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Article

Goldmann V Standard Automated Perimetry Underestimates Central Visual Sensitivity in Glaucomatous Eyes with Increased Axial Length

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Purpose: To investigate the effect of axial length (AL) on the structure–function relationship between retinal nerve fiber layer (RNFL) thickness measurements and visual field (VF) sensitivity measured with Goldmann III and V.

Method: There were 85 eyes of 85 patients with primary open angle glaucoma included in the current study. Optical coherence tomography and VF (Humphrey Field Analyzer 24-2 or 30-2) measurements with Goldmann III and V targets were carried out in all patients. The optic disc and the VF were divided into six clusters and the relationship between circumpapillary RNFL (cpRNFL) thickness and VF sensitivity (with Goldmann III or V), age, and AL were investigated in each cluster.

Result: Visual sensitivity with Goldmann III (19.3 ± 11.7 dB, mean ± standard deviation) was significantly lower than that with Goldmann V (24.6 ± 11.0 dB, $P < 0.001$, linear mixed model). Visual sensitivities with both Goldmann III and V were significantly correlated with cpRNFL thickness in all clusters. Visual sensitivity decreased with increasing AL in the nasal retinal area for both targets, however, this phenomenon was only observed with the Goldmann V target in the temporal area.

Conclusion: Visual sensitivity measured with the size V target decreases with increasing AL in the temporal area, which corresponds to the papillomacular bundle. In the nasal retinal area, visual sensitivity decreases with the increase of AL for both Goldmann III and Goldmann V.

Translational Relevance: Careful consideration is needed when measuring visual sensitivity using Goldmann V target in glaucomatous eyes with increased AL.

Introduction

Standard automated perimetry (SAP) with a Goldmann III target (4 mm^2 or 0.43°) is the gold standard to assess the visual field (VF) in glaucoma; however, previous studies have suggested that SAP measurements with a larger target size, such as Goldmann V (64 mm^2 or 1.72°), are associated with better reproducibility.[1–3] Furthermore, a recent study suggested that SAP sensitivity measurements with Goldmann III are particularly unreliable when VF sensitivity falls below 20 dB.[4] In contrast, previous research suggests that SAP measurements with a smaller target size are beneficial for the early detection of glaucoma.[5–7] Studies have investigated the usefulness of SAP with different target sizes in glaucoma,[5–8] however, these studies were performed in patients without myopia; a limited number of reports have investigated the usefulness of SAP with different target sizes in eyes with increased axial length (AL). Myopia is a risk factor for the development and progression of glaucoma, because a tilted optic disc, parapapillary atrophy, and thinning of the lamina cribrosa and parapapillary sclera alter glaucoma susceptibility.[9–15] It has been reported that the prevalence of myopia in the United

States increased from 25% to 42% from the 1970s to the 2000s, so it is increasingly important to understand the influence of myopia on VF results.[16] This is especially important in areas with a high prevalence of myopia, such as Asia (including Japan), and also for patients of Asian origin because myopia is a common ocular pathology.[17–19]

It is possible to measure glaucomatous structural damage using optical coherence tomography (OCT).[20–25] Investigation of the structure–function relationship is very important, because structural alterations at the optic nerve head[26–28] or in the circumpapillary retinal nerve fiber layer (cpRNFL)[29–31] can precede measurable VF damage. Many previous studies have investigated the glaucoma structure–function relationship using OCT and VF tests,[21,32–40] but most of these studies investigated the relationship using SAP with the Goldmann III target, usually excluding eyes with high myopia. No study has investigated the structure–function relationship in myopic eyes, using Goldmann III and V targets. Thus, the purpose of the current study was to investigate the influence of the increase of the axial length on the structure–function relationship between OCT-measured retinal nerve fiber thickness and SAP thresholds measured with target sizes III and V.

Methods

This cross-sectional study was approved by the Research Ethics Committee of the Graduate School of Medicine and Faculty of Medicine at the University of Tokyo. Written consent was given by the patients for their information to be stored in the hospital database and used for research. This study was performed according to the tenets of the Declaration of Helsinki.

Subjects

There were 85 eyes of 85 subjects with open angle glaucoma (OAG) included in this investigation. All patients were under treatment in the University of Tokyo Hospital, Tokyo, Japan. Criteria for inclusion were visual acuity better than 0.5 logMAR following our previous study,[41] an AL longer than 22 mm and shorter than 30 mm, and no other anterior or posterior segment eye disease, including clinically significant cataract. Aberrant disc morphology and/or with pathological myopic findings on fundus were carefully examined and these eyes were not included in the current study. The patients satisfying the criteria were consecutively recruited and one eye was randomly chosen if both eyes met the inclusion criteria.

VF Testing

VF testing was performed, within 3 months of the spectral-domain (SD)-OCT examination, using the Humphrey Field Analyzer (HFA, Carl Zeiss Meditec, Dublin, CA) with Goldmann III and V targets and a stimulus duration equal to 200 ms. The order of the Goldmann III and Goldmann V VF measurement was decided in a random manner and a sufficient break was given between tests. The same test grid pattern (24-2 or 30-2 test program) was used for both sets of measurements. The Goldmann III measurement was performed using the SITA standard strategy and the full-threshold strategy was used for the Goldmann V measurement, following previous studies.[2,3,42] Near-refractive correction was used as necessary. All of the participants had previous experience in VF testing. VFs with fixation losses greater than 20%, or false–positive responses greater than 15% were excluded, as recommended by the manufacturer.[43]

SD-OCT Measurement

SD-OCT data were obtained using the three-dimensional OCT-2000 (Topcon Corp., Tokyo, Japan), along with the AL measurement. SD-OCT measurements were carried out after pupil dilation with 1% tropicamide and imaging was performed using the raster-scan protocol. cpRNFL thickness was measured as the RNFL thickness along a 3.4-mm diameter circle around the disc, but the radius of the circle was adjusted for AL. The temporal horizontal line (9-o'clock position, right eye) was designated 0°, and angles were counted in a clockwise direction. Left eyes were mirror imaged to a right eye configuration. The optic disc was divided into 12, 30° sectors and the average thickness for each sector was calculated: the angles between −15° and 15° in the temporal area (T), 15° and 30° in the temporo-superior area (TS), 45° and 75° in the supero-temporal area (ST), 75° and 105° in the superior area (S), 105° and 135° in the supero-nasal area (SN), 135° and 165° in the nasal-superior area (NS), 165 and 195° in the nasal area (N), 195° and 225° in the nasal-inferior area (NI), 225° and 255° in the inferior-nasal area (IN), 255° and 285° in the inferior area (I), 285° and 315° in the infero-temporal area (IT), and 315° and 345° in the nasal-inferior area (NI).

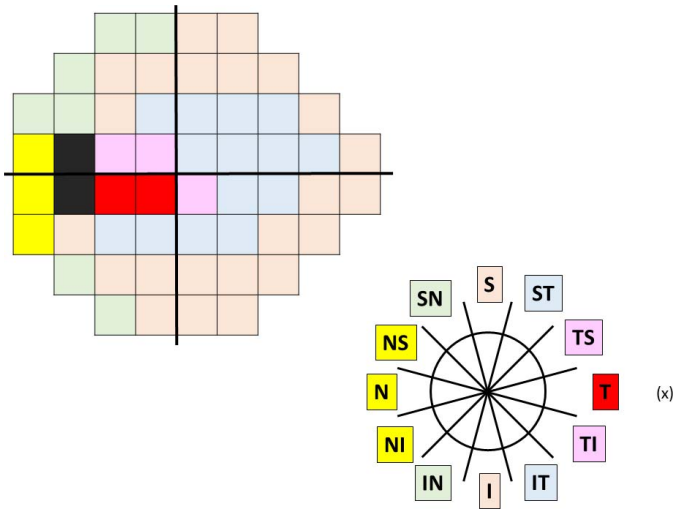

Figure 1. Test points corresponding to five optic disc clusters (left eye). VF test points corresponding to each of the 12, 30° sector were identified following Garway-Heath's structure–function map.[44] TS and TI, ST and IT, SN and NS were analyzed together. Also, because of the small number of test points, the sectors of N, NS, and NI were combined (cluster NS/N/NI) and analyzed altogether.

Data with apparent eye movements and involuntary blinking or saccade during the measurement were carefully excluded. Following the manufacturer's recommendation, imaging data with quality factor less than 30% were also excluded.

Statistical Analysis

Following Garway-Heath's structure–function map (fig. 4 in Ref. 44),[44] we first identified the angle on the optic disc corresponding to each test point. Then, the whole field was divided into 12, 30° sectors, matching the 12 sectors in OCT (see Fig. 1). Because of the approximately horizontally symmetrical structure of the retina, TS and TI, S and I, ST and IT, SN and IN were analyzed together (TS/TI, ST/IT, S/I, and SN/IN, respectively). Also, because of the small number of test points, the sectors of NS, N, and NI were combined (cluster NS/N/NI) and analyzed altogether. The relationship between sectorial cpRNFL thickness and AL was investigated using linear mixed modeling, whereby cpRNFL thickness was nested to each patient. Also, the relationship between visual sensitivity and AL was analyzed using a linear mixed model, whereby test points were nested in each patient. In other words, a linear mixed model analysis was carried out six times for the clusters: T, TS/TI, ST/IT, S/I, SN/IN, and NS/N/NI. Then the relationship between visual sensitivity and cpRNFL thickness, age, and AL was also investigated using a linear mixed model. Lens status (phakic/pseudophakic) was included as a fixed effect, because lens status can interfere with VF test results.

All statistical analyses were carried out using the statistical programming language R (ver. 3.1.3; The R Foundation for Statistical Computing, Vienna, Austria).

Table 1. Subject Demographics

Variable	Value
Age, y, mean ± SD [range]	59.4 ± 11.6 [30–84]
Sex, male:female	42:43
Eye, right:left	39:46
AL, μm, mean ± SD [range]	25.5 ± 1.5 [22.7–29.95]
Refractive error, diopter, mean ± SD [range]	−3.5 ± 3.0 [−11.0–1.75]
MD, dB, mean ± SD [range]	−10.8 ± 5.8 [−32.0–0.74]

MD: mean deviation.

Results

Subject characteristics are given in Table 1. Among the 85 eyes, 12 eyes were pseudophakic. Figure 2 shows the histogram of AL. There was a significant relationship between refractive error and AL ($r = -0.74$, $P < 0.001$, Pearson's correlation).

Visual sensitivity with Goldmann III (19.3 ± 11.7 [0–36] dB, mean ± standard deviation [SD] [range]) was significantly lower than that with Goldmann V (24.6 ± 11.0 [0–40] dB, $P < 0.001$, linear mixed

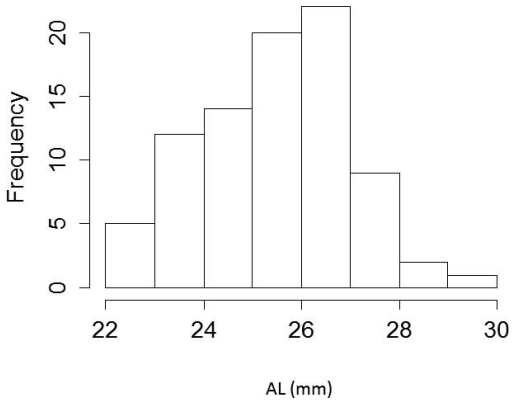

Figure 2. Histograms of AL. AL was 25.5 ± 1.5 (mean ± SD) (range: 22.7–29.95 μm).

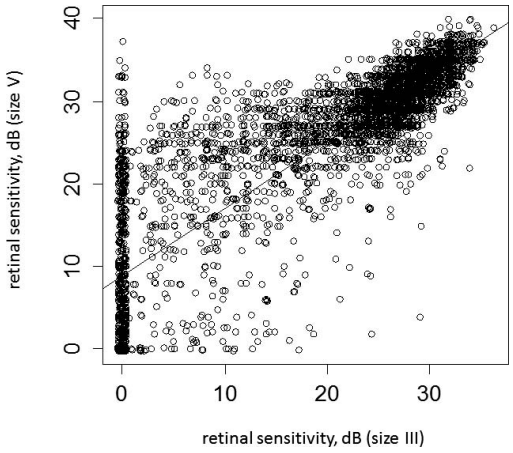

Figure 3. Relationship between visual sensitivity measured with Goldmann III and V target with all test points. There was a significant relationship between visual sensitivity measured with Goldmann III and Goldmann V ($R^2 = 0.74$, $P < 0.001$).

model). As shown in Figure 3, there was a significant relationship between visual sensitivity measured with Goldmann III and Goldmann V ($R^2 = 0.74$, $P < 0.001$). This significant relationship was observed in all clusters (R^2 = between 0.53 and 0.74, all of the P values were < 0.001, linear mixed model).

Table 2 shows the visual sensitivity with Goldmann III and V targets in each cluster. In all clusters, visual sensitivity with Goldmann V target was significantly higher than that with target Goldmann III ($P < 0.05$, linear mixed model). Table 3 shows the RNFL thickness in each cluster.

Figure 4 shows the relationship between visual sensitivity measured with Goldmann III and V, and AL in clusters T, TS/TI, S/I, ST/IT, SN/SI, and NS/N/NI. As shown in Table 4, in the linear mixed models using multiple variables (age, AL, and RNFL thickness), there was a significant relationship between visual sensitivity both with Goldmann III and Goldmann V, and cpRNFL thickness in all sectors ($P < 0.01$), except one: NS/N/NI ($P = 0.16$ for Goldmann III and 0.39 for Goldmann V). In cluster T, increase of AL was significantly related to visual sensitivity measured with the Goldmann V target ($P = 0.010$, linear mixed model), but not with the Goldmann III target ($P = 0.11$). In cluster NS/N/NI, increased AL was significantly related to visual sensitivity measured with target sizes; Goldmann V target ($P = 0.012$) and Goldmann III ($P = 0.019$). Age was not significantly related to visual sensitivity in all clusters ($P > 0.05$).

Table 3. cpRNFL Thickness in Each Cluster

Cluster	RNFL Thickness
T, μm, mean ± SD [range]	62.1 ± 17.5 [28.2–112.00]
TS/TI, μm, mean ± SD [range]	64.3 ± 21.6 [23.0–153.1]
ST/IT, μm, mean ± SD [range]	66.6 ± 27.9 [23.3–189.6]
S/I, μm, mean ± SD [range]	78.5 ± 24.5 [30.7–164.7]
SN/IN, μm, mean ± SD [range]	81.2 ± 23.5 [34.3–130.3]
N3, μm, mean ± SD [range]	63.3 ± 16.7 [33.3–112.8]

Discussion

In the current study, VF measurements were carried out using Goldmann III and Goldmann V SAP, and compared with cpRNFL measurements from SD-OCT. As expected, there was a significant correlation between visual sensitivity measured with Goldmann III and Goldmann V targets, however visual sensitivity measured with Goldmann V SAP was significantly higher compared with Goldmann III SAP. Visual sensitivities with both Goldmann III and Goldmann V targets were significantly correlated with cpRNFL thickness in all clusters around the optic disc. Visual sensitivity significantly decreased

Table 2. Average Visual Sensitivity in Each Cluster

Cluster	Size III	Size V	*P* Value
T, dB, mean ± SD [range]	28.4 ± 7.0 [0–35]	32.4 ± 5.3 [9–40]	<0.001
TS/TI, dB. Mean ± SD [range]	22.2 ± 12.2 [0–36]	27.7 ± 10.5 [0–40]	<0.001
ST/IT, dB, mean ± SD [range]	15.5 ± 12 [0–35]	20.8 ± 11.8 [0–39]	<0.001
S/I, dB, mean ± SD [range]	18.6 ± 12 [0–34]	24.1 ± 11.2 [0–38]	<0.001
SN/IN, dB, mean ± SD [range]	22.1 ± 9.1 [0–34]	27.5 ± 8.3 [0–38]	<0.001
NS/N/NI, dB, mean ± SD [range]	26.1 ± 6.4 [0–34]	30.5 ± 6.4 [0–37]	<0.001

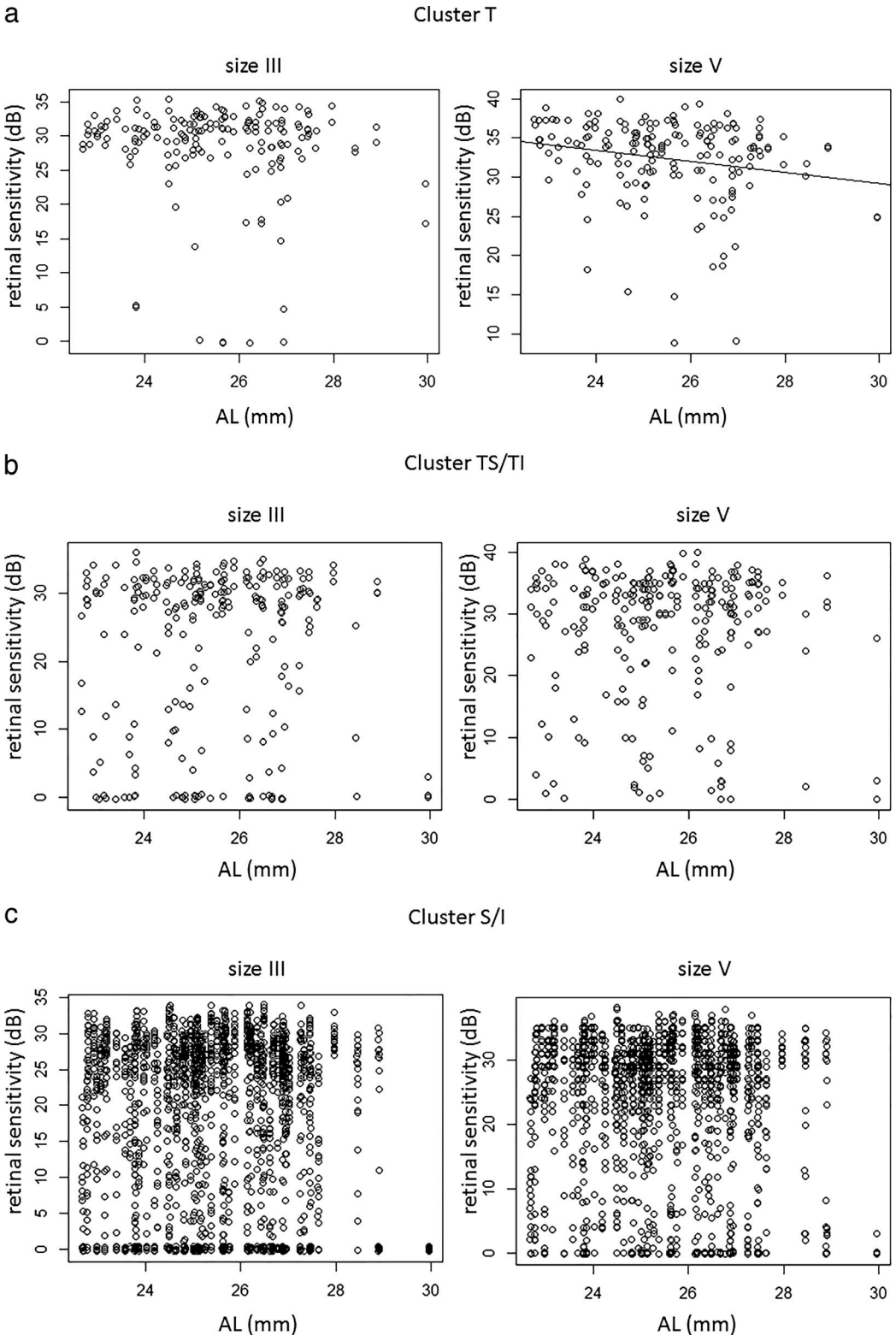

Figure 4. Relationship between visual sensitivity measured with Goldmann III and Goldmann V targets, and AL. (a) Cluster T, (b) cluster TS/TI, (c) cluster ST/IT, (d) cluster S/I, (e) cluster SN/IN, (f) cluster NS/N/NI. Significant relationship was observed between visual sensitivity measured with Goldmann V target and AL in cluster T (coefficient = −0.72, $P = 0.038$).

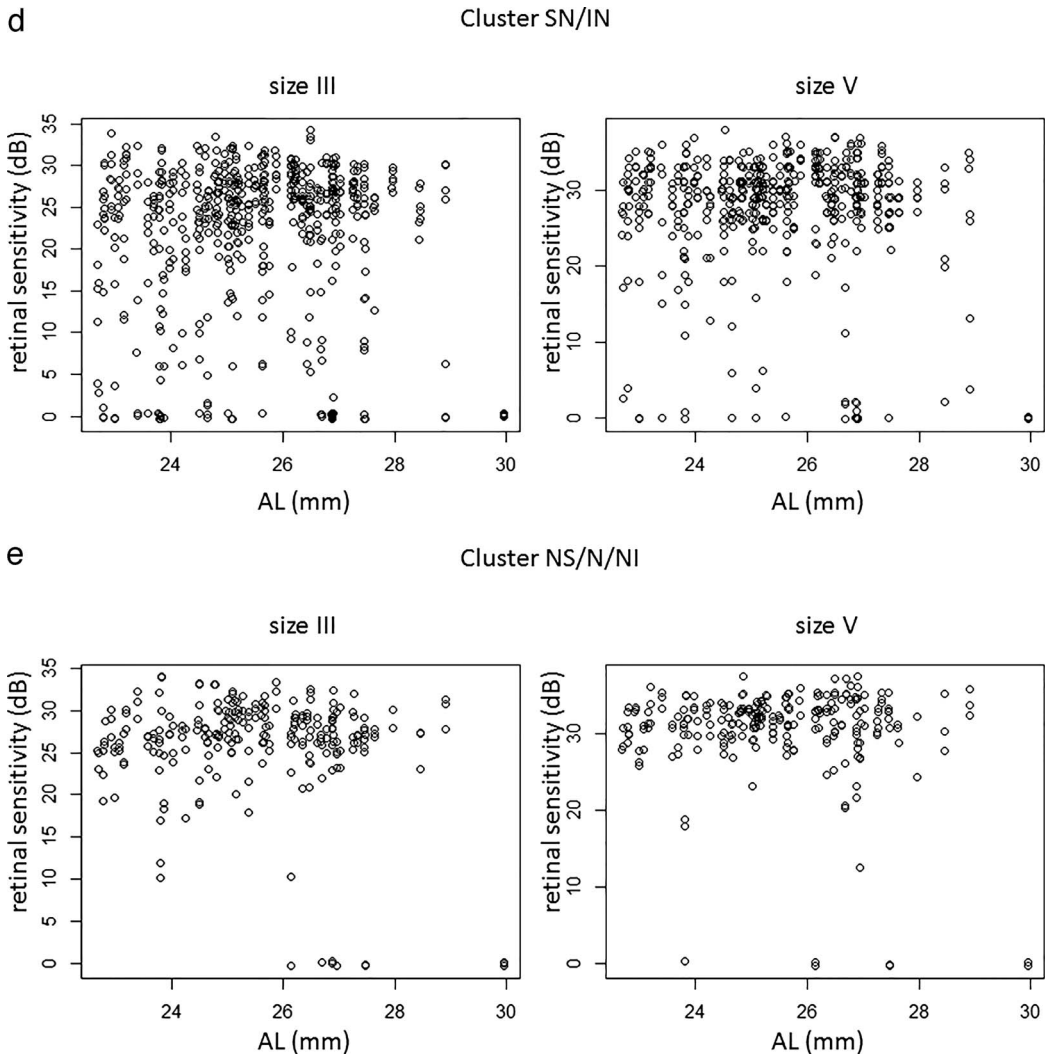

Figure 4. Continued.

with increasing AL with both Goldmann III and Goldmann V targets in the nasal retinal area, whereas this phenomenon was only observed with the Goldmann V target in the temporal retinal area.

SAP with the Goldmann III target is frequently used in the evaluation of glaucomatous VF damage worldwide. However, it has been reported that SAP measurements with a larger target size, such as Goldmann V, are associated with better reproducibility,[1–3] and indeed a recent study suggested SAP sensitivity measured with Goldmann III is not reliable below 20 dB.[4] In the current study, a significant structure–function relationship was observed in all clusters around the optic disc, both with Goldmann III and V targets. However, this structure–function relationship was altered by increasing AL, when visual sensitivity was measured with the Goldmann V target in cluster T. The retinal nerve fiber in cluster T runs along the papillomacular bundle, which corresponds to VF test points located at the center of VF. In this central area, the density of retinal ganglion cell is high.[45] According to Ricco's law, when a small stimulus is projected on the retina, the stimulus's total energy is constant at threshold (complete spatial summation),[46] both in normative and glaucomatous eyes,[47,48] but in contrast, when larger stimuli, such as the Goldmann III and V targets, are projected, only partial, instead of complete summation occurs, and the threshold is determined probabilistically.[49,50] Tolhurst et al.[51] have reported that the psychometric function or multiplicative neural probability summation is the result of pooling over multiple receptive fields. The reason why structure–function relationship was altered by in-

Table 4. Relationship between Visual Sensitivity and Age, AL and cpRNFL Thickness

	Age			AL			RNFL Thickness		
Cluster	Coefficient	SE	*P* Value	Coefficient	SE	*P* Value	Coefficient	SE	*P* Value
Size III									
T	−0.028	0.068	0.68	−0.76	0.49	0.12	**0.10**	**0.039**	**0.0072**
TS/TI	−0.10	0.088	0.25	−0.34	0.67	0.61	**0.23**	**0.035**	**<0.001**
ST/IT	0.17	0.087	0.058	0.22	0.65	0.74	**0.21**	**0.030**	**<0.001**
S/I	0.017	0.065	0.80	−0.16	0.48	0.73	**0.19**	**0.012**	**<0.001**
SN/IN	0.093	0.068	0.18	0.19	0.50	0.71	**0.047**	**0.019**	**0.012**
NS/N/NI	−0.019	0.056	0.74	**−0.96**	**0.41**	**0.021**	0.033	0.022	0.14
Size V									
T	−0.025	0.049	0.61	**−0.92**	**0.36**	**0.013**	**0.089**	**0.029**	**0.0028**
TS/TI	−0.11	0.071	0.14	−0.67	0.54	0.22	**0.17**	**0.030**	**<0.001**
ST/IT	0.13	0.089	0.15	0.037	0.67	0.96	**0.18**	**0.030**	**<0.001**
S/I	0.0029	0.064	0.96	−0.54	0.47	0.26	**0.19**	**0.011**	**<0.001**
SN/IN	0.014	0.064	0.83	−0.65	0.47	0.17	**0.050**	**0.017**	**0.0031**
NS/N/NI	−0.032	0.059	0.59	**−0.99**	**0.44**	**0.025**	0.020	0.022	0.36

SE: standard error.

creasing AL, when visual sensitivity was measured with the Goldmann V target in cluster T is not entirely clear, but this may be because the stretching effect caused by the increase of the eye ball is most obvious in this area, as is seen in the development of peripapillary atrophy. This stretching effect may cause accelerated partial summation, which is sufficient to decrease visual sensitivity measured with Goldmann V, but not that with smaller target size, such as Goldmann III.

Araie et al.[52] investigated the relationship between myopia and the location of VF damage in 217 primary OAG eyes and suggested that the strength of myopia is significantly correlated with VF damage in the lower cecocentral subfield. Similar results were found in another study,[53] which may be related to the torsion of the optic disc.[54] It is important to note that the lower cecocentral subfield corresponds to cluster T in the current study, where visual sensitivity measured with the Goldmann V target decreased with increasing AL. This implies careful consideration is needed when assessing glaucomatous damage in myopic eyes in this area, using the Goldmann V target.

In cluster NS/N/NI, visual sensitivity decreased with increasing AL, not only with the Goldmann III target, but also with the Goldmann V target. The reason for this is not entirely clear, but structural changes, such as a hump of retinal nerve fibers (nasal hump[55] or peripapillary nerve fiber elevation [pNFE][56]) has been reported in the nasal retina area in eyes with long AL, probably because the retina is dragged posteriorly as the AL increases, even if the fundus lacks pathological myopic findings.[56] These structural changes are more prominent with the increase of the eye ball, and this may be the reason why visual sensitivity, measured with both Goldmann III and V targets, is decreased with the increase of AL. In the current 24-2 HFA, only three test points are allocated in the area corresponding to cluster NS/N/NI. In addition, some of the 0-dB test points may be a consequence of an overlapping blind spot. Further investigation should be carried out increasing the number of test points in this area.

In eyes with the nasal hump or pNFE due to increase of AL, a conus was usually present on the side opposite the elevation.[56] As the target is much larger with Goldmann V (64 mm^2), compared with Goldmann III (4 mm^2), the possibility that the projected light overlaps with the conus is much higher with the larger size target (e.g., due to small eye movements). This may be another reason why visual sensitivity measured with Goldmann V target in cluster T decreased with increasing AL, whereas that phenomenon was not observed with the Goldmann III target.

There are a number of limitations with the current study. First, the SITA standard algorithm was used in the Goldmann III measurement while the full-threshold algorithm was adopted in the Goldmann V measurement. It would be of interest to see whether a different result would be observed if the same

strategy was used for both measurements. Also, as discussed above, the Goldmann V stimulus evokes only partial spatial summation, and the threshold is determined probabilistically.[49,50] A further study is needed to understand if evoking complete summation, by changing stimulus duration, gives different results. Although the purpose of the current study was to investigate the structure–function relationship using Goldmann size III and V in a wide range of glaucoma severity patients, it would be of interest to investigate the usefulness of Goldmann V in severe glaucoma cases.

In conclusion, visual sensitivity measured with the Goldmann V target decreases with increasing AL in the area corresponding to the papillomacular bundle, whereas this was not the case with the Goldmann III measurement. Also, visual sensitivity decreases with the increase of AL in the area corresponding to the nasal retina, and this phenomenon was observed with both Goldmann III and V targets.

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References

1. Wall M, Kutzko KE, Chauhan BC. Variability in patients with glaucomatous visual field damage is reduced using size V stimuli. *Invest Ophthalmol Vis Sci*. 1997;38:426–435.
2. Wall M, Doyle CK, Zamba KD, et al. The repeatability of mean defect with size III and size V standard automated perimetry. *Invest Ophthalmol Vis Sci*. 2013;54:1345–1351.
3. Wall M, Woodward KR, Doyle CK, et al. Repeatability of automated perimetry: a comparison between standard automated perimetry with stimulus size III and V, matrix, and motion perimetry. *Invest Ophthalmol Vis Sci*. 2009;50:974–979.
4. Gardiner SK, Swanson WH, Goren D, et al. Assessment of the reliability of standard automated perimetry in regions of glaucomatous damage. *Ophthalmology*. 2014;121:1359–1369.
5. Yamada K, Osako M, Osako S, et al. The Effectiveness of Detecting Early Glaucomatous Field Deffects Using the Size 1 Stimulus. Perimetry Update 2000/2001. Amsterdam: Kugler publication; 2001.
6. Zalta AH, Burchfield JC. Detecting early glaucomatous field defects with the size I stimulus and Statpac. *Br J Ophthalmol*. 1990;74:289–293.
7. Uyama K, Matsumoto C, Okuyama Y, et al. The Influence of the Target Size on the Sensitivity of the Central Visual Field in Patients With Early Glaucoma. Perimetry Update 1992/1993. Amsterdam: Kugler publication; 1993.
8. Zulauf M, Caprioli J. Indications for stimulus 3 and 5 in automatic perimetry. Preliminary results [in German]. *Klin Monbl Augenheilkd*. 1994;204:407–408.
9. Grodum K, Heijl A, Bengtsson B. Refractive error and glaucoma. *Acta Ophthalmol Scand*. 2001;79:560–566.
10. Suzuki Y, Iwase A, Araie M, et al. Risk factors for open-angle glaucoma in a Japanese population: the Tajimi Study. *Ophthalmology*. 2006;113:1613–1617.
11. Casson RJ, Gupta A, Newland HS, et al. Risk factors for primary open-angle glaucoma in a Burmese population: the Meiktila Eye Study. *Clin Exp Ophthalmol*. 2007;35:739–744.
12. Perera SA, Wong TY, Tay WT, et al. Refractive error, axial dimensions, and primary open-angle glaucoma: the Singapore Malay Eye Study. *Arch Ophthalmol*. 2010;128:900–905.
13. Chihara E, Liu X, Dong J, et al. Severe myopia as a risk factor for progressive visual field loss in primary open-angle glaucoma. *Ophthalmologica*. 1997;211:66–71.
14. Araie M, Shirato S, Yamazaki Y, et al. Risk factors for progression of normal-tension glaucoma under beta-blocker monotherapy. *Acta Ophthalmol*. 2012;90:e337–e343.
15. Sakata R, Aihara M, Murata H, et al. Contributing factors for progression of visual field loss in

normal-tension glaucoma patients with medical treatment. *J Glaucoma*. 2013;22:250–254.
16. Vitale S, Sperduto RD, Ferris FL III. Increased prevalence of myopia in the United States between 1971-1972 and 1999-2004. *Arch Ophthalmol*. 2009;127:1632–1639.
17. Rudnicka AR, Owen CG, Nightingale CM, et al. Ethnic differences in the prevalence of myopia and ocular biometry in 10- and 11-year-old children: the Child Heart and Health Study in England (CHASE). *Invest Ophthalmol Vis Sci*. 2010;51:6270–6276.
18. Shimizu N, Nomura H, Ando F, et al. Refractive errors and factors associated with myopia in an adult Japanese population. *Jpn J Ophthalmol*. 2003;47:6–12.
19. Sawada A, Tomidokoro A, Araie M, et al. Refractive errors in an elderly Japanese population: the Tajimi study. *Ophthalmology*. 2008;115:363–370, e363.
20. Huang D, Swanson EA, Lin CP, et al. Optical coherence tomography. *Science*. 1991;254:1178–1181.
21. Garas A, Vargha P, Hollo G. Diagnostic accuracy of nerve fibre layer, macular thickness and optic disc measurements made with the RTVue-100 optical coherence tomograph to detect glaucoma. *Eye (Lond)*. 2011;25:57–65.
22. Rao HL, Kumbar T, Addepalli UK, et al. Effect of spectrum bias on the diagnostic accuracy of spectral-domain optical coherence tomography in glaucoma. *Invest Ophthalmol Vis Sci*. 2012;53:1058–1065.
23. Rao HL, Babu JG, Addepalli UK, et al. Retinal nerve fiber layer and macular inner retina measurements by spectral domain optical coherence tomograph in Indian eyes with early glaucoma. *Eye (Lond)*. 2012;26:133–139.
24. Cordeiro DV, Lima VC, Castro DP, et al. Influence of optic disc size on the diagnostic performance of macular ganglion cell complex and peripapillary retinal nerve fiber layer analyses in glaucoma. *Clin Ophthalmol*. 2011;5:1333–1337.
25. Shoji T, Sato H, Ishida M, et al. Assessment of glaucomatous changes in subjects with high myopia using spectral domain optical coherence tomography. *Invest Ophthalmol Vis Sci*. 2011;52:1098–1102.
26. Sommer A, Pollack I, Maumenee AE. Optic disc parameters and onset of glaucomatous field loss. I. Methods and progressive changes in disc morphology. *Arch Ophthalmol*. 1979;97:1444–1448.
27. Pederson JE, Anderson DR. The mode of progressive disc cupping in ocular hypertension and glaucoma. *Arch Ophthalmol*. 1980;98:490–495.
28. Quigley HA, Katz J, Derick RJ, et al. An evaluation of optic disc and nerve fiber layer examinations in monitoring progression of early glaucoma damage. *Ophthalmology*. 1992;99:19–28.
29. Sommer A, Miller NR, Pollack I, et al. The nerve fiber layer in the diagnosis of glaucoma. *Arch Ophthalmol*. 1977;95:2149–2156.
30. Sommer A, Katz J, Quigley HA, et al. Clinically detectable nerve fiber atrophy precedes the onset of glaucomatous field loss. *Arch Ophthalmol*. 1991;109:77–83.
31. Sommer A, Quigley HA, Robin AL, et al. Evaluation of nerve fiber layer assessment. *Arch Ophthalmol*. 1984;102:1766–1771.
32. Tan O, Li G, Lu AT, et al. Mapping of macular substructures with optical coherence tomography for glaucoma diagnosis. *Ophthalmology*. 2008;115:949–956.
33. Mwanza JC, Oakley JD, Budenz DL, et al. Macular ganglion cell-inner plexiform layer: automated detection and thickness reproducibility with spectral domain-optical coherence tomography in glaucoma. *Invest Ophthalmol Vis Sci*. 2011;52:8323–8329.
34. Mori S, Hangai M, Sakamoto A, et al. Spectral-domain optical coherence tomography measurement of macular volume for diagnosing glaucoma. *J Glaucoma*. 2010;19:528–534.
35. Walji MF, Kalenderian E, Tran D, et al. Detection and characterization of usability problems in structured data entry interfaces in dentistry. *Int J Med Inform*. 2013;82:128–138.
36. Takagi ST, Kita Y, Yagi F, et al. Macular retinal ganglion cell complex damage in the apparently normal visual field of glaucomatous eyes with hemifield defects. *J Glaucoma*. 2012;21:318–325.
37. Kim NR, Lee ES, Seong GJ, et al. Structure-function relationship and diagnostic value of macular ganglion cell complex measurement using Fourier-domain OCT in glaucoma. *Invest Ophthalmol Vis Sci*. 2010;51:4646–4651.
38. Seong M, Sung KR, Choi EH, et al. Macular and peripapillary retinal nerve fiber layer measurements by spectral domain optical coherence tomography in normal-tension glaucoma. *Invest Ophthalmol Vis Sci*. 2010;51:1446–1452.
39. Mwanza JC, Durbin MK, Budenz DL, et al. Glaucoma diagnostic accuracy of ganglion cell-inner plexiform layer thickness: comparison with

nerve fiber layer and optic nerve head. *Ophthalmology*. 2012;119:1151–1158.
40. Kotowski J, Folio LS, Wollstein G, et al. Glaucoma discrimination of segmented cirrus spectral domain optical coherence tomography (SD-OCT) macular scans. *Br J Ophthalmol*. 2012; 96:1420–1425.
41. Matsuura M, Hirasawa K, Murata H, et al. The relationship between visual acuity and the reproducibility of visual field measurements in glaucoma patients. *Invest Ophthalmol Vis Sci*. 2015;56: 5630–5635.
42. Wall M, Doyle CK, Eden T, et al. Size threshold perimetry performs as well as conventional automated perimetry with stimulus sizes III, V, and VI for glaucomatous loss. *Invest Ophthalmol Vis Sci*. 2013;54:3975–3983.
43. Bengtsson B, Heijl A. False-negative responses in glaucoma perimetry: indicators of patient performance or test reliability? *Invest Ophthalmol Vis Sci*. 2000;41:2201–2204.
44. Garway-Heath DF, Poinoosawmy D, Fitzke FW, et al. Mapping the visual field to the optic disc in normal tension glaucoma eyes. *Ophthalmology*. 2000;107:1809–1815.
45. Garway-Heath DF, Caprioli J, Fitzke FW, et al. Scaling the hill of vision: the physiological relationship between light sensitivity and ganglion cell numbers. *Invest Ophthalmol Vis Sci*. 2000; 41:1774–1782.
46. Ricco A. Relazione fra il minimo angolo visuale e l'intensita' luminosa. Memorie della Regia Academia di Scienze. *lettere ed arti in Modena*. 1877; 17:47–60.
47. Redmond T, Zlatkova MB, Garway-Heath DF, et al. The effect of age on the area of complete spatial summation for chromatic and achromatic stimuli. *Invest Ophthalmol Vis Sci*. 2010;51:6533–6539.
48. Redmond T, Garway-Heath DF, Zlatkova MB, et al. Sensitivity loss in early glaucoma can be mapped to an enlargement of the area of complete spatial summation. *Invest Ophthalmol Vis Sci*. 2010;51:6540–6548.
49. Piper H. Ü ber die Abhängigkeit des Reizwertes leuchtender Objekte von ihre Flachen-bezw. Winkelgrasse. *Zeitschrift fur Psychologie und Physiologie der Sinnesorgane*. 1903;32:98–112.
50. Kleitman N, Pieron H. Contribution a' l'e'tude des facteurs re'gissant le taux de summation des impressions lumineuses de surface ine'gale. *L'anne'e psychologiqu*. 1928;29:57–91.
51. Tolhurst DJ, Movshon JA, Dean AF. The statistical reliability of signals in single neurons in cat and monkey visual cortex. *Vision Res*. 1983; 23:775–785.
52. Araie M, Arai M, Koseki N, et al. Influence of myopic refraction on visual field defects in normal tension and primary open angle glaucoma. *Jpn J Ophthalmol*. 1995;39:60–64.
53. Mayama C, Suzuki Y, Araie M, et al. Myopia and advanced-stage open-angle glaucoma. *Ophthalmology*. 2002;109:2072–2077.
54. Park HY, Lee K, Park CK. Optic disc torsion direction predicts the location of glaucomatous damage in normal-tension glaucoma patients with myopia. *Ophthalmology*. 2012;119:1844–1851.
55. Jonas JB, Gusek GC, Naumann GO. Optic disk morphometry in high myopia. *Graefes Arch Clin Exp Ophthalmol*. 1988;226:587–590.
56. Yamashita T, Sakamoto T, Yoshihara N, et al. Peripapillary nerve fiber elevation in young healthy eyes. *Invest Ophthalmol Vis Sci*. 2016;57: 4368–4372.