Imaging Retrobulbar Subarachnoid Space around Optic Nerve by Swept-Source Optical Coherence Tomography in Eyes with Pathologic Myopia

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PURPOSE. To examine the subarachnoid space (SAS) of eyes with pathologic myopia and analyze the characteristics of the SAS and the surrounding tissues by swept-source optical coherence tomography (OCT).

METHODS. One hundred thirty-three eyes of 76 patients with pathologic myopia (spherical equivalent refractive error of >–8.00 diopters (D) or an axial length >26.5 mm) and 32 eyes of 32 subjects with emmetropia were enrolled. The eyes in both groups were not tested to determine whether glaucoma was present. The papillary and peripapillary areas were examined with a swept-source OCT prototype system that uses a wavelength sweeping laser operated at 100,000 Hz A-scan repetition rate in 1-μm wavelength.

RESULTS. In the B-scan images, the arachnoid trabeculae inside the SAS were clearly observed as a pattern of reticular lines and dots interspersed with hyporeflective zones consistent with fluid, whereas orbital fat had more uniform features with gray intervening spaces. The SAS was triangular, with the base toward the eye surrounding the optic nerve in the region of the scleral flange. An SAS was found in 124 highly myopic eyes (93.2%) but not in the emmetropic eyes. The shortest distance between the inner surface of lamina cribrosa and SAS was 252.4 ± 110.9 μm, and the thinnest region of peripapillary sclera above SAS (scleral flange thickness) was 190.6 ± 51.2 μm. In one myopic patient, there appeared to be direct communication between the intraocular cavity and SAS through pitlike pores.

CONCLUSIONS. Optic SAS is seen in 93% of highly myopic eyes, and the SAS appears to be dilated in highly myopic eyes. The expanded area of exposure to CSF pressure along with thinning of the posterior eye wall may influence staphyloma formation and the way in which certain diseases, such as glaucoma, are manifested. (Invest Ophthalimol Vis Sci. 2011;52:9644–9650) DOI:10.1167/iovs.11-8597

Unlike other cranial nerves, the optic nerve (ON) is surrounded by cerebrospinal fluid (CSF) for its entire length. The hydrodynamics of the CSF flow may be complex because the subarachnoid space (SAS) ends blindly at the posterior wall of the eye at the so-called scleral flange.1,2 Interactions between CSF pressure and intraocular pressure have been hypothesized to be involved in the ON damage in glaucomatous eyes.3–10 Highly myopic eyes are at higher risk for glaucomatous ON damage,11–15 although the precise reasons have not been determined. Expansion of the posterior portion of myopic eyes may alter the anatomic relationships in and around the ON, including tilted discs, scleral crescents, peripapillary atrophy, and secondary or acquired megalodiscs.16,17

Swept-source optical coherence tomography (OCT) uses a wavelength swept laser as the light source18 and, in practice, has less sensitivity roll-off with tissue depth than conventional spectral domain OCT. The current swept-source OCT instruments use a longer center wavelength, generally in the 1-μm range, which has improved their ability to penetrate more deeply into tissues than the conventional spectral domain OCT instruments. With the capability of imaging deeper anatomic structures in the eye with a swept-source OCT, evaluations of posterior structures potentially are possible. Thus, the purpose of the present study was to examine the SAS of eyes with pathologic myopia and analyze the characteristics of SAS and the surrounding tissues by swept-source OCT.

PATIENTS AND METHODS

This research adhered to the tenets of the Declaration of Helsinki and the procedures were approved by the Ethics Committee of Tokyo Medical and Dental University and that of the Western IRB (Olympia, WA). Written informed consent was obtained from all participants.

Seventy-six consecutive patients with pathologic myopia were evaluated by swept-source OCT from March 18 to June 3, 2011, in the Department of Ophthalmology and Visual Science, Tokyo Medical and Dental University (Tokyo, Japan) and in the clinics of Vitreous-Retina-Macula Consultants of New York (New York, NY). The definition of pathologic myopia was a refractive error (spherical equivalent) ≥–8.00 diopters (D) or an axial length >26.5 mm. For control, 32 eyes of 32 emmetropic subjects (refractive error ≤±3 D) were examined. All the emmetropic participants were current or former staff members of the university, and all volunteered. Patients with poor image quality because of dense cataract, poor fixation because of macular chorioretinal atrophy, myopic macular holes, or severe visual field defects were excluded.

All participants underwent comprehensive ocular examination, including measurement of the refractive error (spherical equivalent), axial length measurements with a coherence interferometry, biometric measurement device (IOL Master; Carl Zeiss Meditec, Oberkochen, Germany), and detailed ophthalmoscopic evaluation.
Myopic conus was defined as a well-demarcated white or grayish white crescent-shaped area of atrophy of the choroid and overlying retinal pigment epithelium associated with an outpouching of the underlying sclera adjacent to the optic disc within the area of a posterior staphyloma. Annular conus was defined as a ring-shaped conus surrounding the optic disc. The type of myopic conus was determined by two of the authors (MM, KOM) from color fundus photographs, and there was agreement between the two in all cases.

**Swept-Source Optical Coherence Tomography**

All the eyes were examined with a swept-source OCT prototype instrument manufactured by Topcon Corporation (Tokyo, Japan). This OCT system has an A-scan repetition rate of 100,000 Hz, and its light source operates in the 1-μm wavelength region. The light source is a wavelength tunable laser centered at 1050 nm with 100-nm tuning range. Axial resolution was measured to be 8 μm in tissue, and the lateral resolution was 20 μm. The imaging depth was 2.3 mm in tissue, and the lateral scan length was adjustable from 3 to 12 mm.

Three scanning protocols were used: three-dimensional (3D) volumetric scans, radial scans, and seven-line raster scans. 3D volumetric data were acquired in 0.8 seconds, where each 3D scan covered an area of either $3 \times 3$ mm$^2$ or $6 \times 6$ mm$^2$ centered on the optic disc using a resolution of 256 (horizontal) × 256 (vertical) A-scans. To improve the image quality, three consecutive B-scan images were averaged by a weighted moving average technique. From the volumetric data set, en face (C-scan plane) cross-sections were constructed by custom-made software where three reconstructed en face images were averaged along the depth direction followed by slight Gaussian spatial filtering to have better images. Note that this averaging along the depth direction was within a depth resolution (8 μm) of our swept-source OCT system.

The radial scans consisted of 12 meridian scans centered on the optic disc, and the seven-line raster scans were performed as neces-
Each had a scan length of either 6 mm or 9 mm. The distance between regions of interest in the B-scan image was measured using the planimetric caliper function of the built-in software of the swept-source OCT. The following measurements were made: the shortest distance between the inner surface of the lamina cribrosa and the edge of the SAS and the thickness of the sclera at its thinnest part close to the ON scleral canal. One of the authors (MM), who was masked to the refractive error and ophthalmoscopic findings, read and measured the OCT images.

RESULTS

One hundred thirty-three eyes of 76 consecutive patients with high myopia were evaluated by swept-source OCT in the High Myopia Clinic and in the clinics of the Vitreous-Retina-Macula Consultants of New York between March 18 and June 3, 2011. The characteristics of these 76 patients with pathologic myopia and those of the emmetropic controls are shown in Table 1.

In the B-scan images of the swept-source OCT, SAS was seen as a hyporeflective space around the ON (Figs. 1–4). The SAS was triangular, with the base directed toward the eye and the apex toward the orbital apex in the B-scan images. Hyperreflective beams and coarse dots, assumed to be beams in cross-section, were consistent with the gross structure of the trabeculae, and these were surrounded by hyporeflective zones consistent with fluid within a region encircling the visible ON. Posterior to the globe and extending in a much larger angular expanse were smaller punctate reflections surrounded by a gray background; given the ability of the swept-source OCT to image at least 1 mm posterior to the globe in many patients, this reflective pattern was assumed to result from orbital fat.

The SAS was seen in 124 of the 133 highly myopic eyes (93.2%; Fig. 1). The mean (SD) age of these 72 patients was 53.2 (±11.9) years, and the range was 28 to 83 years. The mean refractive error was −15.2 ± 3.4 D, and the mean axial length was 30.4 ± 1.8 mm in these 124 eyes. The SAS was not observed in nine highly myopic eyes of six patients. In three of these six patients, the SAS was observed in one eye and was not observed in the other eye. There was no significant difference in mean age, mean refractive degree, and mean axial length between the highly myopic patients whose SAS was observed and those whose SAS was not observed (Table 1). Among the 124 highly myopic eyes, 74 eyes had a temporal conus, and 49 eyes had an annular conus. An annular myopic conus was observed significantly more frequently in eyes whose SAS was observed by swept-source OCT than the eyes in which the SAS was not observed (49 of 124 eyes [39.5%] vs 0 eyes; *P* = 0.01, Fisher’s exact probability test). SAS was not observed in any of the 32 emmetropic eyes (Fig. 1).

**FIGURE 2.** Change of scleral curvature at the site of attachment of the dura mater of the SAS to the peripapillary sclera. (A) Color fundus photograph of the optic disc with a large annular conus. (B) Swept-source OCT slice scanned along the green line in (A) shows the SAS temporal to the optic disc. There is a change of the scleral curvature at the attachment site of the dura mater of SAS to the peripapillary sclera (arrows). (C) Color fundus photograph of the optic disc showing a large annular conus. (D) Swept-source OCT slice scanned along the green line in (C) shows the SAS temporal and nasal to the optic disc. There is a change of the scleral curvature at the attachment of the dura mater of SAS to the peripapillary sclera (arrows). (E) Schematic drawing showing the change of the scleral curvature at the attachment of the dura mater of SAS to the peripapillary sclera (arrows). T, temporal to the optic nerve; N, nasal to the optic disc. Dotted line: lamina cribrosa.

**FIGURE 3.** Fundus photograph and swept-source OCT images showing different appearances of the arachnoid trabeculae in the SAS. (A) Color fundus photograph of the optic disc with temporal conus. Green lines show the locations of the OCT scans were performed in (B) to (D). Each slice is 230 μm apart. (B–D) Swept-source OCT images showing the arachnoid trabeculae as wide linear streaks or as a reticulated pattern or as multiple dots in cross-section. (D, yellow dotted line) Margin of SAS. Arrows: arachnoid trabeculae in the SAS. Scale bar, 1 mm.
In a corresponding way, the meningeal sheaths surrounding the SAS were only visible as discrete structures separated from the nerve tissue in the highly myopic eyes (Figs. 1, 2) and not in emmetropic eyes. The posterior aspect of the nerve tissue from the region of the neural canal wall was seen to merge with the pia mater along the inner border of the SAS (Figs. 1B, 1D, blue arrowheads). The posterior sclera was contiguous with the dura mater, and this occurred at a circumpapillary site separated from the visible nerve tissue (Figs. 1B, 1D, blue arrowheads). The SAS appeared to protrude toward the ON at the junction between the peripapillary sclera and the pia mater temporally and inferiorly (Fig. 1, arrow). There was a change in the scleral curvature at the attachment of the dura mater of the SAS to the peripapillary sclera (Fig. 2). Only the nerve fiber layer and the scleral flange were observed on the SAS, consistent with a recent study by Jonas et al.\textsuperscript{2} The width of the SAS ranged from 263 to 1850 μm.

The distribution of the SAS around the ON was analyzed in en face images reconstructed from the 3D data (Figs. 5, 6; see Supplementary Video S1, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.11-8597/-/DCSupplemental). In the 74 eyes with temporal conus, the SAS was observed in the area temporal and inferior to the disc (Fig. 5). In the 49 eyes with annular conus, the SAS was observed to surround the optic disc in 26 eyes (53.1%; Fig. 6) and the optic disc except in the nasal region in 23 eyes (46.9%). We have reported that a myopic conus was divided into a consistently hypofluorescent inner zone and an outer zone with delayed choroidal filling.\textsuperscript{19} The peripheral end of the SAS coincided with the margin of the inner zone of the myopic conus in the 20 eyes in which the outer margin of SAS was clearly identified.

In 67 of 124 eyes, the inner surface of the lamina cribrosa was clearly identified and the shortest distance between the lamina inner surface and the SAS of the ON was measured in each B-scan image of the 12 radial scans centered at the disc center (Fig. 7A). The thinnest region of the peripapillary sclera above the SAS was measured in 65 highly myopic eyes in which the margin was clearly detected (Fig. 7B). The average shortest distance between the inner surface of the lamina and the SAS was 252.4 ± 110.9 μm (range, 120–590 μm), and the average thinnest region of the peripapillary sclera to the SAS was 190.6 ± 51.2 μm (range, 62–257 μm).

In one patient (Fig. 8), the distance between the intraocular space and the SAS was 120 μm, but there appeared to be channels of communication through pitlike structures within the area of the optic disc. In another patient there was direct communication between the intravitreal cavity and the SAS through multiple fenestrae in the conus (Fig. 9). The peripapillary sclera had fenestrae, and the nerve fibers were discontinuous at these sites. This patient had a central scotoma (Fig. 9).

**FIGURE 4.** Fundus photographs and swept-source OCT images of the SAS showing different appearances of the arachnoid trabeculae. (A) Color fundus of the optic disc with temporal conus. Green lines show scanned lines by swept-source OCT shown in (B) and (C). (B, C) Swept-source OCT images showing the arachnoid trabeculae (arrows) with a reticulated pattern or as multiple dots in cross-section. Yellow dotted line shows margin of the SAS. Scale bar, 1 mm.

**FIGURE 5.** Fundus photographs and swept-source OCT images of the SAS showing the distribution of the SAS around the optic nerve and different appearances of the arachnoid trabeculae. (A) Color fundus of the optic disc in the same eye shown in Figure 3A. Green square: scanned area in a 3D scan (3 × 3 mm). (B) Single OCT image across the center of the optic disc. Green lines indicate the depths at which en face cross-sectional images are reconstructed in (C) to (F). (C–F) En face cross-sectional images scanned in the area shown as green square in (A). These images are reconstructed at the levels indicated by the green lines in (B). The SAS is temporal and inferior to the optic nerve. The arachnoid trabeculae inside the SAS are visible as wide linear streaks or in a network pattern (arrows, F). The collagenous tissue of the lamina cribrosa is also observed in the inferotemporal area of the optic disc (arrowhead, C). (F) The margin of the SAS is outlined by a yellow dotted line. Scale bar, 1 mm.
that corresponded with the area of the discontinuity of the nerve fibers between the optic disc and the macula.

**DISCUSSION**

Because of the improved ability of swept-source OCT to penetrate more deeply into ocular tissue, we were able to detect SAS surrounding the ON posterior to the globe in 124 of 135 highly myopic eyes (93.2%). The SAS was triangular, with the base directed toward the eye in the B-scan images. This is compatible with earlier descriptions by Killer et al., who examined postmortem human eyes by scanning electron microscopy. Unlike patients with pathologic myopia, an SAS was not observed in any of the emmetropic eyes by swept-source OCT. Although the choroid and sclera are much thinner in myopic eyes, allowing for greater penetration of the light, the penetration of light into the nerve would be expected to be independent of refractive status. As such the perineural tissue is at least partially visualized in all eyes.

The SAS was visible temporal to the ON in eyes with a temporal conus. In contrast, eyes with an annular conus around the nerve were more likely to have SAS of a much greater angular extent around the nerve, including half the annular conus eyes in which the SAS was seen around the full circumference of the nerve. This suggests that the process involved in conus formation, which appears to be related in part to staphylomatous expansion of the posterior wall of the eye, includes an associated expansion of the SAS. We have reported that a myopic conus was divided into a consistently hypofluorescent inner zone and an outer zone with delayed choroidal filling. Indocyanine green angiography showed a dislocation of the Zinn-Haller ring to the border between the two zones. Interestingly, in the present study, the peripheral end of the SAS coincided with the margin of the inner zone of myopic conus, although the number of eyes in which the peripheral end of SAS was visible was limited. The results support our hypothesis, presented earlier, that the inner zone might develop as a result of mechanical stretching and the outer zone might result from a secondary circulatory disturbance and mechanical stretching.

The dura covering of the ON merges with the extrinsic peripapillary sclera. Enlargement of the posterior sclera appears to cause an associated dilation of the dura insertion, with a widening of the SAS as a consequence. In one report, Geeraerts et al. showed the ON sheath diameter and the ON diameter at 3 mm posterior to the globe was 5.08 ± 0.52 mm and 2.70 ± 0.23 mm, respectively, in 36 healthy volunteers using fat-suppressed T2-weighted MRI. Recently, Jonas et al. analyzed highly myopic eyes enucleated for end-stage glaucoma (36 human globes; axial length >26.5 mm) and showed that the thickness of the scleral flange, which they defined as the thickness of sclera between the ON border and the ON dura mater, decreased significantly with axial length. In addition, in all 15 eyes with highly myopic peripapillary conus, the peripapillary region consisted of an elongation of the peripapillary scleral flange associated with an extension of the retrobulbar CSF space into the retropapillary region. The data in the present study support the findings that not only was the lamina cribrosa thinner but the SAS was extended into the peripapillary region in highly myopic eyes.

The arachnoid trabeculae that course through the SAS were also visible by swept-source OCT. The arachnoid trabeculae are a system of branching and anastomosing collagen bundles and they loosely connect the arachnoid mater to the pia mater. The dynamics of the CSF in the SAS is strongly influenced by the trabeculae and meningoepithelial cells covering each tra-
Thus, to image both the SAS and the arachnoid trabeculae in the SAS could be helpful in investigating the hemodynamics of the CSF.

Jonas et al. \(^4\) examined 36 highly myopic eyes (axial length \(>26.5\) mm), most of which (29) were enucleated for end-stage glaucoma, and the rest had no apparent eye disease. The shortest distance between the intraocular space and the SAS was significantly less in highly myopic eyes than in non-highly myopic comparison eyes. They reported that the average shortest distance between the inner lamina surface and CSF space

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**Figure 8.** Fundus photograph and swept-source OCT images showing a close distance between the intraocular space and the SAS. (A) Color fundus photograph of the optic disc showing a large annular conus. (C, D, green lines) Scanned lines by swept-source OCT. (B) Visual fields from Goldmann perimetry show a severe loss of visual field. (C, D) B-scan images showing pitlike structure within the area of the optic disc. The SAS is observed as a hyporeflective space along the optic nerve (arrowbeads in C and yellow dotted line in D). B-scan images showing the close distance between the intraocular space and the SAS (between arrows). Morphometric analysis showed that the distance was 120 \(\mu m\) in (C) and 220 \(\mu m\) in (D). Scale bar, 1 mm.

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**Figure 9.** Fundus photograph and swept-source OCT images showing direct communication between the intraocular space and the SAS. (A) Color fundus photograph of the optic disc showing a large annular conus. (B, C) En face cross-sectional images scanned in the area shown as green square in (A) at the different levels showing that there are two pitlike pores temporal to the optic disc (B) and that these pores are continuous to the SAS at a deeper level (C). (D, E) B-scan images acquired by 3D scan protocol showing the communication between the intraocular space and the SAS temporal to the optic disc within the area of the myopic conus. (F) Schematic drawing of (E). Vitreous cavity is continuous with SAS through pitlike pores. SAS and vitreous cavity are shaded in gray. LC, lamina cribrosa. (G) Visual fields from Goldmann perimetry show a central and a paracentral scotoma in addition to the nasal step. Scale bar, 1 mm.
was $37.4 \pm 102.5 \, \mu m$ in 29 highly myopic glaucomatous eyes, with the shortest measuring 205 $\mu m$. Our measurements were made in living eyes and thus did not have fixation-induced shrinkage. In addition, we did not confine our study group to end-stage glaucoma. However, the findings were similar in that the shortest distance between the inner surface of the lamina cribrosa and the CSF space was very small in our patients (Fig. 8). More strikingly, in one patient, SAS was directly connected with the intraocular space through multiple pitlike pores within the conus temporal to the optic disc (Fig. 9). The thinnest section of the peripapillary sclera was as thin as 62 $\mu m$ in our series.

In nonmyopic eyes, the pressure gradient across the lamina cribrosa is a function of both the intracranial pressure transmitted down the ON and the intraocular pressure. The pressure differential has been hypothesized to be a risk factor for the development of glaucoma. This pressure acts on the lamina, which has an ability to resist deformation by its thickness and resiliency. In highly myopic patients, the magnitude of the pressure differential would be the same. What would differ in these eyes is the increased area exposed to the CSF pressure and the relative thinning of the intervening tissue. Highly myopic eyes often have either tilted discs or megalodiscs because the expansion of the posterior aspect of the eye affects the ON canal and its associated tissue. As part of the ocular changes in highly myopic eyes, the posterior sclera becomes thinner, particularly in the peripapillary region of eyes with staphylomas. Pressure is equal to force per unit area, and, as such, the force load on the lamina is increased in proportion to the enlargement of the surface area exposed; the lamina itself may be less likely to resist deformation because of thinning. In addition, the shape of any staphyloma formed may be altered by the presence of the SAS. The pressure gradient across the sclera may be different in these eyes than it is in eyes with no enlargement of the SAS. Indeed the eyes in this study had an alteration in contour at the area of dural attachment (Fig. 2).

There are several limitations to our study. Even with the swept-source OCT, the SAS was visible only beneath the conus area, and the outer boundary of the SAS was not distinct in some patients. Thus, it was difficult to accurately measure the width of SAS around its perimeter. The thickness of the lamina cribrosa was not measured because the outer border of the lamina was indistinct in many of these highly myopic eyes. CSF pressure was not measured in our patients. However, the in vivo observation of periopictic SAS by swept-source OCT in living eyes offers opportunities to study the eyes in ways not previously possible. With further improvement in OCT technology, it may be possible to routinely image this region in eyes with any refractive error. In the meantime application of this form of imaging may lead to greater understanding of the ocular morbidity of high myopia.

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**References**


