EXTENDED REPORT

Prediction of future scotoma on conventional automated static perimetry using frequency doubling technology perimetry

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Aim: To see if scotoma detected with frequency doubling technology (FDT) is confirmed by Humphrey field analyser (HFA) 3 years later.

Methods: Subjects were first examined with the screening C-20-1 program of FDT. The visual field was examined annually for 4 years using HFA program C30-2. The central 58 test points in HFA were assigned to one of the 17 clusters corresponding to FDT test points. Each cluster was represented as the lowest probability symbol of total deviation (TD) of the HFA test points included in the cluster. Clusters were graded normal, suspected scotoma, and scotoma depending on probability of TD—5% or more, 5%–1%, less than 1%, respectively. Relative risk (RR) of abnormality on FDT for future scotoma on HFA was estimated.

Results: 80 eyes of 42 patients were followed up for 4 years. While 4.0% of normal clusters of HFA with normal FDT results developed into scotoma cluster, 20.8% of normal clusters with abnormal FDT results developed into scotoma cluster with HFA at the third year. RR for future scotoma was 5.24 (95% CI, 2.75 to 10.0, $p < 0.05$).

Conclusion: An abnormal result in FDT shows a high risk of future scotoma on HFA after 3 years even if the original HFA perimetry showed normal results.

Small retinal “P” ganglion cells that project to the parvocellular layers of the lateral geniculate body convey information on colour, high spatial frequency, and pattern discrimination, while larger “M” cells that project to the magnocellular layer deal with motion detection, low spatial frequency, and high temporal frequency.¹ Large ganglion cells have large axons, and vice versa. “M” optic nerve fibres are selectively lost in chronic experimental and human glaucoma.^{2–4} Therefore, tests operating on the M cell pathway—that is, flicker perimetry and motion detection tests, were thought to have advantages for the detection of early glaucoma.^{5–6} In recent reports, however, non-selective ganglion cell loss in glaucomatous eyes was reported, and tests operating on the P cell pathway—that is, colour perimetry^{7–10} and high pass resolution perimetry,^{11–12} were able to reveal early glaucomatous visual field loss. Whether glaucoma damage is selective to specific cells or not, these function selective tests were thought to have an advantage for the detection of early glaucoma as a result of the reduced redundancy of ganglion cells.¹³

When a low spatial frequency sinusoidal grating undergoes high temporal frequency counterphase flicker, its perceived spatial frequency is twice its actual spatial frequency.¹⁴ This phenomenon is called frequency doubling illusion.

Frequency doubling technology (FDT) perimetry^{15–16} was designed to exploit this illusion by measuring thresholds of the M cell pathway across the visual field.

Many cross sectional studies have demonstrated that the glaucomatous field damage is inclined to appear earlier in FDT than in conventional perimetry.^{11–12, 17–34} It has not been demonstrated, however, whether perimetric points showing abnormal results in FDT are associated with decreased sensitivity in conventional perimetry in a follow up study. This is the aim of this study and the result confirms that FDT scotomas are associated with HFA scotomas that appear 3 years later.

MATERIALS AND METHODS

Patients

This prospective cohort study included 64 consecutive Japanese patients, 126 eyes with primary open angle glaucoma (POAG) or suspected glaucoma. The patients visited our clinic between February 1999 and November 1999.

The eyes with ocular hypertension (OH) or suspected normal tension glaucoma (NTG) were included in the study because they might have had glaucoma damage which cannot be detected using Humphrey field analyser (HFA) but might be detected with FDT. Definition of POAG is open anterior chamber angle, intraocular pressure (IOP) of 22 mm Hg or more, glaucomatous optic nerve head and/or retinal nerve fibre layer defects (RNFLD), and visual field defects corresponding to optic disc damage. The difference between NTG and POAG is that NTG has a peak IOP below 21 mm Hg. Suspected NTG eyes had a vertical cup-disc ratio of >0.8 , or a radial nerve fibre layer defect with normal HFA. OH eyes have 22 mm Hg or more IOP, normal optic disc, and normal HFA. Optic disc and RNFLD were examined using colour stereo photographs.

The inclusion criteria were eyes with POAG, OH, NTG, or suspected NTG, which had already been tested twice or more with the HFA program C-30-2, within the last 3 months, with false positive errors and false negative errors of 33% or less and a pupil diameter is 2.5 mm or larger (eyes with small pupils were not included because the influence of small pupil on FDT is significant).¹⁵

The exclusion criteria were any other ocular disease which affects visual field, cataract or other ocular disease causing a

Abbreviations: FDT, frequency doubling technology; HFA, Humphrey field analyser; IOP, intraocular pressure; NTG, normal tension glaucoma; OH, ocular hypertension; POAG, primary open angle glaucoma; RNFLD, retinal nerve fibre layer defects; RR, relative risk; TD, total deviation

loss of two or more lines in the Snellen chart, or cataract surgery during the study period.

The study followed the tenets of the Declaration of Helsinki for research involving human subjects, and was approved by our institutional review board/ethics committee, with all subjects giving informed consent before participation. Treatment of glaucoma and investigation of this study were performed by different doctors, and inclusion in this study did not influence the decision for surgery.

Device

The frequency doubling perimetry (frequency doubling technology; FDT, Welch Allyn Co, USA) screening program C-20-1 was carried out in all subjects after a practice demonstration. Myopic eyes with refraction of -7 dioptres or less were tested with their own glasses in accordance with the recommendations in the manufacturer's manual.

The Humphrey field analyser (HFA) program C-30-2 was carried out in all subjects with correcting lens. The visual field was examined annually for 4 years using HFA program C-30-2. The SITA version of HFA was not used in this study. The changes in visual field defects were determined by results of baseline HFA and HFA after 3 years. We investigated if the initial FDT would predict future scotoma found with HFA.

Methods of comparison

The FDT program C-20-1 gives four values at each of 17 test points in the field. These values (normal, mild, moderate, and severe loss) are defined as follows:

- **Normal:** All recorded sensitivities are equal to or better than the 1% probability level of age corrected normals.
- **Mild loss:** The 1% probability level stimulus was missed twice, but a higher contrast level target (0.5% probability level) was seen.

- **Moderate loss:** The 0.5% probability level target was not seen, but a maximum (100%) contrast target was seen.
- **Severe loss:** None of the targets were seen.

Our definition of an abnormal FDT test point is the point of mild loss or greater abnormal results (1% or less probability level).

Fifty eight of the 76 stimulus locations of the HFA central 30-2 program were divided into 17 clusters to correspond to the field sites examined by FDT. Stimulus points of FDT and the cluster of HFA are shown in figure 1.

The total deviation (TD) of the HFA was used to define abnormality in this test. The probability that the TD is normal is classified as 0.5%, 1%, 2%, 5%, and normal. The point within a cluster that had the lowest probability of being normal was used to define the abnormality of the whole cluster.

These clusters were graded into three degrees—normal, suspected scotoma, and scotoma, depending on probability of TD over 5%, 5%–1%, and less than 1%, respectively. After the 4 year examination, scotoma clusters in the third year were confirmed with HFA results in the fourth year. Only clusters that had third and fourth year scotoma results were defined as scotoma.

In this version of FDT, the right eye is always examined before the left eye. We confirmed the difference between right eye and left eye on FDT and HFA at baseline measurement.

We determined which HFA clusters become scotomatous after the 3 year period, and calculated the relative risk (RR) of the abnormal FDT point for future abnormal HFA clusters. If the RR is greater than 1.0, an abnormal FDT result indicates the likelihood of a future scotoma on HFA—that is, FDT detects glaucoma changes earlier than HFA does.

The 17 FDT test points were divided into three areas—within the central 10 degrees (C10), 20 degrees in upper field

Figure 1 Test locations of Humphrey field analyser (HFA) program C-30-2 and frequency doubling technology (FDT) program C-20-1. The same location numbers (1–17) of FDT (bottom) and HFA (top) were compared. The 17 test points of FDT were divided into three areas, within the central 10 degrees (C10), 20 degrees in upper field (20UF), and 20 degrees in lower field (20LF). The sensitivities of FDT were compared among these areas.

Table 1 Results of HFA and FDT at the baseline measurement

		FDT		
		Normal ($p > 1\%$) Total eyes right eye/left eye	Abnormal ($p < 1\%$) Total eyes right eye/left eye	Total Total eyes right eye/left eye
HFA	Normal ($p \geq 5\%$)	657 (63.7%)	53 (16.2%)	710 (52.2%)
		364 (60.0%)/243 (48.9%)	30 (20.7%)/23 (12.6%)	394 (55.7%)/316 (46.5%)
	Suspect ($5\% > p \geq 1\%$)	167 (16.2%)	59 (18.0%)	226 (16.6%)
		75 (14.0%)/92 (18.5%)	31 (21.4%)/28 (15.3%)	106 (15.6%)/120 (17.6%)
	Scotoma ($1\% > p$)	208 (20.2%)	216 (66.9%)	424 (31.2%)
Total		96 (17.9%)/112 (22.5%)	84 (57.9%)/132 (72.1%)	180 (26.5%)/244 (35.9%)
		1032 (100%)	328 (100%)	1360 (100%)
		535 (100%)/497 (100%)	145 (100%)/183 (100%)	680 (100%)/680 (100%)

FDT, frequency doubling technology perimeter; HFA, Humphrey field analyser.
Each test point/cluster was graded depends on the probability level of total deviation.

(20UF), and 20 degrees in lower field (20LF) to confirm if there is a difference in predictive ability among these areas (fig 1).

Statistical analysis including RR and Fisher's exact test was performed using Stat software Mate III (ATMS, Tokyo, Japan).

RESULTS

In all, 126 eyes of 64 consecutive patients were selected according to the inclusion and exclusion criteria. During the course of the trial 46 eyes were excluded, six because of ocular disease, 32 eyes of 16 patients because of changing hospitals, and the remaining eight eyes of six patients were excluded because of cataract surgery.

Eighty eyes of 42 patients were followed up for 4 years, and 1360 test points of 80 eyes were analysed. Breakdowns of glaucoma types were as follows: 29 eyes with NTG, eight eyes with suspected NTG, 35 eyes with POAG and eight eyes with OH (tables 1, 2).

Analysis of baseline examinations

The mean age of the subjects was 56.9 (13.0) years (range 28–76 years old). The median visual acuity of the subjects was 24/20 (range 20/200–30/20). The mean deviation (MD) of HFA was -5.46 (6.33) dB (range -21.33 – 2.69 dB). The corrected pattern standard deviation (CPSD) was 5.37 (4.95) dB (range 0–15.9 dB). Test time for the C-20-1 screening program was 80.3 (35.8) seconds (range 38–144 seconds).

The breakdown of FDT and HFA results is shown in table 1.

In the initial comparison, there were 424 clusters of scotoma on HFA, while there were 328 abnormal FDT points. HFA detected more abnormal points than FDT.

The ratios of abnormal points at each location on HFA/FDT are shown in figure 2. The FDT had infrequent abnormal points within the central 10 degrees, while HFA had frequent abnormal points in this area. The results in the right eye were very similar to the results in the left eye.

Analysis of visual field changes after 3 years

During the 4 years of observation, the thresholds of all the subgroups of patients rose. However, the probability of developing a scotoma was not the same for all subgroups. Thus, there were initially 657 normal clusters with normal HFA and FDT results. Twenty six of these clusters developed a scotoma on HFA testing at the end of the project (4.0%). There were 53 clusters with normal HFA and abnormal FDT thresholds at the beginning of the observation. Three years later, 11 of the 53 had abnormal HFA (20.8 %). Thus, the relative risk (RR see methods) of developing a scotoma when there was an abnormal FDT is increased to 5.24 (95% CI, 2.75 to 10.0, $p < 0.05$) (fig 3).

The developed scotoma clusters were confirmed with the fourth year HFA results. If the fourth year result was a suspected scotoma, then the third year result was defined as a "suspected" scotoma even if the third year result was a scotoma. Twenty three of 53 (43%) clusters with normal HFA and abnormal FDT developed to suspected scotoma or scotoma cluster. In this study, however, only scotoma results in both years were included in the calculation of RR.

Analysis on test locations

Our results show that the predictive value of the FDT test is dependent upon the retinal site tested. Within the central 10 degrees, FDT rarely shows an abnormality, and the

Table 2 Comparison between high tension glaucoma and normal tension glaucoma

	HTG (n = 41)		NTG (n = 39)	
Age at baseline (mean (SD) years)	57.3 (13.6)		56.5 (12.2)	
MD at baseline (mean (SD) dB)	-6.05 (6.75)		-4.85 (5.64)	
MD at 3rd year (mean (SD) dB)	-6.51 (5.98)		-4.77 (5.42)	
CPSD at baseline (mean (SD) dB)	5.61 (5.19)		5.12 (4.54)	
CPSD at 3rd year (mean (SD) dB)	6.79 (5.06)		6.08 (4.48)	
Number of HFA clusters or FDT points	697		663	
HFA cluster at baseline (normal/suspected scotoma/scotoma)	(339/120/238)		(371/106/186)	
FDT results at baseline (normal/abnormal)	(494/203)		(538/125)	
Normal HFA clusters at baseline	339		371	
	Normal FDT	Abnormal FDT	Normal FDT	Abnormal FDT
FDT results at baseline	303	36	354	17
Converted HFA cluster at 3rd year*	14 (4.6%)	9 (25%)	12 (3.4%)	2 (11.8%)

FDT, frequency doubling technology perimeter; HFA, Humphrey field analyser; HTG, high tension glaucoma (including primary open angle glaucoma and ocular high tension eyes.) NTG, normal tension glaucoma; MD, mean deviation; CPSD, corrected pattern standard deviation.

*A cluster that is normal at baseline measurement and scotoma cluster at 3rd and 4th years.

Figure 2 Abnormal ratio of each test location in HFA and FDT at baseline measurement. The total for the 80 eyes (40 right eyes and 40 left eyes), with a ratio of abnormal clusters, 1% or less probability level, was shown by a grey scale on each test location for FDT (bottom), and HFA (top).

statistical analysis of whether FDT is predictive of later HFA defects is therefore not significant (fig 2). However, this subgroup analysis was limited by the small number of subjects that showed abnormal FDT.

The abnormalities of FDT were more common in the 10–20 degree area from the fovea than in the central 10 degree area (fig 2). In the 20 degree upper field, only five of 225 (2.2%) normal clusters of HFA with normal FDT results developed into a scotoma cluster. However, five of 22 (22.7%) normal clusters with abnormal FDT results developed into scotoma clusters with HFA after 3 years (fig 4). The results for the lower field were similar to the upper field. RR for future scotoma at the 20 degree upper field, and the 20 degree lower field was 10.2 (95% CI, 3.2 to 32.6, $p < 0.05$) and 4.67 (95% CI, 2.0 to 10.8, $p < 0.05$), respectively.

DISCUSSION

We did not choose the FDT threshold program but used the FDT screening program in this study. There are three reasons

for this. In clinical FDT use, the screening program is more popular than the threshold program because of a shorter test time. In clinical decision about scotoma, we usually use probability symbols in the results rather than dB values. The results of the screening program have a four graded assessment of sensitivity, which is close to the threshold program five graded probability symbol. The results of the screening program are very similar to the threshold program, and it appears sensitive enough for clinical purposes.

In the present study, at normal baseline HFA test points, having FDT abnormalities gives a 5.24-fold greater risk for developing scotoma than points with normal FDT.

Although many investigators in cross sectional studies have reported frequent FDT abnormalities in high risk eyes,^{11 17 18 21 33} there were only two longitudinal studies, one of which reported 74.1% of abnormal FDT before the progression HFA,³⁵ and one reported that 10 out of 17 eyes had abnormal FDT earlier than abnormal HFA.³⁶ Although these reports showed high sensitivity for FDT, careful investigation was needed because these studies included cases where the location of scotoma on FDT and HFA did not agree. The present study, however, clearly shows the risk of abnormal FDT for future scotoma at the same test location, and supports these previous reports.

While we showed abnormal FDT is correlated with future scotoma on conventional perimetry, the present study does not indicate that the FDT perimeter always detects glaucoma earlier than a conventional perimeter.

The results of baseline measurement shows HFA has more frequent abnormal clusters than FDT. It may be caused by cluster analysis of this study. Generally, a larger number of test points has a higher chance of abnormal result because of fluctuation in results. In this study, a single cluster has three or four HFA test points. To reduce the false positive error, we confirm the scotoma on HFA with the next year's result.

In some locations, however, FDT detects glaucoma changes earlier than HFA does. In figure 4, we demonstrate that HFA has higher sensitivity in the central 10 degrees while FDT has higher sensitivity in the area of 20 degrees. The reason could

Figure 3 Proportion of HFA results 3 years later. For all locations with normal HFA at baseline, the proportion of HFA results 3 years later was compared with the locations with normal FDT results and abnormal FDT results. A location with abnormal FDT had more scotomas on HFA 3 years later than a location with normal FDT.

Figure 4 The proportion of HFA results 3 years later depends on test locations. Regarding the normal HFA point at baseline, the proportion of HFA results 3 years later were compared with the locations of normal FDT results and abnormal FDT results, depending on 20 degrees in the upper field (A), 20 degrees in the lower field (B), and within the central 10 degrees (C). Abnormal FDT has a 10-fold greater risk for developing scotoma on HFA after 3 years in the 20 degree area in the upper field.

be either that near the fovea the scotoma is sometimes too small and steep to be detected by the relatively large FDT stimulus, or that the stimulus spot of FDT falls on the horizontal meridian, and only the upper or lower arcuate fibres are damaged, so it fails to detect the scotoma. When the FDT tests the foveal/central macular region this is bound to occur and, therefore, this location is worthless for glaucoma detection. To increase the sensitivity at the central area, a smaller stimulus size would be appropriate.³⁷ The newest version of FDT perimeter "Matrix" (Welch Allyn Co, USA) is a promising perimeter because it has a smaller stimulus.

It was reported that FDT is more sensitive for HTG than NTG.^{17, 38} NTG is prevalent in Japanese people. The current study analysed 80 eyes including 29 eyes with NTG and eight eyes with suspected NTG. There is a possibility of underestimating the sensitivity of the FDT, because of the large proportion of NTG eyes. Table 2 shows higher sensitivity in HTG eyes. However, this study showed certain sensitivity for NTG eyes in FDT.

In this study we showed the relative risks of decline on HFA using the FDT perimeter. These relative risks are probabilities on single HFA test after 3 years. To investigate the relative risks of true glaucoma progression, we need to confirm progression of glaucoma the visual field with an additional follow up. This study is ongoing, and will be reported in the near future. Here, we investigated the predictability 3 years after HFA using FDT. This report helps clinicians to utilise current HFA results in combination with the FDT perimeter.

In the near future, a combination of ganglion cell function specific perimeters, such as FDT, will give us information about the risk of glaucoma progression. We must investigate how to use these perimeters rather than investigating which is the best.

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REFERENCES

- 1 Sekuler R, Blake R. Central visual pathways. In: Sekuler R, eds. *Perception*. Singapore: McGraw-Hill, 1994:102-79.
- 2 Chaturvedi N, Hedley-Whyte ET, Dreyer EB. Lateral geniculate nucleus in glaucoma. *Am J Ophthalmol* 1993;116:182-8.
- 3 Dandona L, Hendrichson A, Quigley HA. Selective effects of experimental glaucoma on axonal transport by retinal geniculate nucleus. *Invest Ophthalmol Vis Sci* 1991;32:1593-9.
- 4 Glavinsky Y, Quigley HA, Dunkelberger GR. Retinal ganglion cell loss is size dependent in experimental glaucoma. *Invest Ophthalmol Vis Sci* 1991;32:484-91.
- 5 Anderson RS, O'Brien C. Psychophysical evidence for a selective loss of M ganglion cells in glaucoma. *Vis Res* 1997;37:1079-83.
- 6 Johnson CA. Early losses of visual function in glaucoma. *Optom Vis Sci* 1995;72:359-70.
- 7 Johnson CA, Adams AJ, Casson EJ, et al. Blue-on-yellow perimetry can predict the development of glaucomatous visual field loss. *Arch Ophthalmol* 1993;111:645-50.
- 8 Johnson CA, Adams AJ, Casson EJ, et al. Progression of early glaucomatous visual field loss as detected by blue-on-yellow and standard white-on-white automated perimetry. *Arch Ophthalmol* 1993;111:651-6.
- 9 Falcao-Reis F, O'Donoghue E, Bucetti R, et al. Peripheral contrast sensitivity in glaucoma and ocular hypertension. *Br J Ophthalmol* 1990;74:712-16.
- 10 Kogure S, Chiba T, Saito S, et al. Predicting glaucomatous sensitivity loss using perimetric color saturation test. *Jpn J Ophthalmol* 2003;47:537-42.
- 11 Iester M, Altieri M, Vittone P, et al. Detection of glaucomatous visual field defect by nonconventional perimetry. *Am J Ophthalmol* 2003;135:35-9.
- 12 Kalaboukhova L, Lindblom B. Frequency doubling technology and high-pass resolution perimetry in glaucoma and ocular hypertension. *Acta Ophthalmol Scand* 2003;81:247-52.
- 13 Johnson CA. Selective versus nonselective losses in glaucoma. *J Glaucoma* 1994;3:s32-s44.
- 14 Kelly DH. Frequency doubling in visual responses. *J Opt Soc Am A* [A] 1966;56:1628-33.
- 15 Kogure S, Membrey WL, Fitzke FW, et al. Effect of decreased retinal illumination on frequency doubling technology. *Jpn J Ophthalmol* 2000;44:489-93.
- 16 Johnson CA, Samuels SJ. Screening for glaucomatous visual field loss with frequency-doubling perimetry. *Invest Ophthalmol Vis Sci* 1997;38:413-25.
- 17 Kogure S, Toda Y, Crabb D, et al. Agreement between frequency doubling perimetry and static perimetry in eyes with high tension glaucoma and normal tension glaucoma. *Br J Ophthalmol* 2003;87:604-8.
- 18 Landers JA, Goldberg I, Graham SL. Detection of early visual field loss in glaucoma using frequency-doubling perimetry and short-wavelength automated perimetry. *Arch Ophthalmol* 2003;121:1705-10.
- 19 Bayer AU, Maag KP, Erb C. Detection of optic neuropathy in glaucomatous eyes with normal standard visual fields using a test battery of short-wavelength automated perimetry and pattern electroretinography. *Ophthalmology* 2002;109:1350-61.
- 20 Horn FK, Wakili N, Junemann AM, et al. Testing for glaucoma with frequency-doubling perimetry in normals, ocular hypertensives, and glaucoma patients. *Graefes Arch Clin Exp Ophthalmol* 2002;240:658-65.

- 21 **Landers JA**, Goldberg I, Graham SL. Comparison of clinical optic disc assessment with tests of early visual field loss. *Clin Experiment Ophthalmol* 2002;**30**:338–42.
- 22 **Soliman MA**, de Jong LA, Ismaeil AA, *et al*. Standard achromatic perimetry, short wavelength automated perimetry, and frequency doubling technology for detection of glaucoma damage. *Ophthalmology* 2002;**109**:444–54.
- 23 **Wadood AC**, Azuara-Blanco A, Aspinall P, *et al*. Sensitivity and specificity of frequency-doubling technology, tendency-oriented perimetry, and Humphrey Swedish interactive threshold algorithm-fast perimetry in a glaucoma practice. *Am J Ophthalmol* 2002;**133**:327–32.
- 24 **Bowd C**, Zangwill LM, Berry CC, *et al*. Detecting early glaucoma by assessment of retinal nerve fiber layer thickness and visual function. *Invest Ophthalmol Vis Sci* 2001;**42**:1993–2003.
- 25 **Paczka JA**, Friedman DS, Quigley HA, *et al*. Diagnostic capabilities of frequency-doubling technology, scanning laser polarimetry, and nerve fiber layer photographs to distinguish glaucomatous damage. *Am J Ophthalmol* 2001;**131**:188–97.
- 26 **Serguyn S**, Spiegel D. Comparison of frequency doubling perimetry and standard achromatic computerized perimetry in patients with glaucoma. *Graefes Arch Clin Exp Ophthalmol* 2001;**239**:351–5.
- 27 **Wu LL**, Suzuki Y, Kunimatsu S, *et al*. Frequency doubling technology and confocal scanning ophthalmoscopic optic disc analysis in open-angle glaucoma with hemifield defects. *J Glaucoma* 2001;**10**:256–60.
- 28 **Yamashiro H**, Tanaka M, Saito M, *et al*. [The ability of frequency doubling technology to detect abnormality of visual function in early glaucoma]. [Japanese]. *Nippon Ganka Gakkai Zasshi* 2001;**105**:488–93.
- 29 **Cello KE**, Nelson-Quigg JM, Johnson CA. Frequency doubling technology perimetry for detection of glaucomatous visual field loss. *Am J Ophthalmol* 2000;**129**:314–22.
- 30 **Fabre K**, Michiels I, Zeyen T. The sensitivity and specificity of TOP, FDP and GDX in screening for early glaucoma. *Bull Soc Belge Ophthalmol* 2000;**275**:17–23.
- 31 **Landers J**, Goldberg I, Graham S. A comparison of short wavelength automated perimetry with frequency doubling perimetry for the early detection of visual field loss in ocular hypertension. *Clin Experiment Ophthalmol* 2000;**28**:248–52.
- 32 **Sample PA**, Bosworth CF, Blumenthal EZ, *et al*. Visual function-specific perimetry for indirect comparison of different ganglion cell populations in glaucoma. *Invest Ophthalmol Vis Sci* 2000;**41**:1783–90.
- 33 **Kondo Y**, Yamamoto T, Sato Y, *et al*. A frequency-doubling perimetric study in normal-tension glaucoma with hemifield defect. *J Glaucoma* 1998;**7**:261–5.
- 34 **Quigley HA**. Identification of glaucoma-related visual field abnormality with the screening protocol of frequency doubling technology. *Am J Ophthalmol* 1998;**125**:819–29.
- 35 **Bayer AU**, Erb C. Short wavelength automated perimetry, frequency doubling technology perimetry, and pattern electroretinography for prediction of progressive glaucomatous standard visual field defects. *Ophthalmology* 2002;**109**:1009–17.
- 36 **Medeiros FA**, Sample PA, Weinreb RN. Frequency doubling technology perimetry abnormalities as predictors of glaucomatous visual field loss. *Am J Ophthalmol* 2004;**138**:663–71.
- 37 **Johnson CA**, Cioffi GA, Van Buskirk EM. Frequency doubling technology perimetry using a 24-2 stimulus presentation pattern. *Optom Vis Sci* 1999;**76**:571–81.
- 38 **Horikoshi N**, Osako M, Tamura Y, *et al*. Comparison of detectability of visual field abnormality by frequency doubling technology in primary open-angle glaucoma and normal-tension glaucoma. *Jpn J Ophthalmol* 2001;**45**:503–9.