

Structure–Function Relationship Between Optic Nerve Head Morphometry and Virtual Reality-Based Perimetry in Open-Angle Glaucoma

Jan Niklas Lücke¹, Celina Poell¹, Vincent Lücke¹, Philip Enders¹, Thomas Dietlein¹, Alexandra Lappa¹, and Silvia Schrittenlocher¹

¹ Department of Ophthalmology, Faculty of Medicine and University Hospital Cologne, University of Cologne, Cologne, Germany

Correspondence: Jan Niklas Lücke, Department of Ophthalmology, Medical Faculty and University Hospital of Cologne, Kerpener Str. 62, 50937 Köln, Germany. e-mail: jan.lueke@uk-koeln.de

Received: June 26, 2025

Accepted: December 6, 2025

Published: January 20, 2026

Keywords: intraocular pressure; visual field; OCT; PalmScan2000

Citation: Lücke JN, Poell C, Lücke V, Enders P, Dietlein T, Lappa A, Schrittenlocher S. Structure–function relationship between optic nerve head morphometry and virtual reality-based perimetry in open-angle glaucoma. *Transl Vis Sci Technol.* 2026;15(1):23. <https://doi.org/10.1167/tvst.15.1.23>

Purpose: To investigate the structure–function relationship between optical coherence tomography (OCT) parameters of the optic nerve head and corresponding sectorial mean sensitivity values obtained using virtual reality (VR) headset-based perimetry.

Methods: In a post hoc analysis of a cross-sectional study, patients with suspected or confirmed glaucoma underwent examination with both VR-based perimetry (PalmScan VF2000; Micro Medical Device) and spectral-domain OCT (Spectralis) of the optic nerve head within an 8-week interval. Based on the Garway–Heath map, sensitivity points were assigned to the corresponding OCT sectors of the peripapillary retinal nerve fiber layer (pRNFL) and the Bruch’s membrane opening–minimum rim width (BMO-MRW). Mean sensitivity values were converted to a linear scale. Structure–function correlations were assessed using Spearman’s rank correlation coefficient.

Results: A total of 147 eyes from 86 patients with reliable visual field tests and sufficient OCT quality were included in the analysis. VR-based perimetry showed significant correlations with the BMO-MRW in the nasal ($r = 0.274$; $P < 0.001$), inferotemporal ($r = 0.581$; $P < 0.0001$), superotemporal ($r = 0.485$; $P < 0.0001$), temporal ($r = 0.471$; $P < 0.0001$), inferonasal ($r = 0.416$; $P < 0.0001$), and superonasal ($r = 0.520$; $P < 0.0001$) sectors. For the pRNFL, significant correlations were also observed in the inferotemporal ($r = 0.6581$; $P < 0.0001$), superotemporal ($r = 0.695$; $P < 0.0001$), temporal ($r = 0.473$; $P < 0.0001$), inferonasal ($r = 0.492$; $P < 0.0001$), and superonasal ($r = 0.496$; $P < 0.0001$) sectors. The correlation in the nasal sector was also significant but weaker ($r = 0.343$; $P < 0.0001$).

Conclusions: VR-based perimetry demonstrates a reliable structure–function relationship with optic nerve head morphometry. The strength of the structure–function correlation was comparable regardless of the OCT parameter used (BMO-MRW or pRNFL). This study highlights the potential of VR perimetry as an additional functional diagnostic tool in glaucoma.

Translational Relevance: This study supports the clinical utility of VR-based perimetry by demonstrating its significant correlation with established OCT-derived structural biomarkers of glaucomatous damage. By bridging novel immersive diagnostic technologies with established imaging modalities, these findings lay the groundwork for more accessible, portable, and patient-friendly visual field testing in both clinical and teleophthalmology settings.

Introduction

Visual field examination is an essential diagnostic tool for the detection and monitoring of glaucoma and other diseases affecting the visual pathway. Standard automated perimetry (SAP) with a 24-2 or 30-2 grid is currently considered the clinical reference standard in glaucoma diagnostics, because it remains the most widely used method for detecting functional visual field defects.¹ However, this method requires a high level of concentration and time from patients. Additionally, studies have shown that standard perimetry is perceived as the least favored ophthalmological diagnostic test.² Factors such as anxiety about potential disease progression during the examination can negatively impact the reliability and accuracy of test results.³

Alternative perimetry methods to SAP has been explored, such as virtual reality (VR)-based perimetry and tablet-based perimetry, which have been reported to be more comfortable and user friendly compared with the standard method.⁴ A questionnaire-based direct comparison between SAP and VR-based perimetry showed that VR-based testing was predominantly reported as the preferred examination method.⁴ These alternatives hold potential for future applications in telemedical glaucoma care. However, in addition to patient acceptance, the accuracy and comparability of these methods must be assessed.

Studies evaluating the validity and comparability of standard perimetry and VR headset-based perimetry have been conducted with small patient cohorts.^{5–7} Notably, it has been demonstrated that the PalmScan 2000 VR headset provides high diagnostic accuracy in glaucoma detection.⁸ Studies comparing different visual field examination methods often assess the agreement between two subjective tests performed sequentially,⁹ necessitating the consideration of factors such as learning effects and fatigue.

To further evaluate the diagnostic reliability of VR-based perimetry, it is essential to investigate the structure–function relationship in glaucoma diagnostics. In this study, spectral domain optical coherence tomography (SD-OCT) was used for this purpose. The peripapillary retinal nerve fiber layer (pRNFL) thickness and Bruch's membrane opening–minimum rim width (BMO-MRW) were analyzed, because these parameters have demonstrated superior diagnostic power compared with those obtained via confocal laser scanning tomography.¹⁰ The BMO-MRW is defined as the shortest distance between the BMO and the internal limiting membrane, measured along 24 radial OCT B-scans. This parameter has been shown to provide a

geometrically accurate assessment of neuroretinal rim tissue.¹¹

The structure–function relationship between conventional perimetry and SD-OCT has been previously investigated.^{12–14} In this context, it has been demonstrated that this relationship is more accurately represented using BMO-MRW and pRNFL thickness, compared with other neuroretinal rim parameters. These measurements have shown a greater degree of correlation with visual field sensitivity and offer improved diagnostic precision in the assessment of glaucomatous damage.¹⁵

Methods and Materials

This post hoc analysis is based on data collected during a cross-sectional study that investigated patient acceptance and reliability of VR-based perimetry (PalmScan VF2000; Micro Medical Device, Calabasas, CA). During routine clinical care, a subset of participants also underwent SD-OCT of the optic nerve head. Because OCT was not originally part of the study protocol, only patients with OCT data available from routine clinical examinations were eligible for inclusion in this secondary analysis. OCT imaging was performed in routine clinical practice depending on indication. Patients with and without OCT data did not differ with respect to age, gender, glaucoma subtype, or disease severity (mean deviation).

A total of 147 eyes from 86 individuals in patients with a confirmed diagnosis of open-angle glaucoma—were examined using both SD-OCT and VR perimetry. If suitable data were available for both eyes, both were included in the analysis.

Inclusion and Exclusion Criteria

Eligible cases required at least one SD-OCT scan of the optic nerve head obtained using the Spectralis Glaucoma Module (Heidelberg Engineering, Heidelberg, Germany).

OCT data were available only for a subset of patients, because the original study primarily aimed to evaluate VR perimetry. OCT imaging was performed in routine clinical practice depending on indication. Patients with and without OCT data did not differ with respect to age, gender, glaucoma subtype, or disease severity (mean deviation). OCTs were performed within 8 weeks of VR perimetry owing to clinical scheduling constraints. Previous studies have shown that structural and functional glaucomatous progression usually occurs at a much slower rate (e.g., decrease of 0 to -2.5 dB/year), which is negligible within an

8-week interval and well within test–retest variability.^{16,17} Thus, this time difference is unlikely to have influenced our findings.

Further inclusion criteria were an age over 18 years and a refractive error between -6 and $+3$ diopters (D). Inclusion criteria restricted refractive error to $+3.00$ to -6.00 D to avoid confounding influences of high hyperopia or myopia on OCT measurements and visual field reliability.¹⁸ Patients not fulfilling these criteria were excluded. Prior intraocular surgery was not considered an exclusion criterion. The study cohort included patients across different glaucoma stages and subtypes, including pseudoexfoliation glaucoma. Owing to limited sample size, stratified subgroup analyses were not feasible

VR-Based and Conventional Bowl Perimetry

The PalmScan VF2000 consists of a headset, a wireless handheld trigger, and a tablet. The headset—secured using adjustable straps—contains a smartphone that displays the perimetric stimuli. Patients responded by pressing the trigger button when a stimulus was perceived. The trigger was connected via Bluetooth to the tablet.⁴

The 24-2 glaucoma test pattern, as recommended by the manufacturer, was used. Upon test completion, results were displayed on the tablet and exported as PDF files for analysis. The central 24-2 threshold test, Interactive Fast Threshold, was used. Background illumination was 30 apostilb and the device could produce a maximum 34-dB attenuation for a 200-ms spot. Fixation monitoring implements a Heijl–Krakau blind spot monitor during the central fixation phase, presenting a stimulus 8 to 10 times in the blind spot location. The VR perimetry test was performed using a Goldmann size III stimulus.

The conventional bowl perimetry (Octopus 900, Haag-Streit, Köniz, Switzerland) examination was conducted in a darkened room using the tendency-oriented perimetry strategy (G-pattern) with 59 test points, a Goldmann size III stimulus, and a stimulus duration of 100 ms.

SD-OCT Imaging

All SD-OCT scans were performed following standard procedures careful disc centering, automated real-time averaging, and examiner-based quality control. Image quality of less than 15 dB was considered as insufficient. The Spectralis SD-OCT system was used to acquire 24 radial B-scans (48 points) for measuring BMO-MRW, 3 peripapillary circular scans for assessing pRNFL thickness, and automated calculation of the BMO area. The BMO area was

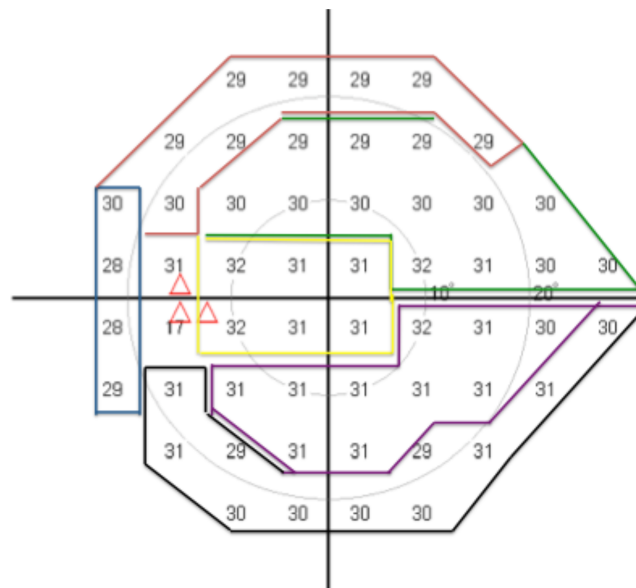


Figure 1. Sectorization of BMO-MRW with corresponding VR visual field value according to Garway-Heath map: nasal (blue), nasal-inferior (red), nasal-superior (black), temporal (yellow), temporal-inferior (green), and temporal-superior (purple) sector.

automatically calculated from the 24 radial B-scans acquired for BMO-MRW analysis. Both global and sectoral measurements were analyzed for BMO-MRW and 3.5-mm pRNFL thickness. For pRNFL thickness, three circular scans were obtained and the 3.5-mm inner circular scan were used for the analysis. Sectoral segmentation followed the anatomical correlation proposed by Garway-Heath et al., with six regions: temporal, inferotemporal, superotemporal, nasal, inferonasal, and superonasal. Scans with a signal strength of less than 15 dB, motion artifacts, or uncorrectable segmentation errors were excluded. Whenever feasible, segmentation errors were manually corrected and validated independently by two investigators (JL, CP) to ensure consistency and reliability. Discrepancies were resolved by consensus or exclusion when no consensus could be reached.

Structure–Function Correlation

Visual field threshold data and OCT-based structural measurements were segmented into corresponding anatomical sectors according to the Garway–Heath map, allowing a topographically accurate comparison (Fig. 1). Sectoral averages were calculated and analyzed on a linear scale.¹⁹ This sectoral division aligns the structural integrity of the pRNFL and BMO-MRW with corresponding functional visual field regions, enabling a precise assessment of glaucomatous damage. The averaged data were kept in a linear scale and presented in a graph (Figs. 2, 3).

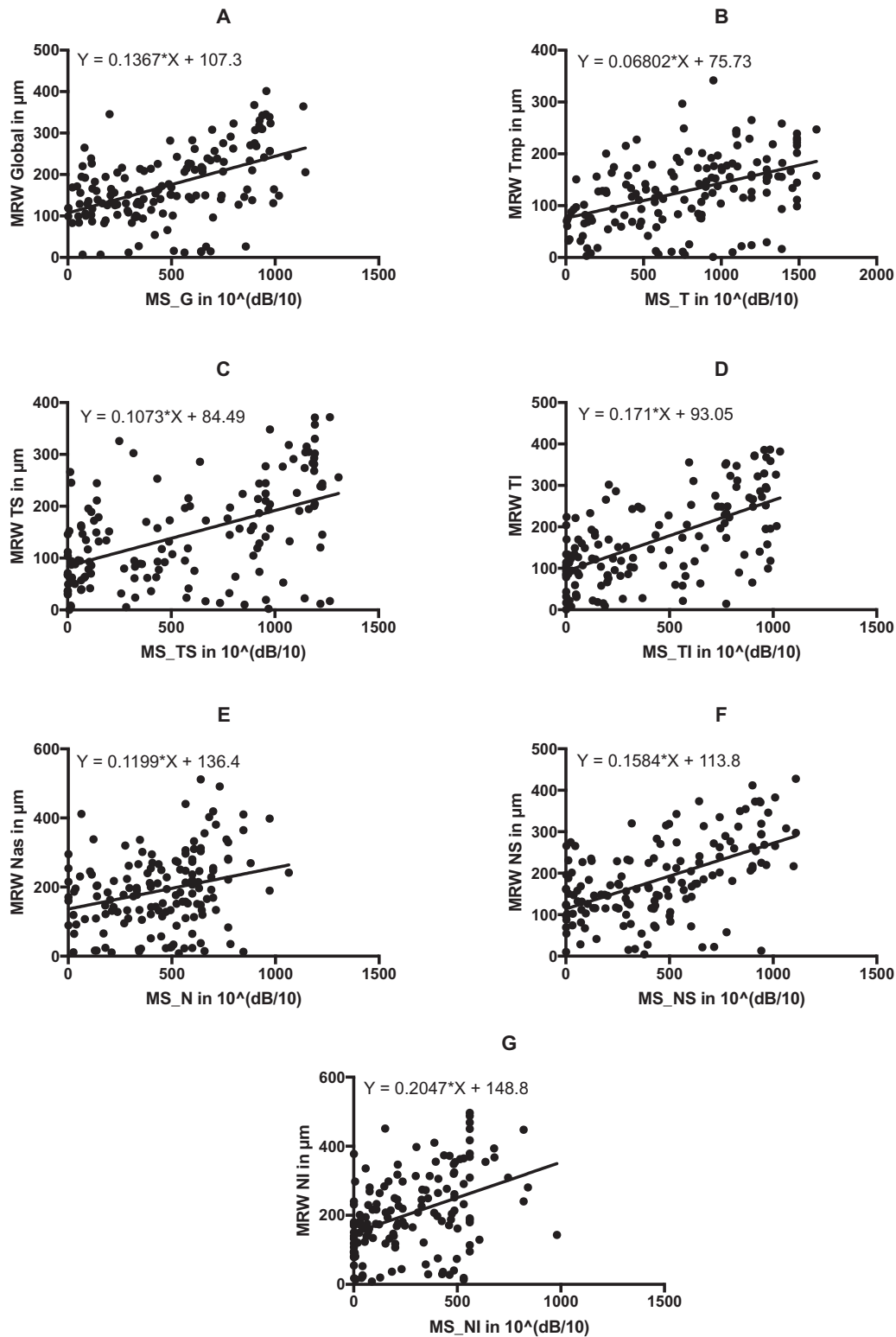


Figure 2. Scatter plots of BMO-MRW and corresponding delogarithmized visual field sensitivity values of VR perimetry in each sector. The effects of visual field sensitivity on OCT thickness were quantified by regression models in the linear-linear scale. **A:** G, global; sensitivity; **E:** N, nasal; **G:** NI, nasal inferior; **F:** NS, nasal superior; **B:** T, temporal; **D:** TI, temporal inferior; **C:** TS, temporal superior.

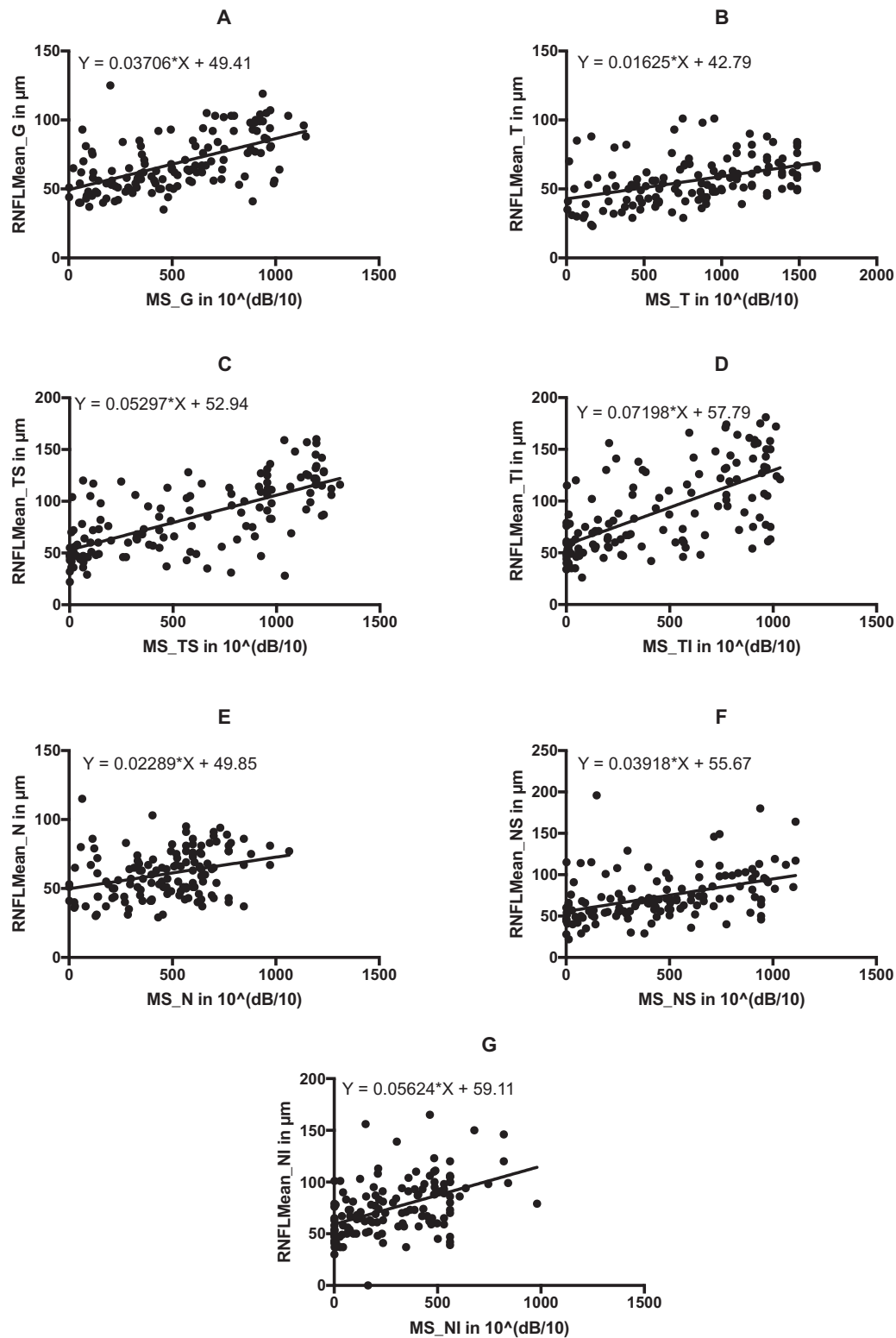


Figure 3. Scatter plots of RNFL and corresponding delogarithmized visual field sensitivity values of VR perimetry in each sector. The effects of visual field sensitivity on OCT thickness were quantified by regression models in the linear–linear scale. **A:** global; **B:** temporal; **C:** superotemporal; **D:** inferotemporal; **E:** nasal; **F:** Superonasal; **G:** inferonasal.

To statistically compare the correlation strengths of VR–OCT and SAP–OCT within the same eyes, we applied the Steiger Z test for dependent overlapping correlations. This test is appropriate when two correlations share a common variable (in this case, the OCT measurement) and are derived from the same subjects.^{20,21} Because the Steiger test is originally defined for Pearson correlations, all variables were rank-transformed before analysis so that the test reflects Spearman-based associations. In addition, a nonparametric bootstrap analysis (3000 resamples) was performed to calculate 95% percentile confidence intervals (CIs) for each individual correlation and for the difference between the two correlations ($\Delta\rho = \rho(\text{VR, OCT}) - \rho(\text{SAP, OCT})$).

Statistical Analysis

Visual field sensitivity measured by VR perimetry is reported in decibels, a logarithmic unit defined by the attenuation of stimulus luminance relative to the device maximum. For a given test location $\text{dB} = 10\log_{10}(L_{\text{threshold}}/L_{\text{max}})$ where L_{max} is the maximum stimulus luminance and $L_{\text{threshold}}$ the luminance that the subject can just detect. To obtain a quantity proportional to the reciprocal of threshold luminance and thus to produce a measure with a direct physical interpretation, decibel values were converted to a linear sensitivity scale using $S_{\text{lin}} = 10(\text{dB}/10)$. Thus S_{lin} corresponds with the ratio $L_{\text{max}}/L_{\text{threshold}}$ and increases with better sensitivity.

The D'Agostino–Pearson test was used to assess normality. Because most variables were not normally distributed, Spearman rank correlation was used to evaluate the relationship between structural OCT parameters and visual field sensitivity. Results were visualized in scatter plots (Figs. 2, 3), showing the relationship between sectoral mean sensitivity and corresponding structural measurements (BMO-MRW and pRNFL thickness).

To model the structure–function relationship between OCT parameters and visual field sensitivity, we applied a linear regression approach based on a model previously established by Hood et al.²² This model assumes that the relationship between retinal sensitivity, expressed in decibels, and structural OCT measures, such as pRNFL thickness and BMO-MRW, follows a logarithmic pattern. In accordance with this assumption, the following function was used: $R = s \cdot 10^{(0.1 D)} + c$, where R denotes the structural OCT measurement (e.g., pRNFL thickness or BMO-MRW, in μm), D is the deviation from normal visual field sensitivity in decibels, s is the scale parameter representing the value attributed to the healthy state, and c

is the residual floor level of the structure in the absence of visual function.

This transformation allows for a linear representation of the exponential decay of structure with increasing functional loss, particularly relevant in early to moderate stages of glaucoma. The model was fitted sector-wise and globally to assess the relationship between structure and function across the visual field.

No formal adjustment for multiple comparisons was applied, given the exploratory nature of this study. To allow interpretation of the magnitude and clinical relevance of the associations, we report effect sizes (Spearman's r) alongside P values. Applying Holm–Bonferroni correction was deemed overly conservative and could obscure meaningful relationships. This strategy may have increased the risk of type I error, which should be considered when interpreting the results.

To account for the nonindependence of including two eyes from some patients, we fitted linear mixed-effects models with a random intercept for patient. The primary linear mixed-effects models used global mean sensitivity (MS_G) as the dependent variable and included centered MRW global and centered peripapillary RNFL thickness as predictors, with ocular laterality ($r = 0$: right; $r = 1$: left) included as a categorical covariate.

Models were estimated using restricted maximum likelihood. We report fixed-effect estimates with standard errors and P values, random-effect variance components, and the intraclass correlation coefficient.

Descriptive statistics are presented as mean $\pm$ standard deviation. Microsoft Excel (Office 2016) was used for data collection and organization, whereas GraphPad Prism 7 (GraphPad Software, La Jolla, CA) and IBM SPSS Statistics (Version 22) were used for all statistical analyses. A significance level of $P < 0.05$ was considered statistically significant.

Ethics Approval

This analysis was conducted on data from a previously approved study. Ethical approval was granted by the Institutional Review Board of the University Eye Hospital Cologne, Germany. All participants had provided written informed consent as part of the original study. The study complied with the principles of the Declaration of Helsinki.

Results

A total of 147 eyes from 86 patients with reliable visual field measurements (fixation losses of $<33\%$, false positives/negatives of $<20\%$) and sufficient OCT

Table 1. Epidemiological Data of the Study Eyes

IOP, mm Hg	
Mean $\pm$ standard deviation	14.3 $\pm$ 5.5
Range	5 to 27
Age, years	
Mean $\pm$ standard deviation	72.8 $\pm$ 10.7
Range	43–96
Male	79 (52.8%)
Female	68 (47.2%)
Right eyes	74 (50.3%)
Left eyes	73 (49.7%)
MD-G, dB	
Mean $\pm$ standard deviation	−8.9 $\pm$ 6.6
Range	0.3 to −25.1)
PSD-G, dB	
Mean $\pm$ standard deviation	−5.0 $\pm$ 2.5
Range	−0.9 to (−13)
Spherical equivalent, D	
Mean $\pm$ standard deviation	−1.22 $\pm$ 2.03
Range	+2.75 to (−6)

D, diopter; MD-G, global visual field mean deviation; PSD-G, global visual field pattern standard deviation.

image quality were included in the analysis. Twenty-eight eyes were excluded owing to inadequate OCT quality. An additional 15 eyes had insufficiently analyzable RNFL measurements and were therefore excluded from the RNFL correlation analysis. Of the included patients, 115 (78.2%) were diagnosed with primary open-angle glaucoma, 7 (4.8%) with open-angle glaucoma owing to pigment dispersion, and 25 (17.0%) owing to pseudoexfolation. The mean age of the study population was 72.7 ± 10.7 years. Baseline characteristics of our cohort can be found in Table 1.

The effects of the OCT parameters—BMO-MRW and pRNFL thickness—on visual field sensitivity were evaluated using a linear regression model on a linear–linear scale. Results are presented as Spearman's rank correlation coefficients (ρ) with 95% CIs. BMO-MRW demonstrated statistically significant, moderate to strong correlations with mean sensitivity in the inferotemporal ($r = 0.581$; 95% CI, 0.459–0.682; $P < 0.0001$), superotemporal ($r = 0.485$; 95% CI, 0.346–0.603; $P < 0.0001$), temporal ($r = 0.471$; 95% CI, 0.330–0.591; $P < 0.0001$), inferonasal ($r = 0.416$; 95% CI, 0.268–0.545; $P < 0.0001$), and superonasal ($r = 0.520$; 95% CI, 0.386–0.631; $P < 0.0001$) sectors. Only the nasal sector showed a statistically significant but weak correlation ($r = 0.274$; 95% CI, 0.113–0.421; $P < 0.001$). On a global level, the BMO-MRW demonstrated a statistically significant moderate correlation

with mean sensitivity ($r = 0.492$; 95% CI, 0.355–0.609; $P < 0.0001$).

Similarly, pRNFL thickness exhibited statistically significant moderate to strong correlations with mean sensitivity in the inferotemporal ($r = 0.6581$; 95% CI, 0.546–0.747; $P < 0.0001$), superotemporal ($r = 0.695$; 95% CI, 0.592–0.776; $P < 0.0001$), temporal ($r = 0.473$; 95% CI, 0.324–0.598; $P < 0.0001$), inferonasal ($r = 0.492$; 95% CI, 0.346–0.614; $P < 0.0001$), and superonasal ($r = 0.496$; 95% CI, 0.351–0.617; $P < 0.0001$) sectors. The correlation in the nasal sector was also significant but weaker ($r = 0.343$; 95% CI, 0.179–0.489; $P < 0.0001$). On a global level, the pRNFL demonstrated a statistically significant moderate correlation with mean sensitivity ($r = 0.584$; 95% CI, 0.456–0.689; $P < 0.0001$).

Of 147 eyes included in the VR analysis, 4 eyes were excluded from the SAP analysis owing to poor reliability indices (fixation losses of $>33\%$ or false-positive/false-negative responses of $>2\%$).

In the remaining paired dataset ($n = 129$ – 143 , depending on OCT sector), both VR-based and SAP-based perimetry demonstrated significant correlations with OCT-derived structural parameters (BMO-MRW and pRNFL).

Across all global and sectoral comparisons, no statistically significant differences were found between VR–OCT and SAP–OCT correlation strengths (all $P > 0.05$), except for the nasal-superior RNFL sector ($P = 0.007$), where SAP exhibited a slightly stronger association. For the temporo-superior RNFL sector, Steiger's test could not be computed owing to near-perfect intercorrelation among variables, indicating highly similar structure–function relationships between VR and SAP in this region. All detailed values can be found in Table 2.

The observed structure–function relationship was described using $R = s \cdot 10^{(0.1 D)} + c$, where R denotes the structural OCT measurement (e.g., pRNFL thickness or BMO-MRW, in μm), D is the deviation from normal visual field sensitivity in decibels, s is the scale parameter representing the value attributed to the healthy state, and c is the residual floor level of the structure in the absence of visual function. It was fitted to the data in each sector and globally. The corresponding regression curves and parameters (s and c) are illustrated in Figures 2, 3 and Table 3.

When accounting for intrasubject correlation by fitting linear mixed-effects models with a random intercept for patient ($n = 75$ patients; 132 eyes), both structural parameters remained significantly associated with MS_G. In the random-intercept model, centered MRW Global was positively associated with MS_G ($\beta = 0.79$ per μm ; spherical equivalent (SE) = 0.38; $P = 0.038$)

Table 2. Comparison of VR–OCT and SAP–OCT Correlations by Sector Comparison of Spearman Rank Correlations (ρ) Between OCT Parameters (BMO-MRW and pRNFL) and Functional Sensitivity Measured by VR Perimetry (PalmScan VF2000) or SAP (G_TOP Octopus)

OCT Parameter	Sector	No.	ρ (VR, OCT)	ρ (SAP, OCT)	ρ (VR, SAP)	t (Steiger)	P Value
MRW	Nasal	143	0.281	0.336	0.530	−0.72	0.475
MRW	Superonasal	143	0.522	0.537	0.648	−0.33	0.742
MRW	Inferonasal	143	0.421	0.378	0.598	0.67	0.506
MRW	Temporal	143	0.476	0.476	0.544	0.00	0.997
MRW	Superotemporal	143	0.490	0.445	0.632	0.79	0.433
MRW	Inferotemporal	143	0.581	0.562	0.593	0.42	0.672
RNFLMean	Nasal	129	0.345	0.419	0.486	−0.95	0.345
RNFLMean	Superonasal	129	0.488	0.614	0.598	−2.76	0.007
RNFLMean	Inferonasal	129	0.500	0.430	0.573	1.08	0.284
RNFLMean	Temporal	129	0.479	0.397	0.471	1.07	0.285
RNFLMean	Superotemporal	129	0.702	0.652	0.586	n	n
RNFLMean	Inferotemporal	129	0.664	0.647	0.553	0.64	0.523
MRW	Global	129	0.506	0.524	0.648	−0.62	0.539
RNFLMean	Global	129	0.587	0.633	0.648	−1.21	0.230

RNFLMean_G, centered MRW global and centered peripapillary RNFL thickness.

Steiger's test for dependent overlapping correlations was used to compare correlation strengths within the same eyes.

Table 3. Summary of Regression Coefficients, R^2 , y Intercept (c), and S for Each OCT Sector

Sector	R^2	S	C (y Intercept)
BMO-MRW_G	0.2475	0.1367 $\pm$ 0.0198	107.3 $\pm$ 11.44
BMO-MRW_TS	0.2535	0.1073 $\pm$ 0.01529	84.49 $\pm$ 10.96
BMO_MRW_TI	0.3883	0.171 $\pm$ 0.01783	93.05 $\pm$ 9.922
BMO-MRW_N	0.07125	0.1199 $\pm$ 0.03594	136.4 $\pm$ 18.21
BMO-MRW_NI	0.1653	0.2047 $\pm$ 0.03819	148.8 $\pm$ 13.78
BMO-MRW_NS	0.2957	0.1183 to 0.1986	91.67 to 135.9
BMO-MRW_T	0.196	0.06802 $\pm$ 0.01144	75.73 $\pm$ 10.22
RNFL_G	0.3284	0.03706 $\pm$ 0.00463	49.41 $\pm$ 2.764
RNFL_T	0.1791	0.01625 $\pm$ 0.00304	42.79 $\pm$ 2.807
RNFL_TI	0.4212	0.07198 $\pm$ 0.007372	57.79 $\pm$ 4.26
RNFL_N	0.09549	0.02289 $\pm$ 0.006154	49.85 $\pm$ 3.207
RNFL_NS	0.1879	0.03918 $\pm$ 0.007116	55.67 $\pm$ 4.039
RNFL_TS	0.4745	0.05297 $\pm$ 0.00487	52.94 $\pm$ 3.592
RNFL_NI	0.2242	0.05624 $\pm$ 0.009141	59.11 $\pm$ 3.39

N, nasal; NI, inferonasal; NS, superonasal; T, temporal; TI, inferotemporal; TS, superotemporal.

and centered MRW global and centered peripapillary RNFL thickness showed a stronger association ($\beta = 6.89$ per μm ; $\text{SE} = 1.58$; $P < 0.001$). The between-patient variance component was 18,933 and the residual variance 42,539, yielding an intraclass correlation coefficient of 0.308, indicating that approximately 31% of the variance in MS_G is attributable to between-patient differences. These results are consistent with the primary analyses and indicate that the reported structure–function relationships are robust to clustering by patient

Discussion

Previous studies on innovative perimetric methods have demonstrated that VR perimetry is perceived by patients as more comfortable and user-friendly compared with conventional perimetry.⁴ This improved patient experience is likely attributed to the portable nature of VR devices, which enable greater flexibility in clinical application. Their mobility allows for bedside examinations, making them particularly advantageous

for patients with physical disabilities. Furthermore, VR perimetry may offer potential benefits in pediatric populations by facilitating a more engaging and accessible testing environment.^{4,23}

It should be noted, however, that threshold perimetry—whether performed with a VR headset or a conventional perimeter—still requires a considerable degree of concentration and may provoke anxiety regarding potential disease progression, which can negatively affect test performance and reliability.²⁴ A questionnaire-based direct comparison between SAP and VR-based perimetry showed that VR-based testing was predominantly reported as the preferred examination method.⁴ Given these facts, it remains important to critically evaluate alternative examination methods to determine whether they can improve patient acceptance without compromising diagnostic accuracy and comparability.

Several studies have already compared VR-based perimetry with conventional perimetry.⁹ However, the landscape of VR perimetry is highly heterogeneous, with substantial variation in test strategies and examination durations across different VR systems. Many of the existing studies have been conducted with relatively small patient cohorts. Despite these limitations, current evidence suggests that, depending on the specific VR system used, the strength of correlation with conventional perimetry varies. For example, in a study by Phu et al.,²⁵ a VR headset (Virtual Field) showed high intraclass correlation with the Humphrey Field Analyzer (intraclass correlation coefficient ~ 0.86 for mean deviation), but more variability in pointwise sensitivities. In another study in Bern (VR vs. Octopus 900), MD correlations were 0.75 or greater, although the VR system slightly underestimated defects in glaucoma subjects.⁷ PalmScan VF2000 also demonstrated high sensitivity and specificity in glaucoma vs. nonglaucoma classification,⁸ although its ability to discriminate severity levels was more limited. Additionally, different studies reported a learning curve for the use of VR perimetry.²⁶ Only for some devices was a high correlation found for both glaucoma screening and general visual field assessments, underlining the need for further validation.²⁷ In a systematic review published in 2024, it was concluded that there is a paucity of validation data for the use of VR headsets across various conditions and during different stages in the disease progression.²⁸ Currently, there is a lack of larger validation studies examining the efficacy of VR headsets compared with SAP.

Shetty et al.⁸ reported that the VF PalmScan 2000 showed 100% agreement with SAP classifications of glaucoma vs. nonglaucoma eyes. However, among patients with glaucoma, there was a relatively

high proportion of misclassification of severity of glaucoma.⁸ Another research group demonstrated that the PalmScan VF2000 device correctly classified glaucoma severity in 86.3% of cases. The mean difference in MD between SAP and PalmScan was $+0.62 \pm 0.26$ dB (range, -3.25 to $+4.60$ dB). The study cohort included eyes with mild to severe glaucoma severity.²⁹

However, it is crucial to recognize that these comparisons involve two subjective testing methods, performed sequentially, and thus may be influenced by variations in attention, concentration, and external factors.

To further assess the diagnostic accuracy of VR perimetry, a structure–function analysis should be incorporated, correlating subjective VR perimetry findings with an objective structural measurement. Currently, limited data are available on this subject,²⁰ but the findings of this study provide additional evidence suggesting good comparability between different perimetric methods.

The sectoral analysis conducted in this study demonstrated a moderate to strong correlation between BMO-MRW and pRNFL thickness with the MS values obtained from visual field testing using the PalmScan VF2000 device. Notably, test points corresponding with the nasal sector, as defined by the Garway–Heath map, exhibited only a weak correlation. This finding is likely attributable to the anatomical location of the central retinal vessel trunk, which has also been associated with weaker correlations in other sectoral structure–function analyses.¹² The stronger correlations observed, particularly in the superotemporal and inferotemporal sectors of BMO-based parameters, are also consistent with previously reported structure–function relationships established using SAP.¹²

In the present study, both VR-based and SAP-based perimetry demonstrated significant correlations with OCT-derived structural parameters (BMO-MRW and pRNFL), reflecting the expected structure–function relationship in glaucoma. Importantly, when directly comparing correlation coefficients using Steiger's *Z* test, excluding the superonasal pRNFL sector, no statistically significant differences were observed between the VR and SAP modalities. This finding suggests that the functional information captured by the VR perimetry system aligns well with that obtained from the clinical standard.

However, this comparison should be interpreted cautiously. The test strategies, thresholding algorithms, and display characteristics differ substantially between VR perimetry and SAP. These methodological discrepancies may influence sensitivity scaling and dynamic range, thereby affecting correlation strength.

Furthermore, the cross-sectional nature of the data preclude definitive conclusions regarding equivalence or diagnostic interchangeability between the two systems.

Nonetheless, the comparable correlation magnitudes between VR and SAP provide encouraging evidence that VR-based perimetry captures meaningful functional information linked to structural glaucomatous damage, supporting its potential as a valid and patient-friendly alternative in clinical settings.

When accounting for the clustering of eyes within patients using a random intercept linear mixed-effects model, the structure–function associations remained statistically significant. This indicates that the observed relationship between OCT-derived parameters and functional sensitivity is robust and not merely attributable to intereye correlation.

Supporting evidence from a separate study that compared VR perimetry with the Humphrey Field Analyzer further reinforces this finding. In that study, VR perimetry conducted in 57 eyes using the IMOVifa system revealed weak to moderate significant correlations between functional sensitivity and structural parameters across the inferior ($r = 0.50$), superior ($r = 0.45$), and temporal ($r = 0.27$) pRNFL sectors. Importantly, no significant differences in the strength of correlation with OCT parameters were observed between the IMOVifa and Humphrey Field Analyzer devices.²⁰ When compared with the correlations observed in the present study, the reported values fall within a similar range. However, it must be considered that the two devices use different test strategies and algorithms, with significant differences in individual point sensitivities.³⁰

Numerous studies have previously investigated the structure–function relationship between conventional perimetry and SD-OCT. In this context, it has been demonstrated that this relationship is more accurately represented using BMO-MRW and pRNFL thickness, compared with other neuroretinal rim parameters. These measurements have shown a greater degree of correlation with visual field sensitivity and offer improved diagnostic precision in the assessment of glaucomatous damage.¹⁵

Several studies have investigated the relationship between macular thickness and visual field sensitivity.^{31–33} In these analyses, linear regression models were commonly applied to quantify the association. Notably, the strongest correlation with mean deviation was identified in the inferior inner macular volume, with a correlation coefficient of $r = 0.50$ ($P < 0.001$).³⁴

In a study conducted by Muth et al.¹² in 2015, the correlation between BMO-MRW and SAP using the Humphrey Field Analyzer (SITA 24-2) was evaluated.

The authors reported similar correlation values, with the strongest structure–function relationship observed in the inferotemporal sector ($r = 0.71$) and the weakest in the nasal sector ($r = 0.27$). Both the magnitude of the correlation coefficients and the sectoral distribution of correlation strength closely align with the findings presented in the current study. This further supports the notion that the structure–function relationship typically observed with SAP may also be reflected through VR perimetry.

The optimal model for representing the structure–function relationship in glaucoma remains a subject of ongoing debate. Various models have been proposed to explain how structural damage measured by OCT relates to functional loss assessed by perimetry. Some studies suggest a linear relationship between RNFL thickness and visual field sensitivity,^{35,36} whereas others have proposed nonlinear or segmented models to better capture the floor effect of OCT parameters at advanced disease stages.^{37,38} Given this diversity of approaches, no single model has been universally accepted, and the optimal way to represent the structure–function relationship continues to evolve.

Similar to most existing approaches, the method presented in this study is based on Hood's model, which uses a linear framework to correlate RNFL thickness with delogarithmized sensitivity reductions in SAP.²² This strategy provides a conceptually simple yet physiologically motivated way to align structural and functional measurements, making it a pragmatic choice for exploratory analyses such as ours.

Reported strengths of these structure–function correlations vary considerably, ranging from weak to strong associations.¹³

Several limitations must be considered when interpreting our results. It is important to note that RNFL loss is typically detectable before the onset of visual field defects.³⁹ Consecutively, thicker neuroretinal tissue are related to greater variabilities in visual field outcomes.^{22,40} In cases of advanced glaucoma, a strong correlation has been reported; however, it is worth noting that a 10-2 strategy was used in this model.¹⁴ The objective of this study was to include a diverse range of patients, thereby striving to accurately reflect clinical practice. This approach may have contributed to a somewhat weaker correlation in the findings.

Because a portion of patients did not undergo SD-OCT examination as a part of routine clinical care and, therefore, could not be included in this post hoc analysis, there is a risk of selection bias. Another limitation to consider is the possibility of deviations from the Garway–Heath structure–function map owing to interindividual anatomical variations,

such as optic nerve head position relative to the fovea, axial length, and optic disc area, shape, and orientation.^{18,41} Another potential limitation of our study is that systemic comorbidities such as diabetes were not systematically assessed, although they may influence the structure–function relationship.

Although OCT does not replace visual field testing, its inclusion underscores the importance of integrating structural and functional analyses to achieve a more comprehensive understanding of glaucomatous damage. This study highlights the complementary nature of these novel diagnostic modalities in glaucoma assessment and management.

Conclusions

VR perimetry demonstrated promising correlations with OCT-derived structural parameters. These exploratory findings suggest that VR perimetry may represent a clinically relevant tool in the future; however, longitudinal studies are required before integration into routine clinical practice.

Acknowledgments

Funded by SFB 1607/1 2024, Project number 501530074 and Deutsche Forschungsgesellschaft.

Disclosure: **J.N. Lüke**, None; **C. Poell**, None; **V. Lüke**, None; **P. Enders**, None; **T. Dietlein**, None; **A. Lappa**, None; **S. Schrittenlocher**, None

References

- Wesselink C, Jansonius NM. Glaucoma progression detection with frequency doubling technology (FDT) compared to standard automated perimetry (SAP) in the Groningen Longitudinal Glaucoma Study. *Ophthalmic Physiol Opt.* 2017; 37(5):594–601. <https://doi.org/10.1111/opo.12401>.
- Gardiner SK, Demirel S. Assessment of patient opinions of different clinical tests used in the management of glaucoma. *Ophthalmology.* 2008;115(12):2127–2131. <https://doi.org/10.1016/j.ophtha.2008.08.013>.
- Chew SSL, Kerr NM, Wong ABC, Craig JP, Chou CY, Danesh-Meyer HV. Anxiety in visual field testing. *Br J Ophthalmol.* 2016;100(8):1128–1133. <https://doi.org/10.1136/bjophthalmol-2015-307110>.
- Schrittenlocher S, Lüke V, Irle H, et al. Akzeptanz von innovativen Perimetriemethoden in Deutschland: Virtual-Reality-Brillen-Perimetrie und Tablet-basierte Perimetrie bei Glaukompatienten. *Klin Monatsblätter Für Augenheilkd.* 2025;242(03):219–227. <https://doi.org/10.1055/a-2511-4087>.
- Berneshawi AR, Shue A, Chang RT. Glaucoma home self-testing using VR visual fields and rebound tonometry versus in-clinic perimetry and Goldmann applanation tonometry: a pilot study. *Transl Vis Sci Technol.* 2024;13(8):7. <https://doi.org/10.1167/tvst.13.8.7>.
- Wroblewski D, Francis BA, Sadun A, Vakili G, Chopra V. Testing of visual field with virtual reality goggles in manual and visual grasp modes. *BioMed Res Int.* 2014;2014:1–10. <https://doi.org/10.1155/2014/206082>.
- Stapelfeldt J, Kucur ŞS, Huber N, Höhn R, Sznitman R. Virtual reality–based and conventional visual field examination comparison in healthy and glaucoma patients. *Transl Vis Sci Technol.* 2021;10(12):10. <https://doi.org/10.1167/tvst.10.12.10>.
- Shetty V, Sankhe P, Haldipurkar SS, et al. Diagnostic performance of the PalmScan VF2000 virtual reality visual field analyzer for identification and classification of glaucoma. *J Ophthalmic Vis Res.* 2022;17(1):33–41. <https://doi.org/10.18502/jovr.v17i1.10168>.
- Hekmatjah N, Chibututu C, Han Y, Keenan JD, Oatts JT. Virtual reality perimetry compared to standard automated perimetry in adults with glaucoma: a systematic review. Gautam N, ed. *PLoS One.* 2025;20(1):e0318074. <https://doi.org/10.1371/journal.pone.0318074>.
- Enders P, Adler W, Kiessling D, et al. Evaluation of two-dimensional Bruch's membrane opening minimum rim area for glaucoma diagnostics in a large patient cohort. *Acta Ophthalmol (Copenh).* 2019;97(1):60–67. <https://doi.org/10.1111/aos.13698>.
- Chauhan BC, O'Leary N, AlMobarak FA, et al. Enhanced detection of open-angle glaucoma with an anatomically accurate optical coherence tomography–derived neuroretinal rim parameter. *Ophthalmology.* 2013;120(3):535–543. <https://doi.org/10.1016/j.ophtha.2012.09.055>.
- Muth DR, Hirneiß CW. Structure–function relationship between Bruch's membrane opening–based optic nerve head parameters and visual field defects in glaucoma. *Invest Ophthalmol Vis Sci.* 2015;56(5):3320. <https://doi.org/10.1167/iiov.14-15845>.

13. Leite MT, Zangwill LM, Weinreb RN, Rao HL, Alencar LM, Medeiros FA. Structure-function relationships using the cirrus spectral domain optical coherence tomograph and standard automated perimetry. *J Glaucoma*. 2012;21(1):49–54. <https://doi.org/10.1097/IJG.0b013e31822af27a>.
14. Imamoglu S, Celik NB, Sevim MS, et al. Structure-function relationship between the Bruch membrane opening-based minimum rim width and visual field defects in advanced glaucoma. *J Glaucoma*. 2017;26(6):561–565. <https://doi.org/10.1097/IJG.0000000000000675>.
15. Danthurebandara VM, Sharpe GP, Hutchison DM, et al. Enhanced structure-function relationship in glaucoma with an anatomically and geometrically accurate neuroretinal rim measurement. *Invest Ophthalmol Vis Sci*. 2015;56(1):98–105. <https://doi.org/10.1167/iovs.14-15375>.
16. Chauhan BC, Garway-Heath DF, Goni FJ, et al. Practical recommendations for measuring rates of visual field change in glaucoma. *Br J Ophthalmol*. 2008;92(4):569–573. <https://doi.org/10.1136/bjo.2007.135012>.
17. Akmaz O, Tokac MG, Garli M, Kusbeci T. Comparison of glaucoma progression rate in glaucoma patients at different stages using guided progression analysis with optical coherence tomography. *BMC Ophthalmol*. 2025;25(1):1. <https://doi.org/10.1186/s12886-024-03837-4>.
18. Lamparter J, Russell RA, Zhu H, et al. The influence of intersubject variability in ocular anatomical variables on the mapping of retinal locations to the retinal nerve fiber layer and optic nerve head. *Invest Ophthalmol Vis Sci*. 2013;54(9):6074. <https://doi.org/10.1167/iovs.13-11902>.
19. Garway-Heath DF, Viswanathan A, Westcott M, Kamal D, Fitzke FW, Hitchings RA. Relationship between perimetric light sensitivity and optic disc neuroretinal rim area. *Perimetry Update 1998/1999*. 381–389.
20. Kang J, Nascimento E, Silva R, Kim JA, et al. Comparison of structure-function correlation among IMO visual function analyser and Humphrey field analyser. *Br J Ophthalmol*. 2025;109(9):1005–1011. Published online March 14, 2025;bjo-2023-324846. <https://doi.org/10.1136/bjo-2023-324846>.
21. Diedenhofen B, Musch J. cocor: A comprehensive solution for the statistical comparison of correlations. Olivier J, ed. *PLoS One*. 2015;10(4):e0121945. <https://doi.org/10.1371/journal.pone.0121945>.
22. Hood DC, Kardon RH. A framework for comparing structural and functional measures of glaucomatous damage. *Prog Retin Eye Res*. 2007;26(6):688–710. <https://doi.org/10.1016/j.preteyeres.2007.08.001>.
23. Freeman SE, De Arrigunaga S, Kang J, et al. Participant experience using novel perimetry tests to monitor glaucoma progression. *J Glaucoma*. 2023;32(11):948–953. <https://doi.org/10.1097/IJG.0000000000002296>.
24. Kutzko KE, Brito CF, Wall M. Effect of instructions on conventional automated perimetry. *Invest Ophthalmol Vis Sci*. 2000;41(7):2006–2013.
25. Phu J, Wang H, Kalloniatis M. Comparing a head-mounted virtual reality perimeter and the Humphrey Field Analyzer for visual field testing in healthy and glaucoma patients. *Ophthalmic Physiol Opt*. 2024;44(1):83–95. <https://doi.org/10.1111/opo.13229>.
26. Alawa KA, Nolan RP, Han E, et al. Low-cost, smartphone-based frequency doubling technology visual field testing using a head-mounted display. *Br J Ophthalmol*. 2021;105(3):440–444. <https://doi.org/10.1136/bjophthalmol-2019-314031>.
27. Chen YT, Yeh PH, Cheng YC, et al. Application and validation of LUXIE: a newly developed virtual reality perimetry software. *J Pers Med*. 2022;12(10):1560. <https://doi.org/10.3390/jpm12101560>.
28. Selvan K, Mina M, Abdelmeguid H, Gulsha M, Vincent A, Sarhan A. Virtual reality headsets for perimetry testing: a systematic review. *Eye*. 2024;38(6):1041–1064. <https://doi.org/10.1038/s41433-023-02843-y>.
29. Wang SK, Tran EM, Yan W, Kosaraju R, Sun Y, Chang RT. Comparing a head-mounted smartphone visual field analyzer to standard automated perimetry in glaucoma: a prospective study. *J Glaucoma*. 2024;33(10):742–747. <https://doi.org/10.1097/IJG.0000000000002452>.
30. Kang J, De Arrigunaga S, Freeman SE, et al. Comparison of perimetric outcomes from a tablet perimeter, smart visual function analyzer, and Humphrey field analyzer. *Ophthalmol Glaucoma*. 2023;6(5):509–520. <https://doi.org/10.1016/j.ogla.2023.03.001>.
31. Boling W, WuDunn D, Cantor LB, Hoop J, James M, Nukala V. Correlation between macular thickness and glaucomatous visual fields. *J Glaucoma*. 2012;21(8):505–509. <https://doi.org/10.1097/IJG.0b013e318239c32b>.
32. Kanadani FN, Hood DC, Grippo TM, et al. Structural and functional assessment of the macular region in patients with glaucoma. *Br J Ophthalmol*. 2006;90(11):1393–1397. <https://doi.org/10.1136/bjo.2006.099069>.

33. Mathers K, Rosdahl JA, Asrani S. Correlation of macular thickness with visual fields in glaucoma patients and suspects. *J Glaucoma*. 2014;23(2):e98–e104. <https://doi.org/10.1097/IJG.0b013e31829539c3>.
34. Nakatani Y, Higashide T, Ohkubo S, Takeda H, Sugiyama K. Evaluation of macular thickness and peripapillary retinal nerve fiber layer thickness for detection of early glaucoma using spectral domain optical coherence tomography. *J Glaucoma*. 2011;20(4):252–259. <https://doi.org/10.1097/IJG.0b013e3181e079ed>.
35. Garway-Heath DF, Poinoosawmy D, Fitzke FW, Hitchings RA. Mapping the visual field to the optic disc in normal tension glaucoma eyes. The authors have no proprietary interest in the development or marketing of any product or instrument mentioned in this article. *Ophthalmology*. 2000;107(10):1809–1815. [https://doi.org/10.1016/S0161-6420\(00\)00284-0](https://doi.org/10.1016/S0161-6420(00)00284-0).
36. Harwerth RS, Wheat JL. Modeling the effects of aging on retinal ganglion cell density and nerve fiber layer thickness. *Graefes Arch Clin Exp Ophthalmol*. 2008;246(2):305–314. <https://doi.org/10.1007/s00417-007-0691-5>.
37. Medeiros FA, Zangwill LM, Bowd C, Mansouri K, Weinreb RN. The structure and function relationship in glaucoma: implications for detection of progression and measurement of rates of change. *Invest Ophthalmol Vis Sci*. 2012;53(11):6939. <https://doi.org/10.1167/iovs.12-10345>.
38. Malik R, Swanson WH, DF G-H. “Structure-function relationship” in glaucoma: past thinking and current concepts. *Clin Exp Ophthalmol*. 2012;40(4):369–380. <https://doi.org/10.1111/j.1442-9071.2012.02770.x>.
39. Medeiros FA, Alencar LM, Zangwill LM, et al. Prediction of functional loss in glaucoma from progressive optic disc damage. *Arch Ophthalmol*. 2009;127(10):1250. <https://doi.org/10.1001/archophthalmol.2009.276>.
40. Gardiner SK, Boey PY, Yang H, Fortune B, Burgoyne CF, Demirel S. Structural measurements for monitoring change in glaucoma: comparing retinal nerve fiber layer thickness with minimum rim width and area. *Invest Ophthalmol Vis Sci*. 2015;56(11):6886. <https://doi.org/10.1167/iovs.15-16701>.
41. Denniss J, McKendrick AM, Turpin A. An anatomically customizable computational model relating the visual field to the optic nerve head in individual eyes. *Invest Ophthalmol Vis Sci*. 2012;53(11):6981. <https://doi.org/10.1167/iovs.12-9657>.