Evaluation of Retinal and Choroidal Thickness by Swept-Source Optical Coherence Tomography: Repeatability and Assessment of Artifacts

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• PURPOSE: To determine the repeatability of automated retinal and choroidal thickness measurements with swept-source optical coherence tomography (SS OCT) and the frequency and type of scan artifacts.
• DESIGN: Prospective evaluation of new diagnostic technology.
• METHODS: Thirty healthy subjects were recruited prospectively and underwent imaging with a prototype SS OCT instrument. Undilated scans of 54 eyes of 27 subjects (mean age, 35.1 ± 9.3 years) were obtained. Each subject had 4 SS OCT protocols repeated 3 times: 3-dimensional (3D) 6 × 6-mm raster scan of the optic disc and macula, radial, and line scan. Automated measurements were obtained through segmentation software. Interscan repeatability was assessed by intraclass correlation coefficients (ICCs).
• RESULTS: ICCs for choroidal measurements were 0.92, 0.98, 0.80, and 0.91, respectively, for 3D macula, 3D optic disc, radial, and line scans. ICCs for retinal measurements were 0.39, 0.49, 0.71, and 0.69, respectively. Artifacts were present in up to 9% scans. Signal loss because of blinking was the most common artifact on 3D scans (optic disc scan, 7%; macula scan, 9%), whereas segmentation failure occurred in 4% of radial and 3% of line scans. When scans with image artifacts were excluded, ICCs for choroidal thickness increased to 0.95, 0.99, 0.87, and 0.93 for 3D macula, 3D optic disc, radial, and line scans, respectively. ICCs for retinal thickness increased to 0.88, 0.83, 0.89, and 0.76, respectively.
• CONCLUSIONS: Improved repeatability of automated choroidal and retinal thickness measurements was found with the SS OCT after correction of scan artifacts. Recognition of scan artifacts is important for correct interpretation of SS OCT measurements. (Am J Ophthalmol 2014;157:1022–1032. © 2014 by Elsevier Inc. All rights reserved.)

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THE INTRODUCTION OF OPTICAL COHERENCE TOMOGRAPHY (OCT) approximately 2 decades ago has contributed to better understanding and management of glaucoma.[1,2] In recent years, OCT technology has undergone several iterations with the incorporation of spectral-domain (SD) imaging that offers significant advantages over the earlier time-domain techniques.[3] These advances have led to considerable improvements in the ability to visualize individual layers of the retina in near-histologic detail,[4,5] whereas deeper ocular structures such as the choroid have remained difficult to image.

The choroid, a heavily vascularized tissue between the retina and sclera, plays a central role in ocular metabolism, volume regulation, and temperature control. Abnormalities of the choroid have been implicated in major ophthalmic conditions, most importantly in the pathophysiologic features of retinal disease.[6,7] Changes in choroidal structure[8–10] and function[11,12] also have been hypothesized to contribute to optic nerve damage in glaucoma. Until recently, postmortem histologic studies[9,11] and ultrasonography[13] were the major source of knowledge on choroidal anatomy and physiology. An important source for uncertainty about the cause-and-effect relationship of choroidal changes and disease processes arises from the lack of precision and effect of artifacts on these methods.[4]

The introduction of enhanced depth imaging (EDI) protocols,[7,14] in which an inverted image is obtained by closer placement of the SD OCT instrument to the eye, has reduced scattering effects and depth-dependent reduction in sensitivity. However in EDI OCT, improved choroidal visualization is achieved at the expense of reduced resolution of retinal layers.[14,15]

Recently, a new generation of high-penetration OCTs has been introduced that may have the potential to improve the understanding of the choroid further.[16] These swept-source (SS) OCTs use a long-wavelength light source of 1050 nm and a tunable laser, the wavelength of which can be altered in a controlled manner.[17] SS OCT systems have the potential for superior and simultaneous imaging of the retina and choroid because of the longer

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wavelength, potentially higher detection efficiency, and lower dispersion.[18] In the absence of automated segmentation software for SS OCT systems, previous investigators[16,19–21] have used manual (mostly single-point) measurement techniques using in-built calibers or modification of retinal segmentation lines[22] to evaluate choroidal thickness. Given the high anatomic variability of the choroid, these are impractical for clinical use, are highly dependent on location of measurement, and may be subject to further operator effects. We recently described the use of automated segmentation for choroidal measurements using SS OCT.[17]

Before a new device can be accepted for use in clinical practice, its repeatability should be evaluated. Estimating repeatability is a prerequisite for quantifying an instrument's ability to separate real change from noise, as in the monitoring of response to treatment in retinal conditions and progression in glaucoma. Studies evaluating the repeatability and reproducibility of choroidal measurements with SS OCT in healthy Japanese subjects have used different image acquisition protocols and manual segmentation techniques, which may explain notable disparities between choroidal thickness measurements among them.[16,19–21,23–25] Artifacts represent another major concern for every imaging technique. However, none of these studies have reported the frequency and effect of image artifacts on SS OCT measurements.

The aim of the current study was to evaluate the repeatability of measurements of retinal and choroidal thickness using a prototype SS OCT instrument in healthy participants. For this purpose, built-in automated segmentation of choroidal borders was applied to 4 different image acquisition protocols. In addition, we sought to study the effect of image artifacts on SS OCT measurements.

METHODS

THIS PROSPECTIVE STUDY WAS COMPLIANT WITH HEALTH Insurance Portability and Accountability Act regulations and adhered to the Declaration of Helsinki and all federal or state laws. It was approved by the University of California, San Diego, Human Research Protections Program (institutional review board protocol no. 111356). This study was registered at http://clinicaltrials.gov (identification no. NCT01507584). Written informed consent was obtained from all participating subjects.

• **SUBJECTS:** Thirty healthy subjects were recruited from among university employees and their families at the Shiley Eye Center, University of California, San Diego. Subjects with current ocular disease, previous ocular surgery, myopia of more than 5 diopters, or hyperopia of more than 3 diopters were excluded. All subjects had normal visual field testing results (using Statpac II, Swedish interactive thresholding algorithm 24-2, Zeiss-Humphrey Field Analyzer; Carl Zeiss Meditec, Inc, Dublin, California, USA), an IOP of 21 mmHg or less on Goldmann applanation tonometry, and no clinical signs of eye disease on slit-lamp anterior segment and fundus examination.

• **SWEPT-SOURCE OPTICAL COHERENCE TOMOGRAPHY:** Images of the optic disc and the macular region were obtained using a prototype SS OCT system (Topcon, Inc, Tokyo, Japan). The SS OCT has an acquisition rate of 100,000 A-scans per second operated at the 1-μm wavelength region. This instrument uses a wavelength-sweeping laser with a tuning range of approximately 100 nm as light source and has a center wavelength of 1050 nm, yielding an 8-μm axial resolution in tissue. These features allow penetration of deeper tissue through the retinal pigment epithelium into the choroid. The device has been described in more detail elsewhere.[17,26]

Four different scan protocols were used for evaluation of choroidal thickness. First, a 3-dimensional (3D) imaging data set was acquired with a 6 × 6-mm raster scan centered on the optic disc (optic disc protocol) composed of 256 B-scans, each consisting of 256 A-scans (total, 65,536 axial scans/volume) with an acquisition time of approximately 0.66 seconds. The resulting scan provides a 3D image of the optic disc and surrounding area. Second, the same 3D imaging data set was obtained covering an area of 6 × 6-mm centered on the fovea (macula protocol). Third, a radial scan protocol centered on the optic disc (12 lines, each composed of 32 B-scans, with each B-scan composed of 1024 A-scans) with an acquisition time of 4 seconds was obtained (Supplemental Figure 1, available at AJO.com). Fourth, a 12-mm horizontal line scan protocol, centered between the optic disc and the fovea and composed of 1024 A-scans for each of 96 B-scans, was obtained (acquisition time, 1 second; Supplemental Figure 2, available at AJO.com).

All scan protocols were acquired in the described order. Each scan protocol was repeated 3 times consecutively on the same visit. Participant and device were repositioned after each scan. The choroidal reference position was used for all scans. The centering of scans was achieved by internal fixation and confirmed by a fundus camera integrated in the instrument. Two experienced examiners (A.J.T., N.M.) scanned all participants. Measurements of both eyes of each study participant were obtained through undilated pupils. To be included in the analysis, all images had to have an image quality score of 45 (of 160) or more, according to manufacturer recommendation. The detailed image quality calculation is generated by a proprietary algorithm that produces an image quality score in the range of 0 to 160, which corresponds to an estimate of the signal-to-noise ratio specifically for the retinal signal. A score of 160 indicates that the all-retinal signal is of greater intensity than the estimated background, whereas a score of 0 indicates that the all-retinal signal is indistinguishable