentially minimise the difference in MLD size measurements obtained in the two different scan patterns, which is important as the horizontal scan pattern is still the preferred standard for some clinicians and researchers, and some relevant publications on MHs are based on horizontal line scans,[8 14] or the scan mode and the distance between the B-scan images have not been specified at all.[15]

The aim of this study was, therefore, to compare MLD measurements between high-density horizontal and high-density radial scan patterns and analyse their interoperability.

MATERIALS AND METHODS

This is a prospective case series of patients with a full-thickness MH who had two radial (radial scans 1 and 2), and two horizontal (horizontal scans 1 and 2) high-density high-resolution volume OCT scans of the macula (with the follow-up mode deactivated) obtained in the same examination session (Heidelberg Spectralis, Heidelberg Engineering, Heidelberg, Germany) at the Ophthalmology Department, TUM University Hospital, Technical University of Munich (TUM), Germany. The second scan in each mode was obtained to measure the inter-scan variability and device error. The horizontal volume scan consisted of 145 B-scans with approximately 30 µm inter-scan spacing and the radial volume scan of 48 cross-sectional B-scans with an angular 3.75° inter-scan spacing. Both scan patterns, including the number of sections and inter-scan spacing, can be routinely selected from the Spectralis interface, and the acquisition of a high-resolution high-density OCT scan takes less than 1 min in either mode. To obtain a steady fixation, patients were asked to fixate a target light presented to their contralateral eye while the OCT scans were taken in the affected eye. In both scan modes, the OCT raster was manually centred on the centre of the MH.

Inclusion criteria required that two sets of horizontal and radial volume scans could be performed concurrently. Exclusion criteria were obvious decentration of the MH on OCT, low-quality OCT images (quality index ≤30) and patients with coexisting macular pathology other than MHs.

Five moderately to highly experienced raters were instructed on how to use The International Vitreomacular Traction Study Group Classification System method to measure the size of the MH.[1] In brief, using the built-in software calliper tool in the Heidelberg Eye Explorer viewing module (1:1 µm mode), the rater selected the scan displaying the largest aperture of the MH and measured the narrowest distance between the two edges of the MH (parallel to the RPE) as MLD size, under avoidance of the area of the operculum if present.

The raters measured with at least a 2-weekly interval 6 sets each of 60 OCT scans (horizontal volume scan 1, radial volume scan 1, horizontal volume scan 2, radial volume scan 2, repeat horizontal volume scan 1 and repeat radial volume scan 1). The raters were blinded to their previous measurements and to those of the other raters. For each radial OCT scan, the raters noted the scan number they used to measure the MLD as an indication of the localisation of the largest MLD. A MH was defined as having a horizontal orientation if the widest MLD was measured within 15° of the horizontal axis, to have a vertical orientation if the largest MLD was

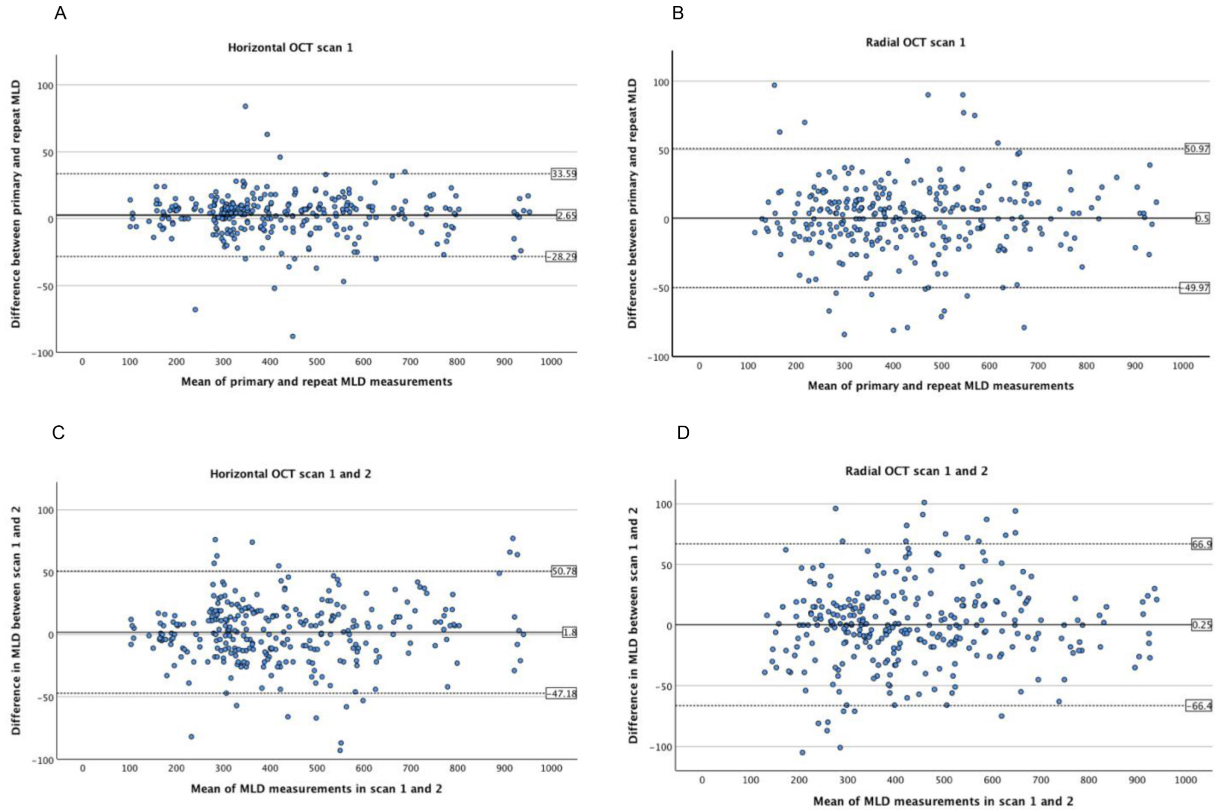

Figure 1 Bland-Altman plots illustrating the differences in MLD measurements obtained by the five raters in the high-density horizontal (n=300) and radial OCT scan modes (n=300) against their means. (A, B) The x-axis displays the mean of primary and repeat MLD measurements obtained in horizontal volume scan 1 (A) and in radial volume scan 1 (B), while the y-axis shows the difference between the two readings provided by each rater. (C, D) The x-axis represents the mean of MLD measurements obtained in horizontal volume scan 1 and 2 (C) and in radial volume scan 1 and 2 (D), while the y-axis shows the difference between the two readings provided by each rater. The variability between the differences in the primary and repeat MLD measurements in horizontal scan 1 (A) and in radial scan 1 (B) and between the differences in the MLD measurements between scan 1 and scan 2 in horizontal (C) and radial mode (D) was smaller in the horizontal than in the radial mode with 95% LOAs of −28.29 to 33.59 vs −49.97 to 50.97 µm and −47.18 to 50.78 vs −66.40 to 66.90 µm, respectively. LOAs, limits of agreement; MLD, minimum linear diameter; OCT, optical coherence tomography.

measured within 15° of the vertical axis and as oblique for the remaining MHs.

Statistical analysis

The data were collected and analysed using SPSS V.29.0 (SPSS). Normality of the distributions was assessed formally using a Shapiro-Wilk's test (p>0.05) and graphically using their histograms, normal Q-Q plots and box plots. A Levene's test was carried out to assess the homogeneity of variance within two sets of measurements, and an F-test based analysis of variance (ANOVA) was performed to test the variance of the differences between raters. To compare the MLD measurements and the differences in MLD measurements between two sets of measurements, a Wilcoxon signed rank test and a t-test were used. A Bonferroni correction was used for multiple tests. To compare the means and differences of more than two groups, an ANOVA was performed. Continuous variables were reported as mean (±SD).

To calculate the effect size (Cohen's d), the mean and SD of the differences of the primary MLD measurements of rater 1 in the horizontal volume scan 1 and of rater 2 in the horizontal volume scan 2 ($mean_1$, SD_1), and the mean and SD of the differences of the primary MLD measurements of rater 1 in the radial volume scan 1 and of rater 2 in the radial volume scan 2 ($mean_2$, SD_2) were calculated and the difference between $mean_1$ and $mean_2$ was divided by $((SD_1^2+SD_2^2)/2)^{1/2}$.

For the repeat measurements of each rater, the 95% upper and lower limits of agreement (LOA) were determined. The difference between the two measurements for each MH was plotted against their mean (Bland Altman Plots, BAPs). The coefficient of repeatability (CR=1.96×SD) was used to determine intra-rater and inter-rater repeatability of the repeated sets of measurements.[16] The significance level was set at p<0.05. The intra-rater and inter-rater intraclass correlation coefficients (ICCs) were calculated.

RESULTS

60 eyes of 60 consecutive patients with a MH were included in this study. Mean MLD of all measurements (n=1800) was 432.94 (±185.99) µm (range 125–924 µm).

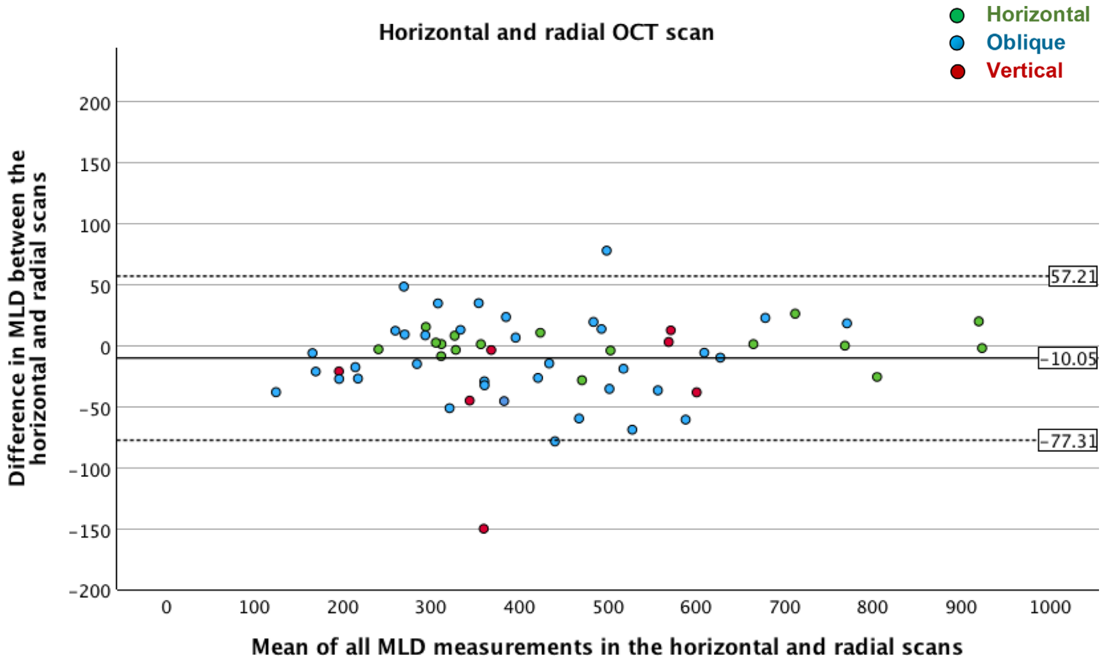

Figure 2 The x-axis illustrates the mean of all MLD measurements obtained from five raters for each of the 60 eyes with a MH (scan 1, repeat scan 1 and scan 2 in both the horizontal and radial mode) while the y-axis shows the difference between the mean of all horizontal and the mean of all radial measurements for each MH. The green, red and blue colours of the data points refer to the different orientations of the radial scan section containing the maximum MLD in which the raters' measurements in the radial mode were conducted. Green data points represent the MHs in which the largest MLD was measured within 15° along the horizontal meridian, red data points represent the MHs in which the largest MLD was measured within 15° along the vertical meridian, and blue data points those with an oblique orientation. The maximum MLD was identified in 17/60 (28.3%) in a horizontal, in 7/60 (11.7%) in a vertical and in 36/60 (60.0%) in an oblique orientation. The difference between the mean of all MLD measurements in the horizontal and the mean of all MLD measurements in the radial mode was 0.77 (±13.88) µm for MHs with a horizontal, -10.39 (±34.62) µm for MHs with an oblique and −34.43 (±55.22) µm for MHs with a vertical orientation. MH, macular hole; MLD, minimum linear diameter; OCT, optical coherence tomography.

Homogeneity of variance of the differences in MLD measurements across the included range of MH sizes was confirmed for rater 1, 2, 3, 4 and 5 in the horizontal (p=0.987, p=0.997, p=0.998, p=0.992 and p=0.971) and radial (p=0.972, p=0.945, p=0.949, p=0.998 and p=0.987) scan modes and between the five raters in the horizontal (p=0.994) and radial (p=0.0.988) modes. This suggests that the differences in the measurements are unrelated to their mean, that is, to the magnitude of the MH size, which is further supported by the absence of any obvious systemic bias in the ten BAPs for the MLD measurements of each rater in both scan modes (online supplemental figure 1).

The repeatability of measurements for rater 1, 2, 3, 4 and 5 was assessed using the coefficient of repeatability (CR=1.96×SD), which assumes that two repeat measurements of the same MH will be within 1.96×SD of the differences for 95% of MHs.[16] The intra-rater CRs were for the horizontal mode 25 µm, 9 µm, 35 µm, 32 µm and 41 µm, and for the radial mode 31 µm, 33 µm, 58 µm, 69 µm and 49 µm, respectively. The inter-rater CR (calculated for the first set of measurements of each rater and taking rater 1 as nominal reference standard) was for the horizontal mode 16 µm, 42 µm, 36 µm and 51 µm, and for the radial mode 41 µm, 65 µm, 75 µm and 72 µm, respectively. The intra-rater ICCs were all ≥0.997 in the horizontal and ≥0.991 in the radial mode, and the inter-rater ICC was 0.998 in the horizontal and 0.994 in the radial mode.

There were no statistically significant differences between the primary and repeat measurements of all raters (n=300 each) in scan 1 in the horizontal (429.39 (±187.67) µm and 426.75 (±188.25) µm, respectively, p=0.10) and in the radial mode (438.21 (±186.26) µm and 437.72 (±185.68) µm, p=0.74), and between the measurements in scan 1 and scan 2 in the horizontal (429.39 (±187.67) µm and 427.59 (±185.71) µm, p=0.21) and in the radial mode (438.21 (±186.26) µm and 437.97 (±183.45) µm, p=0.90).

Furthermore, there was no correlation between the differences in the measurements and their mean and no obvious systemic bias in the corresponding BAPs for the repeat measurements of all raters (n=300 each) in the horizontal (r=−0.04, p=0.53; figure 1A) and in the radial scan mode (r=0.02, p=0.69; figure 1B), and for the primary measurements in scan 1 and the measurements in scan 2, either in the horizontal (r=0.08, p=0.17; figure 1C) or in the radial scan mode (r=0.08, p=0.15; figure 1D), suggesting that the differences in the measurements are unrelated to the magnitude of the MH size.

However, the variability between the differences in the repeat MLD measurements in the horizontal and

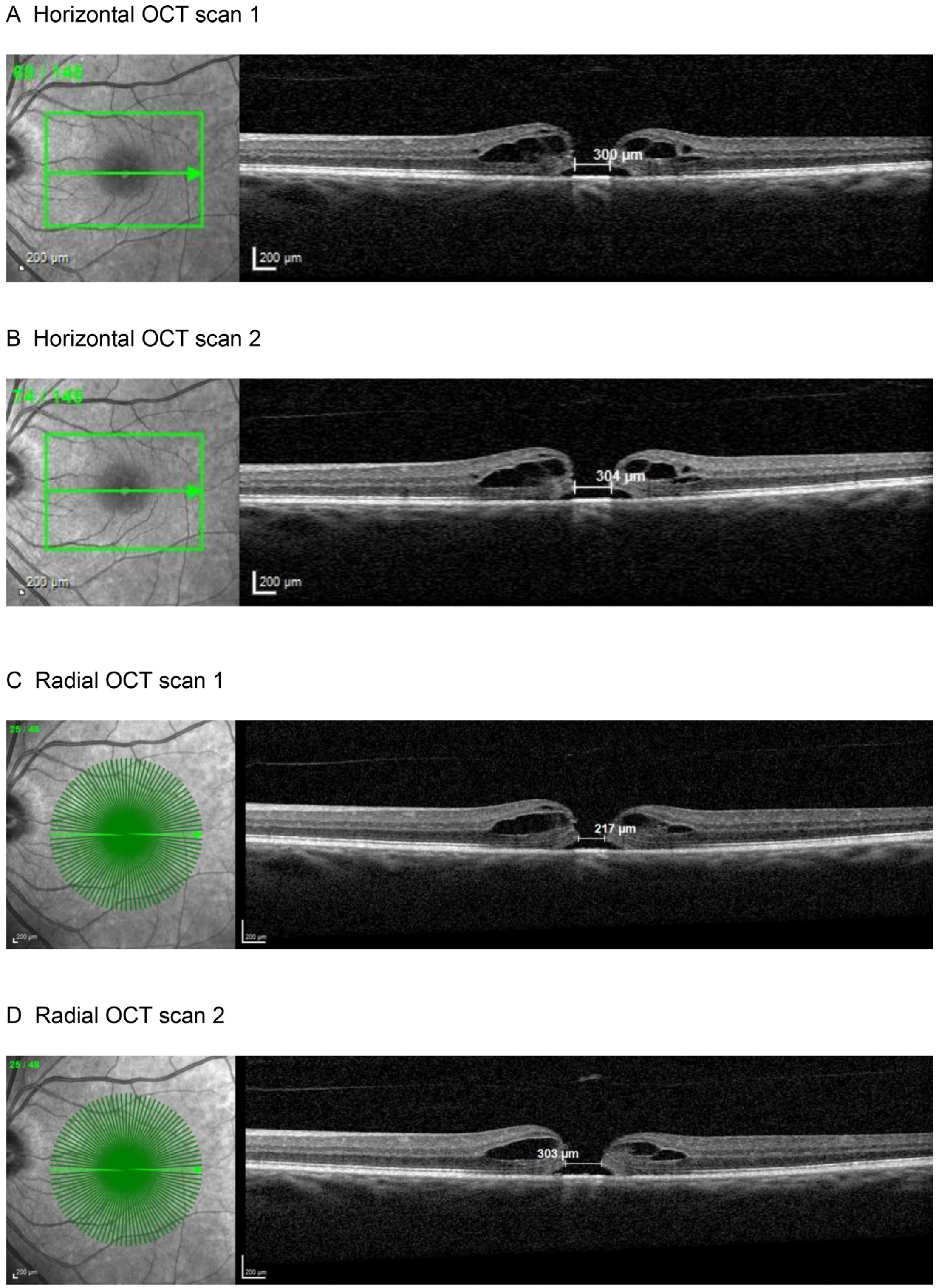

Figure 3 The largest MLD in this MH was measured along the horizontal axis. Due to some degree of decentration of radial OCT scan 1 (C), the MLD measured in this scan was lower compared to the measurements obtained from the other OCT scans in the horizontal axis (A, B, D). MH, macular hole; MLD, minimum linear diameter; OCT, optical coherence tomography.

radial scan 1 (figure 1A,B) and between the differences in the MLD measurements between scan 1 and scan 2 (figure 1C,D) was smaller in the horizontal than in the radial mode as reflected by their corresponding 95% LOAs (−28.29 to 33.59 vs −49.97 to 50.97 µm and −47.18 to 50.78 vs −66.40 to 66.90 µm, respectively).

Horizontal versus radial OCT scan mode

There was a statistically significant difference of −10.05 (±34.32) µm between the mean MLD of all measurements in the horizontal (n=900) and in the radial (n=900) mode (427.91 (±187.01) vs 437.97 (±184.93) µm; $p<0.001$). The variability of these

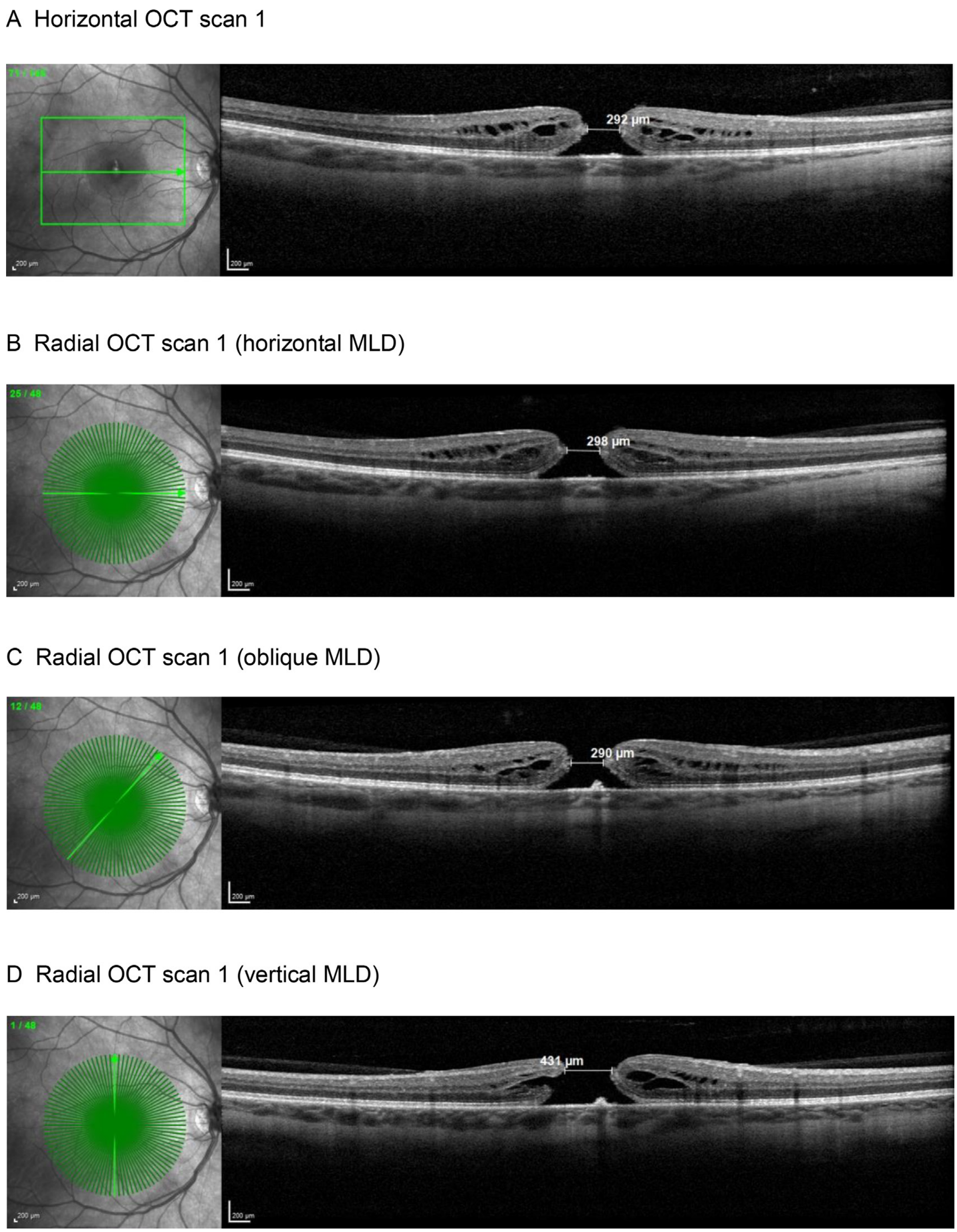

Figure 4 The largest MLD measured in the high-density horizontal scan (A) is similar to the MLD measured in the horizontal axis using the radial scan (B), suggesting that the radial pattern was well centred at the centre of the MH. The MLD measured in the vertical axis using the radial scan (D) was clinically significantly larger than in the horizontal axis, demonstrating that MHs are not necessarily round but sometimes rather oval shaped, and the exclusive use of a high-density horizontal scan would underestimate the true MLD size of this MH. MH, macular hole; MLD, minimum linear diameter; OCT, optical coherence tomography.

differences around the mean MLD in both modes, measured as the corresponding 95% LOA, was −77.31 to 57.21 µm, which is large (figure 2), even though the ICC between the mean MLD values measured in the horizontal and radial mode was 0.991, which suggests excellent reliability.

The difference between the mean of all MLD measurements in the horizontal and the mean of all MLD measurements in the radial scans was plotted against the mean of all MLD measurements in both the horizontal and radial mode for each MH (figure 2). The BAP does not show any obvious systemic pattern, but larger MHs

(≥600 µm) are only represented by a few data points. Pearson's correlation did not demonstrate an association between the difference in MLD measurements obtained in the horizontal and radial mode across the range of MLD sizes included in this study (r=0.05, p=0.16), formally supporting the graphical impression that there is no systemic pattern or bias in the BAP.

The mean difference between all horizontal and all radial MLD measurements in a MH was 0.77 µm (±13.88) µm for all MHs that had their widest MLD within 15° of the horizontal meridian in the radial scan, −10.39 (±34.62) µm for those with an oblique orientation, and −34.43 (±55.22) µm for all MHs that had their widest MLD within 15° of the vertical meridian in the radial scan.

A post hoc two-sided power analysis was performed, and with a power of 0.9 and an effect size (Cohen's d) of 0.428 (80/187) a sample size of 60 would allow detecting a difference in MLD measurements of ≥80 µm between the horizontal and radial high-density scans.

DISCUSSION

OCT has markedly improved the evaluation of MHs.[11 17 18] However, routine MH size measurements are still performed manually and do not always provide consistent results,[9 10] as MHs often exhibit irregular shapes with varying diameters across different meridians.[10 11] Previous studies reported that the mean MLD obtained from horizontal scans was significantly smaller than that derived from radial scans,[11 13] suggesting a potential tendency to underestimate the true MLD size when horizontal scanning techniques are used. However, the densities of the horizontal raster applied were only moderate (61 horizontal raster lines with an inter-scan spacing of 125 µm, along with 24 radial cross-sections)[13] to low (19 horizontal raster lines with inter-scan spacing of 240 µm and 24 radial cross-sections).[11]

We demonstrate that MLD measurements obtained from high-density horizontal scans (ie, 145 B-scans with 30 µm inter-scan spacing), and from high-density radial scans (ie, 48 B-scans with an angular 3.75° inter-scan spacing) did not significantly differ within raters, between raters and between scans in the same mode. The intra-individual and inter-individual repeatability measured as ICC was high, and the intra- and inter-rater CRs were comparable to those in previous publications.[11 18]

We found a statistically significant difference of −10 µm between the mean MLD of the measurements obtained in the horizontal and in the radial mode. However, the variability of the differences around the mean MLD of both modes with the corresponding 95% LOA is much wider (range 135 µm), suggesting that this difference is not practically relevant. The large variability of these differences and the wide LOA are a combination of intra-rater and inter-rater as well as inter-scan or device error. The inter-scan error is particularly obvious for the radial scan mode as there is no automated control of pattern centration on the centre of the MH during scan acquisition (figure 3).

The mean difference between all horizontal and all radial MLD measurements in a MH was close to zero for MHs that had their widest MLD within 15° of the horizontal meridian, but negative for MHs that had their widest MLD within 15° of the vertical or oblique meridian, suggesting that horizontal and radial scans are only interchangeable for MHs with their widest MLD in the horizontal plane, but horizontal scans systematically underestimate the maximum MLD if located vertically or diagonally (figure 4).

However, the variability (intra-rater and inter-rater as well as inter-scan) between horizontal scans is less than between radial scans, due to the lack of perfect centration of the radial raster on the centre of the MH. Therefore, the two scan modes are not interchangeable but rather complement each other and should both be performed to get the best appreciation of the widest MLD. Ultimately, automated software-controlled centration of the high-density radial scan pattern on the centre of the MH would be required to make the additional acquisition of a high-density horizontal scan redundant.

In our study, using high-density scanning patterns, one MH was misclassified in the radial (≤250 µm) compared with the horizontal mode (>250 µm), and three MHs were misclassified in the horizontal (≤400 µm) compared with the radial mode (>400 µm). We could decrease the rate of misclassification to 6.7% (4/60) as compared with the rate of 22% previously reported when low-density scanning patterns were used,[11] which may be important if the choice of treatment is based on the classification of small, medium and large MHs.[1–3 5 8 14 15] This emphasises the need for standardisation of OCT scan patterns and inter-scan spacing to enhance the precision and comparability of MLD measurements in MHs.

Our study has several limitations: Our findings regarding MLD measurements between the two high-density scan modes may be restricted to the investigated range (125–924 µm); however, this range covers most MH sizes we see in clinical practice. Larger MHs (≥600 µm) were represented by fewer data points. Employing moderately to highly experienced raters for the MLD measurements, we have obtained a realistic reflection of real-world measurements. However, the results may differ for measurements obtained by less experienced raters.[11] We have acquired two separate volume scans in both the horizontal and the radial mode to analyse the effect of device and pattern centration errors; however, these may vary between different OCT devices[12] and technicians.

In summary, our findings indicate that both high-density horizontal and radial scanning modes contribute to the detection of the largest MLD in a MH and, therefore, to the accuracy of MLD size measurements. While a horizontal OCT scan offers advantages in terms of less intra-rater and inter-rater as well as inter-scan variability, relying solely on this scanning mode will lead to an underestimation of the true MLD size of a MH when its largest diameter aligns with the vertical or oblique axis. Ultimately, there is a need for the development of software applications that are capable of automated detection and tracking of pattern centration during scan acquisition, and that provide automated MLD measurements.

Acknowledgements We would like to thank our optometrist Veronika Knoeferle who obtained the OCT scans for this study.

Contributors NJ-M and CB concepted and designed this study and drafted the original manuscript. All authors (NJ-M, LC, SG, KG, PCI and CB) have made substantial contributions to the acquisition and/or analysis and interpretation of the data and to the revision of the original manuscript and have given final approval of the version to be submitted. CB is the guarantor.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests PCI received research equipment from Heidelberg Engineering. An editor (CB) is an author of the manuscript. No conflicting relationship exists for the other authors.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Consent obtained directly from patient(s).

Ethics approval This study involves human participants and was approved by Ethics Committee of the TUM University Hospital; reference ID: 2021-331-S-NP. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request.

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