Retinal nerve fibre layer and visual function loss in glaucoma: the tipping point

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Retinal nerve fibre layer and visual function loss in glaucoma: the tipping point

Gadi Wollstein,1 Larry Kagemann,1,2 Richard A Bilonick,1 Hiroshi Ishikawa,1,2 Lindsey S Folio,1 Michelle L Gabriele,1,2 Allison K Ungar,1 Jay S Duker,3 James G Fujimoto,4 Joel S Schuman1,2,5

ABSTRACT

Aims To determine the retinal nerve fibre layer (RNFL) thickness at which visual field (VF) damage becomes detectable and associated with structural loss.

Methods In a prospective cross-sectional study, 72 healthy and 40 glaucoma subjects (one eye per subject) recruited from an academic institution had VF examinations and spectral domain optical coherence tomography (SD-OCT) optic disc cube scans (Humphrey field analyser and Cirrus HD-OCT, respectively). Comparison of global mean and sectoral RNFL thicknesses with VF threshold values showed a plateau of threshold values at high RNFL thicknesses and a sharp decrease at lower RNFL thicknesses. A ‘broken stick’ model was fitted to global and sectoral data to estimate the RNFL thickness ‘tipping point’ where the VF threshold values become associated with the structural measurements. The slope for the association between structure and function was computed for data above and below the tipping point.

Results The mean RNFL thickness threshold for VF loss was 75.3 μm (95% CI: 68.9 to 81.8), reflecting a 17.3% RNFL thickness loss from age-matched normative value. Above the tipping point, the slope for RNFL thickness and threshold value was 0.03 dB/μm (CI: −0.02 to 0.08) and below the tipping point, it was 0.28 dB/μm (CI: 0.18 to 0.38); the difference between the slopes was statistically significant (p<0.001). A similar pattern was observed for quadrant and clock-hour analysis.

Conclusions Substantial structural loss (~17%) appears to be necessary for functional loss to be detectable using the current testing methods.

The structural and functional relationship in glaucoma has been extensively studied, but the point at which the clinical functional loss as measured by visual fields (VFs) becomes detectable and related to structural changes is unknown. Fundus photography demonstrated the occurrence of retinal nerve fibre layer (RNFL) defects before measurable VF defects.1 Longitudinal observations revealed that RNFL thinning was associated with future VF damage.2 3 Detection of structural changes that precede the loss of visual function could be used to improve disease management and preserve vision.

Precise measurements of RNFL thickness are possible with optical coherence tomography (OCT).4 5 Previous studies proposed models to relate RNFL thickness and functional assessment, but none of them identified the threshold where functional changes can be expected to be detected clinically.7 8 Our hypothesis is that there is an RNFL thickness threshold at which VF loss becomes clinically observable, where for values above the threshold there will be little correspondence between OCT measured structure and VF measured function, and in values below the threshold there will be a strong association between RNFL thickness and VF. The purpose of this study is to determine the RNFL thickness at which VF damage becomes detectable and associated with structural loss.

METHODS

Subjects were consecutively enrolled from the Pittsburgh Imaging Technology Trial, a prospective longitudinal study designed to assess ocular structure over time carried out at the University of Pittsburgh Eye Center. The study followed the principles of the Declaration of Helsinki and was performed in accordance with the Health Insurance Portability and Accountability Act. Institutional review board and ethics committee approval was obtained, and all participants gave their informed consent to be enrolled.

Subjects were included if they were either healthy volunteers or open-angle glaucoma subjects of age 18 years or older. Subjects were excluded if any of the following was present: history of diabetes mellitus or any other systemic disease or medical treatment that might affect VF or retinal thickness, history of intraocular surgery except for uncomplicated cataract extraction at least a year prior to enrolment, best corrected visual acuity worse than 20/40, refractive error outside −12.00 to +8.00 dioptres and any ocular abnormality other than glaucoma. One eye of each subject was randomly selected. In unilateral glaucoma cases, the affected eye was selected.

In order to prevent selection bias in a study that evaluates the relationship between structure and function, the diagnostic definition of all subjects was based solely on VF findings without consideration of structural appearance. Healthy subjects had a normal VF examination in both eyes. Glaucoma subjects had typical and reproducible glaucomatous scotomas. Subjects who were clinically suspected of having glaucoma due to optic nerve head or RNFL appearance or because of elevated intraocular pressure but with normal VFs were included in the healthy group to ensure representation of the full spectrum of disease.

VF testing

Swedish Interactive Thresholding Algorithm standard 24-2 perimetry (Carl Zeiss Meditec, Dublin,
Clinical science

California (CZM)) was performed in all subjects. Qualified tests had a false positive of <15% and fixation loss and false negative of <30%. Healthy subjects had a glaucoma hemifield test (GHT) within normal limits and their mean deviation (MD) and pattern SD within 95% of healthy population. Glaucomatous VFs were defined as those with at least one of the following confirmed on two consecutive visits: GHT outside normal limits or pattern standard deviation probability outside the 95% of the healthy population.

VF total deviation values were recorded in all 52 testing points. The individual values were grouped in correspondence with the distribution of the sectors as given by spectral domain optical coherence tomography (SD-OCT). The allocation of the individual threshold points to their group was determined according to Garway-Heath et al distribution map. Total deviation values were unlogged, and the average of all values in each group was log transformed back to the decibel scale. A secondary analysis was performed using the mean of the unlogged total deviation values. MD was also recorded.

SD-OCT

SD-OCT was acquired at the same visit as the clinical examination and VF. Detailed descriptions of the principles of SD-OCT have been published previously. All OCT scans were performed using the Cirrus HD-OCT (CZM). Optic disc 200×200 cube scans were obtained, quantifying a 6x6x2 mm volume. Scan quality scores >7 were acceptable, with no overt eye movement as detected by observing blood vessel discontinuity or distortion in the OCT enface image. Mean, quadrant and clock hour peripapillary RNFL thicknesses were used in the statistical analysis. SD-OCT sectors corresponding to a single VF threshold value (clock hours 2-4 and 10) were removed from the analysis because the reliability of the data might be limited.

Statistical analysis

VF values and OCT data were registered at the right eye orientation. Scatter plot of RNFL thicknesses with threshold values shows a plateau of VF at high RNFL thicknesses and a steep decrease at lower RNFL thicknesses. A ‘broken stick’ nonlinear statistical model was fit to the data to calculate the ‘tipping point’. The estimation is considered to be nonlinear because the tipping point is simultaneously estimated along with the slopes. An initial estimate of the tipping point was determined using Davies’ test, then a segmented regression model with unknown breakpoint was fit to the data using the estimated threshold from Davies’ test as the initial value:

\[ Y_i = \alpha + \beta_1 X + \beta_2 (X - \Psi)_+ + \epsilon_i \]

where \( Y_i \) denotes the threshold for subject \( i \), \( X \) denotes the RNFL thickness for subject \( i \), \( \alpha \) is the intercept, \( \beta_1 \) is the slope for the segment below the threshold \( \Psi \), \( \beta_2 \) is the slope for the segment above the threshold \( \Psi \) and \( \epsilon \) is a random error which is assumed to be statistically independent and normally distributed with mean 0 and SD \( \sigma \). Note that if there is no breakpoint, \( \beta_2 \) will equal zero. Similar analysis was performed in the secondary analysis using the 1/L values.

All analyses were conducted using R Language and Environment for Statistical Computing program (http://www.R-project.org) and the segmented R library. P<0.05 was considered statistically significant.

RESULTS

One hundred twelve subjects were recruited: 72 healthy and 40 glaucoma subjects; 44 men and 68 women. Demographics are summarised in table 1. Scatter plots of RNFL thickness and VF threshold values showed a region where the OCT measured RNFL thickness was unrelated to VF measured visual function followed by a region where the relationship between these parameters was strong (figure 1). Estimates of the statistically optimal tipping points between these regions for average and quadrant RNFL thicknesses are listed in table 2. The global mean and the superior, temporal and inferior quadrants showed tight CI around the deflection point and the location of the tipping point was statistically significant (all p<0.05, Davies’ test). The nasal quadrant showed a wide CI and the tipping point location was not significant (p=0.82). Using population-based normative data of RNFL thickness values at the mean age of the participants in this study (personal communication with Michael V Patella, OD, Carl Zeiss Meditec), the percentage of RNFL loss necessary to reach the tipping point was also calculated for the mean and quadrants (table 2). The tipping point for the mean RNFL measurement occurred after a loss of 17.5% from the expected aged-matched value and approximately 25% loss in the superior and inferior quadrants. The RNFL thickness at the tipping point for the global mean and the inferior quadrant was considered as a borderline measurement based on the comparison with the normative data set criteria set by the manufacturer and outside normal limits for the superior quadrant.

Tipping points for clock hours with percent loss from the mean normative values are summarised in table 2. The percentage of RNFL loss from the mean of age-matched normative thickness was highest for 1:00 (59.9%), while for all other sectors the range was 18.5–29.5%, with the lowest loss in the 9:00 location. The tipping point was located in the borderline zone for 1:00 when compared with the normative values, and for all other locations the tipping point occurred within the normal range.

The slopes for VF threshold as a function of RNFL thickness above and below the tipping points are listed in table 3. The models for the slope estimate did not converge for clock hours 1, 5 and 8, and therefore the slope could not be determined with confidence in these particular locations. The slopes above the tipping point in all tested locations were not different than a zero slope (CI included zero), except for the inferior quadrant and 1:00. The slopes below the tipping point were statistically significantly different than a zero slope except for the nasal quadrant. The slopes below the tipping points were statistically significantly steeper than the slopes above the tipping point for all locations except for the nasal quadrant.

A similar segmented relationship was noted in the secondary analysis using 1/L values (figure 2). The estimated tipping point was 77.0 μm (95% CI: 67.5 to 86.5), with a slope above the tipping point of 0.01 1/(L×μm) (CI: −0.01 to 0.01) and a slope below the tipping point of 0.03 1/(L×μm) (CI: 0.02 to 0.04). The

| Table 1 Demographic characteristics of the healthy and glaucomatous subjects |
|---|---|---|
| | Healthy n=72 | Glaucoma n=40 | p |
| Age (yrs) | 50.0±16.4 | 65.5±10.9 | <0.001† |
| Female/Male | 29/33 | 28/11 | 0.06* |
| VF MD (dB) | −0.21±0.80 | −5.04±4.64 | <0.001† |
| VF PSD (dB) | 1.46±0.25 | 5.98±3.97 | <0.001† |
| OCT mean RNFL (μm) | 90.8±8.6 | 68.8±12.1 | <0.001† |

† Student t test. † Wilcoxon test. VF MD, visual field mean deviation; VF PSD, visual field pattern SD; OCT, optical coherence tomography; RNFL, retinal nerve fiber layer.
Figure 1  Healthy (H) and glaucoma (G) retinal nerve fibre layer (RNFL) thickness in the mean and in quadrants with corresponding visual field threshold values. Spline fit is the grey line; ‘broken stick’ model is the black line.
difference between the slopes was 0.02 1/(L×μm) (CI: 0.01 to 0.03) and statistically significant (p=0.003).

Employing the same approach using VF MD instead of the threshold values identified the tipping point at 76.7 μm (CI: 71.5 to 81.9), with slopes above the tipping point of 0.03 dB/μm (CI:0.03 to 0.06) and below the tipping point of 0.02 dB/μm (CI:0.02 to 0.05), with a statistically significant difference between the slopes.

**DISCUSSION**

In the present study, analysis of ocular structural and functional data by a ‘broken stick’ statistics identifies a tipping point at which the relationship between RNFL thickness and VF threshold values are clearly different. The tipping point allows us to define the RNFL threshold where strong association with VF abnormalities can be expected. This study reveals that substantial structural loss (approximately 17%) appears to be necessary for functional loss to be detectable, using the current testing methods.

Similar to numerous previous studies, we demonstrate that thicker RNFL values are not associated with abnormalities in the VF threshold.7–8 15–19 Moreover, our analysis indicates that in this region (above the tipping point) the slope of VF threshold versus RNFL is not statistically significantly different than zero for global and most sectoral analysis. This can be mostly attributed to the higher variability in VF outcomes than structural outcome in the early stage of glaucoma.7–8 From the clinical perspective, this can be interpreted as an indication that structural evaluation is a more sensitive measure of health at the early stage of glaucoma, as it was suggested previously by histology and disc photography assessment.1–3 Below the tipping point, there is a strong association between structure and function with a rate of change that varies substantially by RNFL location.

```
The tipping point could be detected in all tested locations except for the nasal quadrant. The estimate for the tipping point in the nasal quadrant presented with a wider CI than the other quadrants, reflecting the lack of prominent deflection point between the subpopulation of data. The wide CI in the nasal quadrant may be the result of undersampling (relative to the other quadrants) of the corresponding tissues in the VF. In addition, OCT measurements in the nasal quadrant have the lowest test-retest reproducibility.19 The combined influences of fewer nasal VF data points and lower nasal OCT reproducibility may have masked a tipping point in the nasal quadrant. Additionally, the statistical model did not converge in clock hours 1, 5 and 8; although a tipping point was detected, the accuracy of the actual value is questionable. Because the analysis is based on detection of the optimal deflection point in multi-dimensional plane, it is difficult to discern the reason for the non-convergence.
```

### Table 2 Retinal nerve fibre layer thickness tipping point with corresponding optical coherence tomography normative values.

<table>
<thead>
<tr>
<th>Tipping point</th>
<th>Normative values</th>
<th>Mean 95% CI</th>
<th>Mean BDL cut-off</th>
<th>Outside normal limit cut-off</th>
<th>% Loss for tipping point from mean normative</th>
<th>Davies’ test p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td></td>
<td>75.3 68.9 to 81.8</td>
<td>91.1 77.5 to 69.9</td>
<td>17.3 0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Temporal</td>
<td></td>
<td>51.1 46.6 to 55.6</td>
<td>62.1 46.4 to 42.2</td>
<td>19.0 0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Superior</td>
<td></td>
<td>83.0 76.3 to 89.7</td>
<td>115.0 92.1 to 85.6</td>
<td>27.8 &lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Nasal</td>
<td></td>
<td>70.2 52.7 to 87.7</td>
<td>68.2 51.3 to 43.0</td>
<td>NA 0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td></td>
<td>87.5 73.6 to 101.4</td>
<td>117.9 93.4 to 85.8</td>
<td>25.8 0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>1:00</td>
<td></td>
<td>62.7 53.1 to 72.2</td>
<td>104.4 76.2 to 61.9</td>
<td>39.9 0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>5:00</td>
<td></td>
<td>73.4 66.7 to 80.1</td>
<td>95.5 65.7 to 56.8</td>
<td>23.1 &lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>9:00</td>
<td></td>
<td>97.2 77.2 to 117.3</td>
<td>128.5 88.9 to 74.0</td>
<td>24.4 0.004</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td>94.4 82.3 to 106.5</td>
<td>124.2 89.9 to 71.1</td>
<td>24.0 &lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

All measurements are reported in micrometers. BDL, borderline; NA, non-applicable.

### Table 3 Fitted slopes of retinal nerve fibre layer thickness and visual field threshold above and below the tipping point. All slopes are in decibels per micrometre

<table>
<thead>
<tr>
<th>Slope below tipping point (95% CI)</th>
<th>Slope above tipping point (95% CI)</th>
<th>Difference between slopes (95% CI)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.29 (0.18 to 0.38)</td>
<td>0.03 (−0.02 to 0.08)</td>
<td>0.25 (0.13 to 0.36)</td>
</tr>
<tr>
<td>Temporal</td>
<td>0.39 (0.14 to 0.63)</td>
<td>−0.01 (−0.06 to 0.06)</td>
<td>0.39 (0.13 to 0.64)</td>
</tr>
<tr>
<td>Superior</td>
<td>0.25 (0.16 to 0.34)</td>
<td>0.02 (−0.01 to 0.05)</td>
<td>0.23 (0.14 to 0.33)</td>
</tr>
<tr>
<td>Nasal</td>
<td>0.11 (−0.02 to 0.24)</td>
<td>−0.03 (−0.20 to 0.14)</td>
<td>0.14 (−0.07 to 0.36)</td>
</tr>
<tr>
<td>Inferior</td>
<td>0.16 (0.09 to 0.23)</td>
<td>0.03 (0.01 to 0.06)</td>
<td>0.13 (0.05 to 0.20)</td>
</tr>
<tr>
<td>1:00</td>
<td>0.55 (0.07 to 1.03)</td>
<td>0.04 (0.13 to 0.77)</td>
<td>0.51 (0.02 to 0.99)</td>
</tr>
<tr>
<td>5:00</td>
<td>0.35 (0.20 to 0.49)</td>
<td>0.01 (−0.03 to 0.05)</td>
<td>0.33 (0.18 to 0.48)</td>
</tr>
<tr>
<td>9:00</td>
<td>0.11 (0.06 to 0.15)</td>
<td>0.02 (−0.01 to 0.05)</td>
<td>0.09 (0.03 to 0.14)</td>
</tr>
<tr>
<td>12:00</td>
<td>0.15 (0.06 to 0.23)</td>
<td>0.01 (−0.02 to 0.03)</td>
<td>0.14 (0.05 to 0.22)</td>
</tr>
</tbody>
</table>

Eye movements have a greater impact on sectoral measure-
ment variability than global variability, resulting in lower 
sectoral reproducibility and wider range of the sectoral CIs 
(table 2). This may have contributed to the tipping point being 
outside the normal range for mean, while inferior and superior 
quadrants being within the normal range in the corresponding 
clock hours.

Ageing has been shown to cause gradual thinning of the 
RNFL and reduction in visual sensitivity. In order to account 
for this effect, we use VF total deviation threshold values that 
are age corrected. For RNFL measurements, we use the mean 
age-adjusted normative value, allowing us to identify the 
percentage tissue loss while accounting for the ageing effect. 
The tipping point occurs with a mean RNFL thickness 17% below 
the level that would be expected in the age-matched healthy 
population. In the superior and inferior quadrants and clock 
hours, the tipping point occurs after \(~\~25\%\) loss. The highest 
loss (40%) occurs at the 1:00 location, but as stated above the 
reliability of the analysis in this location is questionable. The 
lowest sectoral percentage loss is at 8:00 and the temporal 
quadrant. This finding might be explained by the high concen-
tration of thinner axons in the papillomacular bundle passing 
through this location. Therefore, in the same RNFL thickness 
as in other locations, the number of axons passing through the 
temporal quadrant is larger, leading to the appearance of VF 
abnormality after a smaller RNFL thickness loss. A ‘floor ef-
fect’, where no further structural damage can be detected while 
functional changes can still occur, was not identified in this 
study, but this could be expected in situations where very 
advanced stages of structural damage exist.

Numerous studies evaluate the relationship between structure 
and function in glaucomatous eyes. Most of the studies 
employ a single model throughout the data, either linear or 
curvilinear. Ajetin et al have speculated that a mean 
RNFL thickness of approximately 70 \(\mu\)m might represent 
a profound threshold value in glaucomatous structure changes.10

In the present study, we utilise a statistical method to accurately 
determine this location that is found to be at 75.3 \(\mu\)m. Identifi-
ying the actual location where VF abnormality is expected to 
occur is of utmost importance in clinical management especially 
for individuals suspected of having glaucoma.

Our secondary analysis shows that with both decibel and 1/L 
units, the tipping point appears approximately at the same 
RNFL thickness, thus confirming the true basis of this range for 
distinguishing between phases of structure and function rela-
tionship. We also performed an analysis using VF MD because 
this parameter is commonly used in clinical practice. The tipping 
point for MD occurs at an RNFL thickness of 77 \(\mu\)m.

The limitations of the study include its cross-sectional nature 
and the population data used. Caution should be used when 
applying these results to individual subjects. A person might 
start with a thicker or thinner RNFL and their actual tipping 
point RNFL thickness value might vary from the one reported 
herein. The study design, however, is appropriate for initial 
testing of the hypothesis.

In conclusion, the ‘broken-stick’ analysis allows the identifi-
cation of a structural and functional tipping point. It appears 
that ‘pre-perimetric’ glaucoma (using current standard auto-
mated perimetry) can be identified by OCT RNFL thickness, 
with the detectable VF loss first appearing with RNFL approxi-
imately 17% below that expected for healthy eyes.


Figure 2 Scatter plot of healthy (H) and glaucoma (G) values using 
unlogged (1/l) visual field threshold values. The grey line is a spline fit, 
and the black line is the two-segment ‘broken stick’ model. RNFL—retinal 
nerve fiber layer, L—Lambert.

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