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Optic Disc Margin Anatomy in Glaucoma Patients and Normal Controls with Spectral Domain Optical Coherence Tomography

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Abstract

Objective—To characterize optic nerve head (ONH) anatomy related to the clinical optic disc margin with spectral domain optical coherence tomography (SD-OCT).

Design—Cross-sectional study.

Participants—Open-angle glaucoma patients with focal, diffuse and sclerotic optic disc damage, and age-matched normal controls.

Methods—High-resolution radial SD-OCT B-scans centered on the ONH were analyzed at each clock hour. For each scan, the border tissue of Elschnig was classified for obliqueness (internally oblique, externally oblique, or non-oblique), and presence of Bruch's membrane overhang over border tissue. Optic disc stereo-photographs were co-localized to SD-OCT data with customized software. The frequency with which the disc margin identified in stereo-photographs coincided with (1) Bruch's membrane opening, defined as the innermost edge of Bruch's membrane; (2) Bruch's membrane/border tissue, defined as any aspect of either, outside Bruch's membrane opening or border tissue; or (3) border tissue, defined as any aspect of border tissue alone, in the B-scans was computed at each clock hour.

Main Outcome Measures—SD-OCT structures coinciding with the disc margin in stereo-photographs.

Results—There were 30 patients (10 with each type of disc damage) and 10 controls, with median (range) age 68.1 (42–86) and 63.5 (42–77) years respectively. Although 28 (93%) patients had 2 or more border tissue configurations, the most predominant one was internally oblique, primarily superiorly and nasally, frequently with Bruch's membrane overhang. Externally oblique border tissue was less frequent, observed mostly inferiorly and temporally. In controls, there was predominantly internally oblique configuration around the disc. While the configurations were not statistically different between patients and controls, they were among the 3 glaucoma groups. At most locations the SD-OCT structure most frequently identified as the disc margin was some

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aspect of Bruch's membrane and border tissue, outside Bruch's membrane opening. Bruch's membrane overhang was regionally present in the majority of glaucoma patients and controls, however, in most cases not visible as the disc margin.

Conclusions—The clinically perceived disc margin is most likely not the SD-OCT detected innermost edge of Bruch's membrane. These findings have important implications for the automated detection of the disc margin and estimates of the neuroretinal rim.

The optic nerve head (ONH) comprises of retinal ganglion cell (RGC) axons, blood vessels, glia and connective tissue. It is thought to be the primary site of damage in glaucoma.^{1–3} The optic disc margin is a clinical construct for structures that encompass the neural tissue within the ONH. Its accurate clinical identification is central to the quantitative estimate of cup-disc ratio as well the foundation of all quantitative assessments of the neuroretinal rim by modern imaging techniques. However, histologically, what the clinician sees as the disc margin has been a source of controversy, with the possibility that structures that most accurately define the outer boundary of the ONH neural tissue are not always visible by clinical examination techniques. Furthermore, assessments of optic disc size vary according to examination technique.^{4, 5}

The border tissue of Elschnig (Fig. 1) is fibrous tissue that rises up from the anterior edge of the sclera to fuse with Bruch's membrane to separate the choroid from RGC axons as they pass through the anterior portion of the neural canal.^{6, 7} Border tissue is highly relevant to the optic disc margin because its anatomy relative to the anterior edge of the sclera determines whether or not it is visible to the clinician and what structure is perceived as the edge of the optic disc. Recent advances in three-dimensional histomorphometric reconstructions of post-mortem tissues^{8, 9} allow a better understanding of optic disc margin anatomy while spectral domain optical coherence tomography (SD-OCT)^{10, 11} permits *in vivo* detection of these structures,^{12, 13} thereby providing an opportunity to determine what the clinician perceives as the disc margin and to what degree SD-OCT detected structures that clearly define the outer border of the neural tissues are clinically visible.

Border tissue anatomy is regionally variable within individual ONHs and can be characterized as internally or externally oblique relative to the underlying sclera.^{14, 13} Internally oblique border tissue extends internal to the anterior scleral opening to fuse with Bruch's membrane such that the underlying sclera is not clinically visible (Fig. 1). Externally oblique border tissue extends external to the anterior scleral opening to fuse with Bruch's membrane such that a portion of border tissue, and sometimes the underlying sclera, is clinically visible. Finally, as regions of internally oblique border tissue transition to externally oblique within an individual ONH, there can be regions of vertical or non-oblique border tissue, perpendicular to the clinical plane of view.

In most monkey eyes there is overhang of Bruch's membrane, extending beyond the innermost termination of border tissue (Fig. 1B). Strouthidis and colleagues recently compared clinical, histomorphometric and SD-OCT optic disc margin anatomy in monkey eyes.¹² They proposed that what the clinician recognizes as the disc margin depends mainly on the three-dimensional architecture of Bruch's membrane and underlying border tissue, rather than a single structure. Furthermore, they observed that where Bruch's membrane extended beyond border tissue, the extension was clinically visible and represented the optic disc margin in most regions of most monkey eyes.¹³

In humans, even though the anatomy underlying the optic disc margin is well described,^{6, 15} there is no systematic characterization of SD-OCT disc margin anatomy. In particular, the frequency of Bruch's membrane overhang and whether it is visible as the clinical disc margin in glaucomatous and healthy eyes is not known.

In this study, we co-localized SD-OCT data sets to optic disc stereo-photographs of glaucoma patients with a variety of optic disc appearances and normal controls from which the clinical optic disc margin was determined. We had three objectives; first to characterize border tissue orientation; second, to identify the deep ONH structures detected with SD-OCT that co-localize with the clinically visible optic disc margin; and third, to determine the frequency of SD-OCT detected Bruch's membrane extending beyond the clinically visible disc margin. The latter has implications for the accuracy with which neuroretinal rim assessments, such as cup-disc ratio and automated neuroretinal rim area, are currently made.

METHODS

Participants

Thirty patients with open-angle glaucoma with early to moderate visual field loss and 10 healthy age-matched normal control subjects were recruited from two prospective longitudinal observational studies being conducted at the Eye Care Centre, Queen Elizabeth II Health Sciences, Halifax, Nova Scotia, Canada. In order to include a range of optic disc appearances in glaucoma, patients with focal, diffuse or sclerotic optic disc damage were recruited. These forms of optic disc damage have been described in detail elsewhere¹⁶⁻¹⁸ with evidence that recognizing these appearances has clinical importance.¹⁹ Briefly, in focal damage there is a superior or inferior notch, with the remaining neuroretinal rim relatively well preserved. In diffuse damage there is concentric cup enlargement, and no localized areas of loss or pallor. In sclerotic damage the cupping is shallow, with marked areas of peripapillary atrophy and choroidal sclerosis.

If both eyes were eligible, one eye was randomly selected as the study eye. For the present study, 10 patients representing each optic disc damage group were randomly selected, in addition to 10 age-matched control subjects. In accordance with the declaration of Helsinki, all subjects gave informed consent to participate, and the Ethics Review Board of the QEII Health Sciences Centre approved the study.

Inclusion criteria were diagnosis of open-angle glaucoma, including primary, pseudoexfoliative or pigmentary glaucoma with glaucomatous visual field loss with standard automated perimetry and glaucomatous optic disc damage. The visual field was tested with the Swedish Interactive Thresholding Algorithm²⁰ program 24-2 of the Humphrey Field Analyzer (Carl Zeiss Meditec, Dublin, CA). Glaucomatous visual field loss was defined with an abnormal Glaucoma Hemifield Test.²¹ Exclusion criteria were concomitant ocular disease and systemic medication known to affect the visual field. Normal controls had a normal eye examination with an intraocular pressure less than 21 mm Hg and a normal visual field defined as a Glaucoma Hemifield Test, mean deviation and pattern standard deviation within normal limits. Additional inclusion criteria for all subjects were: best corrected visual acuity equal to or better than 0.3 (20/40) logarithm minimum angle of resolution (logMAR) in the study eye; refraction within ± 6.00 diopters sphere and ± 3.00 diopters astigmatism.

Imaging

Optic disc stereo-photographs were acquired with a fundus camera (FF3 Carl Zeiss Jena GmbH, Jena, Germany) with an Allen separator. The images were captured on 35 mm slide film, which was developed and processed into color slides. Stereo-photograph slides were digitized at a resolution of 4800 dpi using a color-calibrated slide scanner (Nikon LS-5000 ED, Nikon Corporation, Tokyo, Japan). Each subject had the study eye imaged with a commercially available SD-OCT device (Spectralis, Heidelberg Engineering GmbH, Heidelberg, Germany). A radially equidistant scanning pattern centered on the optic disc

was used (24 high-resolution 15° radial scans, each averaged from 30 B-scans, with 1536 A-scans per B-scan), with a scanning speed of 40,000 A-scans per second. Optic disc photographs and SD-OCT scans were acquired at the same day or within 3 months of each other.

Co-localization of SD-OCT Volumes and Optic Disc Photographs

An infrared image was extracted from the SD-OCT raw data for each subject. Depending on a subjective determination of the best quality photograph, with clear focus at the disc margin, either the right or left side of the stereo-photograph pair was selected for each eye and rescaled to 1536 × 1536 pixels. Using an automatic sub-pixel registration algorithm,²² each selected photograph (source image) was aligned and matched with its corresponding infrared image (target image) to generate a registered photograph. The registration was performed with public domain software (ImageJ, version 1.43u, TurboReg plug-in, National Institutes of Health, USA). In order to test the alignment, a 65% transparent registered photograph was superimposed on the corresponding infrared image (Adobe Photoshop CS3; Adobe Systems, San Jose, CA), and saved as a two-layer image file. Co-localization required the outline of the central retinal vessels and their bifurcations to be matched between the infrared OCT image and the photograph. If present, misalignments between the two images were corrected by shifting, scaling and rotating the registered image. A single observer (ASCR) performed all the co-localizations. The co-localization process is illustrated in Figure 2 (available at <http://aaojournal.org>).

Because the infrared and disc photographs are two-dimensional projections of three-dimensional surfaces, the accuracy of the registration process was evaluated to determine whether there were differences in projection between the two imaging modalities. The distance between two approximately horizontal landmarks and two approximately vertical landmarks in the infrared image was computed in all 40 subjects. Landmarks were clear vessel bifurcations. The procedure was repeated with the corresponding landmarks in the aligned disc photograph. The horizontal-to-vertical ratio was computed for the two image types and an analysis of the differences performed. The median modulus of the difference in ratios was 0.009 or 0.9% (95 CI, 0.008 to 0.020, or 0.8% to 2.0%) indicating that the registration process was accurate and did not induce meaningful projection errors.

Optic Disc Margin Assessment

One observer (ASCR) delineated all the optic disc margins in the registered photographs by placing a line along the disc margin using commercial software (Adobe Photoshop CS3, Adobe Systems, San Jose, CA). The observer also had access to the original stereo-photograph slides that were viewed on a light table with a stereo-viewer in order to accurately perform the delineation. The disc margin was defined as the innermost border of reflective tissue that was internal to any pigmented tissue and within which only neural tissue was present. If there was no clear reflective tissue present, then the disc margin was defined as the innermost termination of pigmented tissue. Thereafter he and three additional observers (MTN, CFB and BCC) together reviewed all optic discs and concurred on the location of the optic disc margin. For each subject, the observers had access to digitized stereo-photograph pairs on a computer monitor with a Screen-Vu stereoscope (PS Mfg., Portland, OR) and the original stereo slides. The registered image with the delineated optic disc margin was saved as an image file.

Delineation of Optic Disc Margin Structures in SD-OCT Images

SD-OCT raw data were imported into customized software enabling three-dimensional visualization and delineation of SD-OCT structures. The software is based on the Visualization Toolkit (VTK, Clifton Park, NY),^{12, 13} and allows delineation of structures in

the SD-OCT B-scan with simultaneous corresponding projection in the two-dimensional infrared image (extracted from the SD-OCT data) and registered photograph. After loading the registered photograph with a line demarcating the optic disc margin, one operator (ASCR) identified and delineated the SD-OCT structure coinciding with the optic disc margin in all radial B-scans.

Identification of Optic Disc Margin Structures in SD-OCT Images

All eyes were transformed to right-eye format. The SD-OCT scans were categorized in terms of border tissue obliqueness, presence of Bruch's membrane overhang, and the SD-OCT structure coinciding with the optic disc margin delineated in the photographs. While the analysis was performed on all 24 radial scans, for this report, only data for the 12 clock hour positions are presented (Fig. 3).

Border tissue was classified at each clock hour into 3 categories of obliqueness: (1) internally oblique, where border tissue extends internal to the anterior scleral opening (Fig. 1A, B); (2) externally oblique, where border tissue extends external to the anterior scleral opening (Fig. 1C) and (3) non-oblique where border tissue is perpendicular relative to scleral opening (Fig. 1D). The presence of Bruch's membrane overhang (Fig. 1B) was also quantified. Border tissue classification was initially made by one observer (ASCR) and then reviewed and verified by three additional observers (MTN, CFB and BCC).

The SD-OCT structure coinciding with the optic disc margin, identified in the optic disc stereo-photograph, was classified at each clock hour into three categories: (1) Bruch's membrane opening (BMO), when the clinically identified disc margin co-localized with the innermost edge of Bruch's membrane, with or without overlying retinal pigment epithelium, in the SD-OCT image (Fig. 4A); (2) Bruch's membrane/border tissue, when the disc margin co-localized with Bruch's membrane and border tissue when the innermost edges of Bruch's membrane and border tissue did not coincide (Fig. 4B) and (3) border tissue alone, when the disc margin co-localized with border tissue alone (Fig. 4C).

Statistical Analysis

Categorical variables were analyzed with the chi-squared test while continuous variables were analyzed with the Mann-Whitney test with commercial software (PASWStatistics v. 18, SPSS Inc., Chicago, IL).

RESULTS

The subjects comprised 20 (50%) men and 20 (50%) women of European ancestry. Table 1 summarizes the age, gender and visual field mean deviation statistics. There were no group differences in age or gender distribution, however, the mean deviation was significantly worse in patients compared to controls.

Overall in glaucoma patients, the most frequent border tissue configuration was internally oblique (Fig. 5, available at <http://aaojournal.org>). It was the most frequent configuration superior temporal to inferior nasal (from the 10 through 5 o' clock positions). In the remaining sectors (from the 6 through 9 o' clock positions), the most frequent border tissue orientation was externally oblique, though not as preponderant as the internally oblique configuration in the remaining sectors. In normal controls the most frequent configuration was internally oblique around the whole optic disc (Fig. 5, available at <http://aaojournal.org>), though, like in glaucoma patients, it was substantially more frequent temporally to inferior nasally (from the 9 through 5 o' clock positions). The border tissue configurations were not statistically different between patients and controls ($P > 0.08$, across all clock hours). Nineteen (63%) patients showed all three border tissue configurations, 9

(30%) showed two and 2 (7%) showed the same configuration throughout the disc. The corresponding figures in controls were 4 (40%), 2 (20%) and 4 (40%) respectively.

Glaucoma patients with focal damage had a predominantly internally oblique border tissue configuration in the superior and nasal quadrants, and an externally oblique configuration in the inferior and temporal quadrants (Fig. 6, available at <http://aaojournal.org>). While patients with diffuse damage had a similar pattern of internally oblique configuration, there was an almost complete absence of externally oblique border tissue (Fig. 6, available at <http://aaojournal.org>). Patients with sclerotic damage had mostly internally oblique configuration around the optic disc except inferiorly (at the 6 and 7 o'clock positions, Fig. 6, available at <http://aaojournal.org>). These configurations were statistically different among the glaucoma groups inferior temporally to superior temporally (from the 7 through 10 o'clock positions, $P < 0.05$), but not in the other sectors.

The SD-OCT structure most commonly coinciding with the clinically identified disc margin in glaucoma patients and controls was a location on Bruch's membrane with border tissue beneath (Fig. 7). This pattern was most obvious inferior temporally to superior nasally in both patients (from the 8 through 1 o'clock positions) and controls (from the 8 through 2 o'clock positions). At other locations, BMO and less frequently border tissue alone corresponded to the clinical disc margin (Fig. 7). There were no statistical differences between patients and controls in the frequency of SD-OCT structures identified as the disc margin ($P > 0.10$ at all clock hours), however, there were statistically significant differences among the three glaucoma groups inferior temporally to superior temporally (from the 7 through 10 o'clock positions, $P < 0.05$). These differences were due to the focal and sclerotic disc damage groups having relatively more cases where the disc margin corresponded to border tissue alone, which was not observed in any eyes with diffuse damage. Within the same disc in 14 (47%) patients, all 3 SD-OCT structures individually corresponded to the disc margin; in 14 (47%) patients 2 structures corresponded to the disc margin, while a single structure only corresponded to the disc margin in 2 (7%) patients. The respective figures in controls were 4 (40%), 5 (50%) and 1 (10%).

There was Bruch's membrane overhang in the majority of glaucoma patients and controls around the optic disc (except for the 6 and 7 o'clock positions in patients and 7 o'clock position in controls, Fig. 8). The proportion of patients with Bruch's membrane overhang in whom BMO was identified as the clinical disc margin ranged from 5 of 26 (19%) at 12 o'clock to 13 of 24 (54%) at 3 o'clock (Fig. 8). In controls the respective figures were 0 of 8 (0%) at 9 o'clock to 4 of 5 (80%) at 7 o'clock (Fig. 8). Hence, in the majority of patients and controls where there was Bruch's membrane overhang, it was not clinically visible. A clinical case illustrating Bruch's membrane overhang identified by SD-OCT but invisible by disc photography is shown in Figure 9.

DISCUSSION

Characterizing the anatomic variations of structures that define the optic disc margin may more accurately describe the clinical construct we currently recognize as the disc margin. To the best of our knowledge, this is the first published study to utilize SD-OCT ONH data co-localized to clinical photographs to identify structures that underlie optic disc margin appearance in glaucoma patients and normal controls. The patients were selected to represent the broad appearances of the optic disc observed in patients with glaucoma.

In this study we found that the obliqueness of border tissue varied according to location in the optic disc with most patients and controls showing 2 or all 3 of the configurations in the same eye. The most common configuration was internally oblique, most often observed in

the superior and nasal quadrants, frequently accompanied with Bruch's membrane overhang. The externally oblique configuration was less common, observed most often in the inferior and temporal quadrants, and infrequently accompanied with Bruch's membrane overhang. The SD-OCT structure identified most frequently as the optic disc margin in the disc stereophotographs was some aspect of Bruch's membrane and border tissue. It is important to note that at these locations, the termination of Bruch's membrane was internal to the border tissue and not visible as the disc margin. Hence in most cases what the clinician sees as the disc margin is not a discernable junction or edge of an anatomic structure. BMO corresponded to the disc margin in some locations of a fewer number of subjects while border tissue alone accounted for the disc margin in a minority of eyes. What the clinician identifies as the margin in a single optic disc is rarely a single structure; most commonly, 2 or all 3 of the SD-OCT structures corresponded to the disc margin.

The border tissue configurations described by Strouthidis and colleagues in monkey eyes^{14, 13} are similar to the present findings. In both patients and controls, border tissue most frequently had an internally oblique configuration from the superior temporal to inferior nasal (from the 10 o' clock through 5 o' clock positions) aspect of the disc. While not statistically different, there was a tendency for the glaucomatous eyes to have relatively more externally oblique border tissue inferotemporally compared to controls. These distinct border tissue configurations may correspond with the oblique course of RGC axons through the sclera.^{23, 24}

The various forms of optic disc damage in glaucoma¹⁶⁻¹⁸ indicate differential susceptibility to further progression¹⁹ and may be important to recognize clinically. There were significant differences in the frequency of border tissue orientation among the three types of disc damage (Fig. 7). Patients with focal damage had more prevalent externally oblique border tissue configuration, especially in the inferotemporal sector compared to the other two groups. The inferotemporal sector is the first to present neuroretinal rim loss in glaucoma²⁵ and has been shown to have the highest rate of neuroretinal rim deterioration.^{26, 27} Finally, patients with focal damage appear to have the highest rate of visual field and optic disc progression, than other forms of damage.¹⁹ The potential correspondence between a specific border tissue configuration and susceptibility to damage may be important to investigate in future research.

Three-dimensional histomorphometric reconstructions in monkey eyes suggest that the SD-OCT detected termination of Bruch's membrane consistently co-localizes to the optic disc margin.^{24, 14} In the present study the SD-OCT detected termination of Bruch's membrane infrequently co-localized with the optic disc margin highlighting important differences between monkey and human eyes. In addition to species difference, these differences may be age-related as the monkeys were relatively young and the humans relatively old.

With automated segmentation of Bruch's membrane with SD-OCT,²⁸ Hu and colleagues concluded that BMO coincided well with the disc margin. In the present study, most often Bruch's membrane/border tissue or border tissue alone coincided most frequently with the disc margin. Although in some patients BMO was coincident with the optic disc margin, often there was identifiable border tissue underneath (Fig. 4, A1 and A2), making it difficult to assess whether it was the overlying BMO or border tissue that made the disc margin clinically visible. For practical purposes and maintaining the terminology proposed by Strouthidis and colleagues,^{12, 13} we classified these eyes as those in which BMO was identified as the disc margin. The findings of this study strongly suggest that the goal of automated disc margin segmentation should not be to detect the clinically defined disc margin because at a given clock hour, it may not identify those clinically invisible anatomic structures that most accurately define the amount of remaining neuroretinal rim tissue.

Our disc margin findings are in partial agreement with Hogan and colleagues.⁶ They suggested that, although Bruch's membrane can overhang the anterior scleral canal opening, it is not usually visible alone or with overlying retinal pigment epithelium. Fantes and Anderson,¹⁵ reached similar conclusions in clinical histologic correlations in 21 eyes enucleated for choroidal melanomas. In the present study we found that in the majority of patients in whom Bruch's membrane overhang was detected by SD-OCT, the clinically visible disc margin was not identified by the termination of Bruch's membrane. ONH complexity, inter- and intra-individual variation in the clinical visibility of an overhanging Bruch's membrane in human eyes may explain the large discordance between the BMO and optic disc margin. The discordance between these two landmarks may influence the accuracy of clinical neuroretinal rim tissue assessment. An analysis of the effects of Bruch's membrane visibility on clinical rim assessment is beyond the scope of this study, however, this work is underway and will be the focus of a separate report.

Our study has some limitations. The sample was randomly chosen from a selected cohort of patients with distinct forms of glaucomatous optic disc damage. While it is likely that we have captured the range of deep ONH characteristics, they may be more heterogeneous in a general glaucomatous population. The delineations performed are laborious and time-consuming, and the sample size was therefore necessarily constrained, limiting the possibility of extending the study beyond its descriptive nature. We expect that with automated delineations in the future, larger samples could be analyzed. Finally, while the analysis in this study indicates that SD-OCT detected, but clinically invisible, extensions of Bruch's membrane exist (Fig. 9), SD-OCT with a longer wavelength light source in humans may capture a fuller extent of the extension which will require confirmation histologically. Hence in the present study, BMO refers to the SD-OCT detected, and not necessarily the histological, entity.

In conclusion, the anatomic basis for the human optic disc margin is complex and can be highly variable within individual eyes and between different eyes. We observed structural differences in tissues associated with the disc margin in patients with distinct forms of optic disc damage. In addition, what the clinician perceives as the optic disc margin in an individual eye is rarely a single structure; most frequently it is some aspect of Bruch's membrane and border tissue and less frequently, BMO or border tissue alone. Finally, clinically invisible SD-OCT detected extensions of Bruch's membrane beyond the clinical disc margin were regionally present in the majority of glaucomatous and normal eyes.

Because the location where Bruch's membrane terminates is potentially the most consistent site from which to quantify the neuroretinal rim, current disc margin based clinical and confocal scanning laser tomography examinations may overestimate the amount of remaining rim in those regions in which the full extent of Bruch's membrane is detected by SD-OCT, but not clinically. Furthermore, as the clinically visible disc margin seldom appears to represent a single anatomic structure, our findings challenge the long-standing paradigm of disc margin based neuroretinal rim tissue assessment.

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Figure 1.

Schematic representation of border tissue (BT) configurations. A. Internally oblique: BT extends internally from the posterior BT/scleral junction to fuse with Bruch's membrane (BM). B. Internally oblique with BM overhang. C. Externally oblique: BT extends externally from the posterior BT/scleral junction to fuse with BM. D. Non-oblique: BT is perpendicular relative to the scleral opening. For simplicity, the retinal pigment epithelium overlying Bruch's membrane is not shown. BMO, Bruch's membrane opening.

Figure 2.

Co-localization of optic disc images. A. Fundus photograph (source image). B. Infrared image (target image) extracted from spectral domain optical coherence tomography raw data. C. Registered photograph after co-localization. D. Two-layer image of the infrared image (background) and registered photograph (65% transparency).

Figure 3.

Registered photograph with optic disc margin delineation (green dots), and 12-clock hour radial B-scans (displayed with the same orientation), acquired in the positions indicated by black dashed lines. The green dots on the B-scans show the spectral domain optical coherence tomography structure corresponding to the clinical visible disc margin.

Figure 4. Schematic representation and spectral domain optical coherence tomography examples of optic nerve head delineations. Black dots (white arrows) in the B-scans indicate the spectral domain optical coherence tomography structure corresponding to the clinically visible optic disc margin. A. Bruch's membrane opening (BMO) corresponding to the optic disc margin when BMO was coincident with the innermost edge of Bruch's membrane and border tissue (BM/BT, A1 and A2), or when there was a BM overhang (A3). B. BM/BT corresponding to the optic disc margin when the innermost edges of BM and BT did not coincide. C. BT alone corresponding to the optic disc margin.

Figure 5. Polar plots with connected points showing the frequency of border tissue configuration by clock hour, for all glaucoma patients ($n = 30$) and healthy control subjects ($n = 10$). The distance from the origin at each clock hour represents the frequency of each configuration by clock hour.

Figure 6. Polar plots with connected points showing the frequency of border tissue configuration by clock hour, for the focal ($n = 10$), diffuse ($n = 10$) and sclerotic ($n = 10$) glaucomatous optic disc damage groups. The distance from the origin at each clock hour represents the frequency of each configuration by clock hour.

Figure 7.

Polar plots with connected points showing the frequency of spectral domain optical coherence tomography structure corresponding to the optic disc margin by clock hour, for all glaucoma patients ($n = 30$) and healthy control subjects ($n = 10$). The distance from the origin at each clock hour represents the frequency of each spectral domain optical coherence tomography structure analyzed by clock hour.

Figure 8.

Polar plots with connected points showing the frequency of Bruch's membrane (BM) overhang by clock hour, for all glaucoma patients ($n = 30$) and healthy control subjects ($n = 10$). The external areas (light grey) show the frequency of BM overhang by clock hour. The internal areas (dark grey) show the frequency of Bruch's membrane opening (BMO) identified as the optic disc margin in those subjects with BM overhang. The distance from the origin at each clock hour represents frequency.

Figure 9.

Right eye of a glaucoma patient in which the presence of a clinically visible cilioretinal artery (cra) within vertical spectral domain optical coherence tomography (SD-OCT) B-scans provides evidence that the SD-OCT detected region of Bruch's membrane (BM) overhang adjacent to it is invisible by optic disc stereo-photography. A. Optic disc photograph registered to B, infrared image. Inset in A. Magnification of the rectangular area (broken white lines) showing the clinical disc margin determined with stereo-disc photography (green dots) and BM opening determined with SD-OCT B-scans and co-localized to the disc photograph (red dots). C, D and E. Equidistant line B-scans (x, y and z in A and B, respectively). The line scan x (shown in C) is at a location where BM is intact while the line scan z (shown in E) is at a location just inside BM. These B-scans were not part of the study protocol and obtained additionally (left to right represent bottom to top in A and B). The locations of only x and z are shown in A and B for clarity. BM is continuous in x and y (shown in C and D) indicating that the scan locations are outside the neural canal. BM shows a break in z (shown in E) verifying that the central locations of this scan are inside the neural canal. A cross-section of the cra appears beneath BM in x and y (shown in C and D) and curves around BM overhang in z (shown in E). Since the cra beneath BM is visible in the photograph, it indicates that the temporal region of BM overhang is clinically transparent and invisible. Because in this region BM opening is internal to the clinical disc

margin and is clinically invisible, conventional clinical examinations overestimate the amount of remaining neuroretinal rim tissue.

Table 1

Characteristics of Glaucoma Patients and Healthy Controls*

	Glaucoma	Controls	<i>P</i>
Age (yrs)	68.1 (42 to 86)	63.5 (42 to 77)	0.43
Gender (M/F)	16/14	4/6	0.72
Mean Deviation (dB)	-2.9 (-13.0 to -0.21)	+0.6 (-1.7 to 1.7)	< 0.01

* values shown are median (range)

M = male; F= female