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Wide field of view swept-source optical coherence tomography for peripheral retinal disease

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Abstract

Background/Aims—To assess peripheral retinal lesions and the posterior pole in single, widefield optical coherence tomography (OCT) volumes.

Methods—A wide field of view swept source OCT (WFOV SSOCT) system was developed using a commercial swept source laser and a custom sample arm consisting of two indirect ophthalmic lenses. Twenty-seven subjects with peripheral lesions (choroidal melanomas, choroidal nevi, sclerochoroidal calcification, retinitis pigmentosa, diabetic retinopathy, retinoschisis, and uveitis) were imaged with the WFOV SSOCT. Volumes were taken in primary gaze. Using the optic nerve to fovea distance as a reference measurement, comparisons were made between the lateral field of view (FOV) of the WFOV SSOCT, current generation spectral domain OCT (SDOCT), and widefield scanning laser ophthalmoscopy (SLO) of the same eyes.

Results—Peripheral pathologies were captured with WFOV SSOCT in 26 of the 27 subjects. The one not captured was in the far nasal periphery and was not seen in the primary gaze volume. Posterior pole associated pathologies were captured in all subjects. Current generation SDOCT had a mean lateral FOV of 2.08 ± 0.21 optic nerve-to-fovea distance units, WFOV SSOCT had a FOV of 4.62 ± 0.62 units, and SLO had a FOV of 9.35 ± 1.02 units.

Conclusion—WFOV OCT can be used to examine both peripheral retinal pathology and the posterior pole within a single volume acquisition. SLO had the greatest FOV, but does not provide depth information. Future studies using widefield OCT systems will help further delineate the role of WFOV OCT to quantitatively assess and monitor peripheral retinal disease in three dimensions.

MeSH Keywords

optical coherence tomography; melanoma; nevus; retinitis pigmentosa; diabetic retinopathy; uveitis

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Competing Interests

D. Grewal, R. Mehta, S.G. Schuman, T.H. Mahmoud, and P. Mruthyunjaya have no related financial disclosures.

INTRODUCTION

Optical coherence tomography (OCT) has revolutionized clinical observation of the retina since its inception and is an indispensable part of modern ophthalmic practice.^{1,2} Unlike other ophthalmic imaging techniques, OCT provides three-dimensional (3D) information about the imaged retina. However, the common clinically available OCT systems' current field of view (FOV) in the United States is only up to approximately 30°. ³ This FOV is sufficient to examine macular diseases that primarily affect the posterior pole, but for conditions that affect the retinal periphery, this standard FOV may be insufficient to capture 3D information about the disease process.

When standard FOV OCT systems are aimed appropriately, they can be used to image peripheral retinal pathology clinically,⁴⁻⁹ but there are potential challenges associated with this type of use. These challenges include optical distortions, limited depth range, increased scan time for multiple scan positions, and post-processing time if images are montaged.¹⁰ To address these challenges, widefield OCT systems have been developed ranging from research modifications¹¹⁻¹² to commercial systems from Optovue, Topcon, Nidek, and Heidelberg that are available internationally.¹³⁻¹⁵ These commercial systems have reported scan ranges of 45° to 55°.

In this work, we describe the development of a wide FOV (80° relative to posterior nodal point of a normal eye or 20mm by 20mm on the retina) swept source OCT system using off-the-shelf parts capable of high resolution imaging of both the posterior pole and more peripheral regions in a single volume acquisition. In addition, we show its feasibility and utility for assessing common peripheral retinal pathologies such as choroidal tumors, retinitis pigmentosa, diabetic retinopathy, retinoschisis, and uveitis.

METHODS

Wide field of view swept source OCT (WFOV-SSOCT) system

Our WFOV-SSOCT system was based on a commercially available swept source laser ($\lambda_0 = 1050\text{nm}$, $\lambda = 100\text{nm}$, Axsun Technologies, Inc.) with an A-scan rate of 100 kHz. A custom retinal sample arm was created using two clinical widefield, indirect ophthalmic lenses (Volk V20LC, V40LC; Mentor, OH). These double aspheric lenses were chosen for their known clinical performance in peripheral retinal viewing. The retinal FOV of this OCT system relative to the posterior nodal point of a schematic model eye¹⁶ was 80°. Prior to each imaging session, light output from the system was measured using a power meter (Thorlabs S120VC sensor and PM100D console; Newton, NJ) and attenuated to ensure that ocular light exposure was below maximum permissible exposure for this wavelength range.¹⁷

Current clinical OCT systems often decrease scan time by densely sampling the B-scan dimension (commonly nasal-temporal) and sub sampling the perpendicular dimension (commonly inferior-superior). For our volumes, we opted instead to have isotropic lateral sampling resolution to allow arbitrary, non-horizontal volume slicing in post-processing.

The imaging depth range was 3.2 mm in air. At an A-scan rate of 100 kHz, a $688 \times 720 \times 720$ (depth $\times$ A-scans $\times$ B-scans, all dimensions in pixels) wide FOV volume was acquired in 5.2 seconds. This scan pattern was used for all but 2 subjects: in the first subject, a $651 \times 500 \times 500$ volume was acquired (2.5 seconds), and in one cooperative later subject, a larger $688 \times 1000 \times 1000$ volume was acquired (10 seconds). The lateral sampling density affected only the acquisition time. The optical FOV was independent of the sampling.

In addition to the volume, registered and averaged B-scans at $[688 \times 2500] \times 100$ were acquired in 2.5 seconds. During image acquisition, images were viewed in real time using custom software with graphics processing unit acceleration enabled (Keller B, et al. IOVS 2014;55: ARVO Abstract 1631). ImageJ (U.S. National Institutes of Health; Bethesda, MD) was subsequently used to regenerate the *en face* voxel projection, volumetric data, and averaged B scans from the saved processed data format. Additionally, custom, non-horizontal B scans through targeted regions were extracted from the isotropic volumetric data using ImageJ.

Imaging of peripheral retinal pathologies

Twenty-seven subjects with peripheral retinal pathologies were recruited from the Ocular Oncology and Retina clinics of the Duke Eye Center. Informed consent was obtained from each subject under a Duke University Medical Center Institutional Review Board approved protocol prior to any imaging. The study was performed in accordance with HIPAA regulations.

Subjects were imaged with the WFOV-SSOCT after their standard of care clinical exam which included dilation. Each subject was seated, and a standard interface consisting of a chin and forehead rest was used to stabilize each subject. Each subject was asked to simply gaze straight ahead in primary gaze; no redirection was performed. A volume and an averaged B scan in the eye with the peripheral retinal pathology were then acquired with the scan densities described above.

Comparison with other clinical imaging modalities

As part of their standard of care clinical exam, subjects also had current generation OCT imaging (Heidelberg Spectralis; Carlsbad CA) using the 61 line raster scan protocol, and 21 of 27 subjects had widefield scanning laser ophthalmoscope imaging (SLO: Optos 200Tx; Marlborough, MA).

The horizontal FOV of each imaging modality was measured using optic nerve to fovea distance units (center of optic nerve to center of fovea centralis in the *en face* images or B scans) as illustrated in Fig. 1. This internally referenced measure (optic nerve to fovea distance units) allowed comparison between different imaging modalities though in a qualitative sense. In some current generation OCT images, the center of the optic nerve was not present in the B scan. In those cases, the edge of the B scan including any portion of the optic nerve was used as the center of the optic nerve. This method overestimated the FOV for the current Heidelberg OCT system, but allowed us to obtain at least an estimate of the FOV instead of recording no measurement for this parameter.

RESULTS

Choroidal tumors

16 subjects (7 males, 9 females; mean age 60.4 ± 10.6 years) with choroidal tumors were imaged with WFOV-SSOCT. Of these, 13 subjects were diagnosed with choroidal melanomas (CMM), 2 with choroidal nevi (Fig. 2), and 1 with a sclerochoroidal calcification (Fig. 3). All CMM subjects had been treated previously with plaque I-125 brachytherapy and had associated macular findings including cystoid macular edema (CME), subretinal fluid, epiretinal membranes, and retinal atrophy.

The targeted tumor was imaged and identified in 15 of 16 subjects with the single volume WFOV-SSOCT acquisition in primary gaze. The one that was not captured within a single volume in primary gaze was a CMM in the far nasal periphery. For comparison, the targeted tumor was captured in only 2 of 16 subjects with the current generation spectral domain OCT in primary gaze. However, for the purposes of clinical care, the tumor could ultimately be imaged with the current generation spectral domain OCT with non-primary gaze redirection but also with variable image quality.

Retinal architecture and the deep choroid – including the choroidal scleral junction – were readily visible in all subjects with the WFOV-SSOCT. This allowed not only confirmation of the choroidal location of the tumors but also visualization in the same single volume of any associated CME, subretinal fluid, epiretinal membranes, retinal atrophy, and – in one subject – prominent glaucomatous optic nerve cupping. Visualization of the choroid was also useful for examining choroidal transitions around and over particular lesions such as with the scleral mass in Fig 3.

The posterior (deep) boundary of the tumor was visible in only one subject with a choroidal tumor. In the remainder of the tumors, the OCT light was absorbed within the thick, pigmented tumors which limited depth visualization of the posterior boundary.

Retinitis pigmentosa, Diabetic retinopathy, Retinoschisis, and Uveitis

2 subjects with retinitis pigmentosa (one with Usher's syndrome) were imaged (2 females aged 42 and 61). In both, peripheral retinal atrophy with anterior migration of retinal pigment epithelium (bone spicules) was readily visualized. Within the single volume acquisitions, retinal layers and choroid were visualized, allowing identification of features such as a lamellar macular hole in one subject (Fig. 4).

4 subjects with various degrees of proliferative diabetic retinopathy were imaged (4 females; mean age 57.0 ± 21.4 years). Representative images are in Fig. 5A–G. In these WFOV OCT volumes, peripheral pathologies such as retinoschisis with vitreous traction and atrophic peripheral outer retinal changes were visualized in addition to the macula.

5 subjects with posterior uveitis were imaged (4 females, 1 male; mean age 48.8 ± 20.5 years). Representative images from a subject with Vogt-Koyanagi-Harada syndrome are seen in Fig. 5H–K. In this WFOV OCT volume, diffuse shallow subretinal fluid with subretinal

hyperreflective dots, extending beyond the macula from resolving inflammation could be seen.

Field of View Comparison

The mean horizontal FOV for the WFOV-SSOCT was 4.62 ± 0.62 optic nerve to fovea distance units (27 subjects). For standard current generation OCT, the mean horizontal FOV was 2.08 ± 0.21 optic nerve to fovea distance units (26 subjects). For SLO (Optos), the mean horizontal FOV was 9.35 ± 1.02 optic nerve to fovea distance units (21 subjects).

DISCUSSION

It is important to detect architectural changes caused by peripheral retinal pathology to aid in their identification, characterization, and diagnosis. Three dimensional OCT can clearly differentiate between different lesions like sclera-choroidal calcification, congenital hypertrophy of the retinal pigment epithelium, choroidal metastasis, and choroidal nevi.^{18–21} However, most available macular scanning OCT systems have limited ability to scan the entirety of a peripheral retinal lesion, especially the anterior border of lesions. Furthermore, with these systems, it is not easy to obtain high density image stacks in the periphery. Cooperative patient redirection is required to reach the periphery making it difficult to recapture the same area in subsequent exams. In this pilot work, we have shown that WFOV OCT allowed 3D imaging of both peripheral retinal lesions and important macular features within the same volume scan with the patient fixating only in primary gaze.

Overall, this WFOV-SSOCT visualized slightly more than twice the lateral extent of current generation macular OCT. The widefield SLO provided the most lateral FOV, but the SLO images do not contain the 3D depth information present in OCT images. In the WFOV-SSOCT images, assessment of the retinal and choroidal morphology of peripheral retinal lesions as well as any associated changes in the posterior pole (e.g., intraretinal cysts and fluid, subretinal fluid, epiretinal membranes, integrity of the external limiting membrane and ellipsoid zone) was possible within the same single volumetric scan. It should be noted that the relative FOV measurements provided here are not absolute quantitative measurements as we did not stereographically project the images²² for any modality. Using relative internal landmarks (nerve head to fovea) result in estimates that may overestimate the area of the periphery and total FOV for the wider SLO and hence the OCT FOV may be relatively underestimated. Development of a stereographic projection algorithm that includes ocular axial length²³ for devices other than SLO would enable more accurate, absolute quantitative measurements for interdevice comparisons.

Other techniques to obtain wide FOV with OCT including research and commercial systems are available. Of the commercial systems, the largest reported scan range is currently 55°. While this is less than the FOV of our system and another research system,¹² we expect that continued development by commercial vendors will produce comparable FOV in the near future. Also, of the commercial systems, two are spectral domain systems and one is swept source as was used in this work. This feature is notable given the advantages in imaging speed and depth penetration of longer-wavelength swept source over spectral domain systems and explains our choice of a swept source OCT engine.

Imaging speed is particularly important as the scan FOV increases. OCT is a scanning technique that requires multiple individual A-scan imaging across the retina to create a volume. For a given A-scan resolution, increasing the FOV requires a geometric increase in the number of A-scans needed to create the volume; doubling the FOV from regular to widefield OCT requires greater than double the number of A-scans for the same resolution. This substantial increase in A-scans requires an increase in scan time which in turn increases patient motion, blinks, and other artifacts. While our use of a 100 kHz swept source engine (about 1.5–5× faster than most available SDOCT systems) mitigated most patient motion, artifacts were still present in some volume acquisitions (e.g., Fig. 3C). Scan time could be decreased by reducing the number of A-scans but at a cost of reduced resolution. Alternatively, faster sources and detectors could be used. A custom laboratory laser source running at a 1.68 MHz A-scan rate was recently used for widefield volumetric OCT in the eyes of six normal volunteers.¹²

Swept source systems with a 1050 nm source also provide increased depth visualization. This approach can be useful to image deeper retinal lesions without SDOCT enhanced depth imaging (EDI) techniques.²⁴ In most images acquired by our WFOV SSOCT, the choroid was visualized without using EDI techniques. This method allowed us to visualize the transition between normal and abnormal choroid areas and the choroidal architecture across a wide FOV (e.g., Fig. 3E) -- not just local to the lesion. The increased depth sensitivity and range afforded by swept source is also important when one images widely across the back of the curved eye because there are large changes in elevation from the peripheral to central retina. This allowed us to readily visualize the elevation of a peripheral retinoschisis with a single, primary gaze volume. However, when safe light exposure levels are used, there are limits to light penetration and recovery from very thick, pigmented lesions, and therefore our ability to see the deep border of CMMs was limited despite the use of longer wavelength SSOCT.

There were some limitations we encountered using our system. The volumes were acquired with subjects looking only in primary gaze. In some cases, the lesion extended beyond this field of view. As with other OCT systems, redirecting patient gaze would allow full coverage of the peripheral lesion but would require multiple volumes and montaging to create a unified volume. Lateral resolution can also be affected by more peripheral, off-axis scanning. With the signal to noise benefit from averaging, though, retinal layers in the periphery can still be distinctly visualized with our WFOV SSOCT system despite any peripheral losses in lateral resolution and remain qualitatively comparable to standard SDOCT. When arbitrary sections without averaging were taken through the captured OCT volume in post-processing, there was more variability in image quality with significant losses in some cases and less so in others. More consistent image quality could be obtained in these arbitrary sections by intentionally taking averaged scans at those meridians or by increasing system speeds to limit motion artifacts. Additionally, customized widefield sample arm development²⁵ would help improve lateral resolution peripherally, particularly to extend FOV beyond the limits of currently available ophthalmic lenses.

In conclusion, we have demonstrated the feasibility of widefield examination of peripheral retinal pathology and the posterior pole within a single, seconds long OCT volume

acquisition. Future studies using widefield OCT systems will help further delineate the role of WFOV OCT to quantitatively assess and monitor peripheral retinal disease in 3D.

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Figure 1. Field of view (FOV) measurement in a normal subject for A. wide field scanning laser ophthalmoscope (SLO), B. current generation spectral domain optical coherence tomography (SDOCT, Heidelberg), and C. wide FOV swept source OCT (SSOCT) in a normal subject

The greyscale summed voxel projection from the wide FOV SSOCT volume is overlaid over the SLO image in 1A for comparison. The white dotted line represents the optic nerve to fovea distance and is used as the reference unit of measurement for the horizontal FOV of each system. In this subject, the current generation SDOCT has a horizontal FOV of 1.9 optic nerve-to-fovea distance units, the wide FOV SSOCT has a FOV of 4.2 units, and the wide-field SLO has a FOV of 9.3 units.

Figure 2. Wide FOV images of a choroidal nevus (white arrows) and associated subretinal fluid
A: Red/green and **B:** autofluorescence SLO images. **C:** Wide FOV swept source OCT (WFOV SSOCT) summed voxel projection composed of B scans (blue and green lines indicate cross sectional scans in 2D and 2E). Subtle elevation of the retinal vessels over the nevus can be seen. **D:** WFOV SSOCT averaged B scan through fovea and optic nerve head demonstrating normal foveal contour with preserved external limiting membrane and ellipsoid zone. **E:** Unaveraged B scan from same WFOV SSOCT volume as Top Middle image at a custom angle showing the peripheral choroidal nevus with subretinal fluid at the

nasal margin of the nevus, mild overlying retinal pigment epithelium alteration, absence of overlying drusen, and loss of choriocapillaris over the lesion. The posterior margin of the nevus was not completely visualized. The graininess in the images is due to the unaveraged nature of this arbitrarily cut B scan.

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Figure 3. Wide FOV images of a calcified scleral mass seen in the superotemporal macular region (white arrow)

A: Red/green SLO. **B:** Standard field of view clinical SDOCT B-scan showing only the lesion due to limits on field of view. Scleral thickening compressing the overlying choroid is seen. **C:** Three-dimensional rendering of wide field of view swept source OCT (WFOV SSOCT) volume with large elevated mass (white arrow), fovea (green arrow), and optic nerve head (blue arrow). Fine horizontal “ripples” on the retinal surface are due to patient motion captured during the volume scan. **D:** Un-averaged custom oriented WFOV SSOCT B scan through data in 3C showing both the lesion and optic nerve head in the same scan. **E:** Averaged horizontal WFOV SSOCT B scan through lesion. In both 3D and 3E, scleral thickening with overlying choroidal atrophy due to compression with loss of choriocapillaris and retinal pigment epithelial atrophy is seen. There is no subretinal fluid present.

Figure 4. Wide FOV images of retinitis pigmentosa (RP) and a lamellar macular hole
A: Red/green SLO image. **B:** Wide FOV swept source OCT (WFOV SSOCT) summed volume projection with blue arrow locating the **C:** WFOV SSOCT arbitrary direction B-scan through fovea and optic nerve head. The foveal area has a lamellar macular hole (arrowhead), extensive outer retinal atrophy with loss of subfoveal external limiting membrane and ellipsoid zone, and alteration of subfoveal choroidal morphology. Peripherally in the same B-scan, advanced retinitis pigmentosa with significant choroidal and retinal atrophy temporally and nasally with inner retinal hyperreflectivity corresponding to the bone spicules is present. The graininess in the image is due to the unaveraged nature of this arbitrarily cut B scan.

Figure 5. Wide FOV OCT images of proliferative diabetic retinopathy (PDR) with retinosis, PDR with peripheral ischemia, and also images of uveitis
PDR with retinosis. **A:** Wide FOV swept source OCT (WFOV SSOCT) summed volume projection with blue arrow locating the cross sectional scan in B and the green arrow the cross sectional scan in C. **B:** WFOV SSOCT B-scan through fovea and optic nerve head. The temporal retina shows retinoschisis, and there is absence of macular edema (white arrow) with relative preservation of the outer retinal bands. **C:** WFOV SSOCT B-scan through the area of peripheral retinoschisis showing the area of vitreous traction corresponding to the inactive fibrovascular proliferation. WFOV SSOCT allowed confirmation of absence of inner retinal breaks in the areas of retinoschisis.
PDR with peripheral ischemia. **D:** Wide field SLO fluorescein angiogram (late phase) showing a preserved central macular island of perfusion with extensive peripheral ischemia

and staining corresponding to dense pan retinal photocoagulation scars. **E:** WFOV SSOC T summed volume projection with blue arrow locating the cross section in F and the green arrow the cross sectional scan in G. **F:** WFOV SSOC T B-scan through fovea and optic nerve head. There is disorganization of the retinal inner layers in the macula, absence of diabetic macular edema and severe peripheral retinal thinning and atrophy (also in **G**) corresponding to the peripheral ischemia seen on the fluorescein angiogram.

Uveitis (Vogt-Koyanagi-Harada syndrome). **H:** Red/green SLO image with macular SDOCT inset (arrow indicates approximate scale) taken at initial presentation. There is a pronounced serous retinal detachment involving the macula and extending nasally. The SDOCT obtained at this initial presentation showed subretinal fluid with hyperreflective material extending beyond the margins of the scan and loss of outer retinal layers and granular deposits anterior to the retinal pigment epithelium. **I:** WFOV SSOC T summed volume projection with blue arrow locating the cross section in J and the green arrow locating the cross section in K. **J:** WFOV SSOC T scan through the fovea obtained 2 months after starting immunosuppressive therapy showing significant improvement in the subretinal fluid with persistent mild choroidal thickening. There is a thin residual sliver of subfoveal subretinal fluid (inset) with subretinal hyperreflective dots. **K:** WFOV SSOC T B-scan through a different area of the volume. Residual subretinal fluid with hyperreflective dots is also present here with loss of outer retinal structures. The yellow arrow corresponds to the location in the projection in I. Other localized areas similar to this were present throughout this volume.