Noninvasive Imaging of the Outflow Pathway

Update on OCT technology for visualizing Schlemm canal.

BY LARRY KAGEMANN, PHD, AND JOEL S. SCHUMAN, MD

Higher resolution and faster scanning have extended the application of optical coherence tomography (OCT) technology in ophthalmology far beyond measuring the macula and retinal nerve fiber layer thickness. As recently as 5 years ago, the first reports of the visualization of Schlemm canal by OCT scans were published.[1,2] Since then, the noninvasive imaging of the primary aqueous humor outflow pathway has spurred a new and promising branch of research that may find applications in clinical practice. OCT technology could facilitate glaucoma specialists' assessment of the patency of the outflow pathway and improve surgical planning by giving them foreknowledge of the optimal sites for procedures targeting Schlemm canal.

OVERVIEW OF CURRENT DEVICES

Of the commercially available retinal OCT devices, only one comes equipped for anterior segment scanning, the Cirrus (Carl Zeiss Meditec, Inc.). A built-in internal lens automatically configures the device for anterior segment imaging when an anterior scan protocol is selected. The HS-100 (Canon Medical Systems) requires an optical adapter, the RTVue has a CAM option (cornea-anterior module; Optovue, Inc.), the Spectralis (Heidelberg Engineering GmbH) has an optional anterior segment module, the Optos OCT SLO (Optos) has a cornea lens, and the 3D OCT 2000 (Topcon Medical Systems, Inc.) has an optional anterior segment attachment.

Logistically, the Cirrus greatly facilitates the clinical examination of the anterior segment, because hardware adjustments are not required to allow changes from retinal to limbal scans. On the other hand, limbal scans from the Cirrus require additional processing to adequately visualize Schlemm canal (unlike the other OCT devices in our clinic). Figure 1 shows the quality of a typical Cirrus scan of the limbus, with the arrow identifying Schlemm canal. Customized averaging greatly improves scan quality by clarifying the boundaries of the canal and bringing a number of distal aqueous vessels into view.

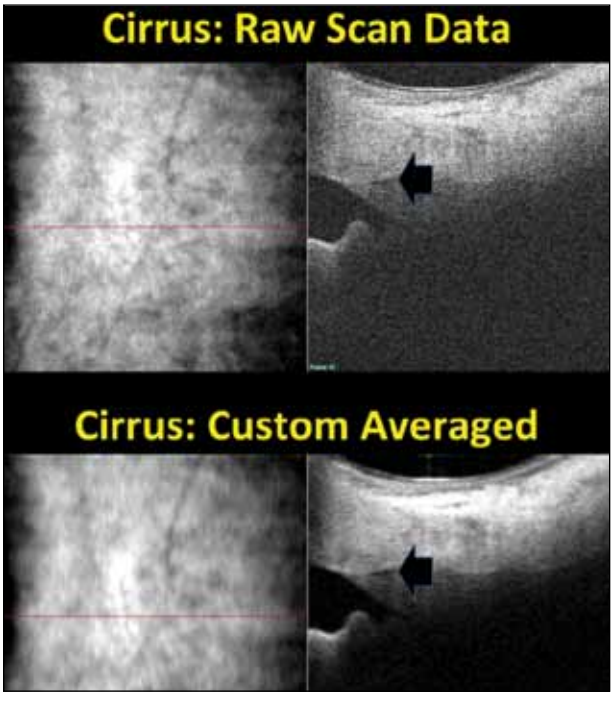

Figure 1. Raw scans of the anterior segment taken with the Cirrus (top) benefit greatly from customized averaging (bottom) to enable visualization of Schlemm canal (arrow). Images on the left are enface views of the scanned limbus, with the red line identifying the location of the B-scan slice (right).

None of the currently available OCT scanners is specifically designed for scanning Schlemm canal and the aqueous humor outflow system, a procedure we have begun to call *OCT canalography*. Consequently, the acquisition of high-quality "canalograms" is a learned art, requiring patience and practice on the part of the imaging technician. Optimal canalograms are those in which Schlemm canal is slightly off-center in the scan window, favoring tissues of the sclera posterior to the limbus (Figure 2). This orientation provides visualization of the rich vascular

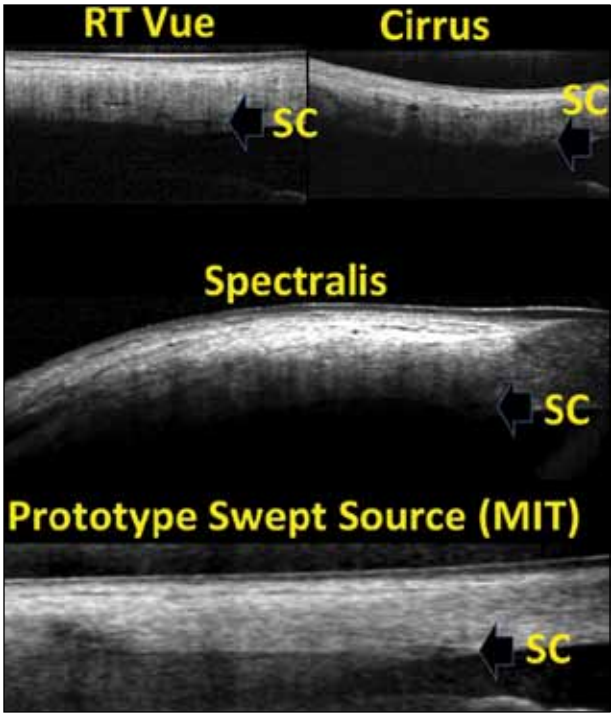

Figure 2. The processed 4-mm Cirrus scan is nearly on par with raw 3-mm RTVue and wide-field Spectralis OCT canalography for visualization of Schlemm canal (arrows). None of the commercially available units (light sources centered near 850 nm) offers the superior penetration of the 1,060-nm centered, prototypic, swept-source OCT scan from Dr. Fujimoto's laboratory at the Massachusetts Institute of Technology (bottom).

networks distal to Schlemm canal. More importantly, the best light penetration into the deep limbus occurs when the surface of the limbus is approximately horizontal in the scan window (Figures 1 and 2). With head-on images, visualization of the limbus at the depth of Schlemm canal is obscured by shadows and poor signal quality.

TECHNIQUE

Traditionally, histological visualization of the outflow pathway is accomplished in radial sections. We have continued that tradition in our OCT canalograms. To that end, comprehensive examination of the limbus requires that the OCT unit allow free rotation of the raster scan pattern. The default orientation of all scanners is currently horizontal fast scans (B-scans) stacked either superior to inferior or vice versa. Horizontal scans provide radial sections of the nasal and temporal quadrants alone. This is a limitation for the Cirrus OCT, which only provides horizontal raster scanning. The RTVue and Spectralis both allow the user to designate any scanning angle, facilitating 360º raster scan orientation and radial optical sectioning of the limbus.

FUTURE DIRECTIONS

We expect future OCT scanners to truly leverage the three-dimensional (3D) volumetric data contained in scans of aqueous humor outflow. We have demonstrated how to stitch an overlapping array of radial scan samples of the limbus to process and build a 3D visualization of the outflow vasculature distal to Schlemm canal.[3,4] The best 3D imaging is accomplished with a uniform distribution of A-scans throughout the volume, but no clinical scanner provides such a scanning protocol. The Cirrus anterior segment raster scan pattern uses 512 × 128 A-scans, the RTVue only 106 B-scans, and the Spectralis uses only 136 B-scans. Each device provides a higher density of A-scans in the fast direction, yielding B-scans of good quality but sacrificing quality in the slow direction.

As technology continues to improve and 3D volumetric data processing matures, scanning densities will become standardized and uniform. Processing algorithms will also continue to develop, allowing virtual isolation and visualization of the structures of the aqueous humor outflow system. ■

Larry Kagemann, PhD, is an assistant professor at the University of Pittsburgh School of Medicine in the Department of Ophthalmology, and he has a secondary academic appointment in the University of Pittsburgh Swanson School of Engineering in the Department of Bioengineering. He acknowledged no financial interest in the products or companies mentioned herein. Dr. Kagemann may be reached at (412) 648-6409; lek19@pitt.edu.

Joel S. Schuman, MD, is the Eye and Ear Foundation professor and chairman of the Department of Ophthalmology at the University of Pittsburgh School of Medicine, and he is the director of the UPMC Eye Center. He is also a professor of bioengineering at the University of Pittsburgh School of Engineering and a professor at the Center for the Neural Basis of Cognition, Carnegie Mellon University and University of Pittsburgh. He receives royalties for intellectual property licensed by the Massachusetts Institute of Technology and the Massachusetts Eye and Ear Infirmary to Carl Zeiss Meditec, Inc. Dr. Schuman may be reached at (412) 647-2205; schumanjs@upmc.edu.

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