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Review article

Choroidal imaging by spectral domain-optical coherence tomography☆

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ABSTRACT

Despite the fact that the choroid plays an important role in the structure and function of the eye, it has not been studied in detail *in vivo*. Improvements in optical coherence tomography (OCT) imaging technology allow the routine imaging of the choroid and deep optic nerve structures in most patients. As with any new technology, it needs validation in both healthy and diseased eyes. Reproducible measurements of choroidal and lamina cribrosa thickness are possible. Several variables such as age, axial length, and time of day, affect choroidal thickness and must be taken into account when interpreting data on choroidal thickness. Lamina cribrosa thickness appears to be affected by age as well but other factors need to be determined. Choroidal thickness may be used to differentiate between central serous chorioretinopathy (CSC), polypoidal choroidal vasculopathy (PCV) and exudative age-related macular degeneration (AMD). Enhanced depth imaging-optical coherence tomography (EDI-OCT) of the choroid may detect tumors not detectable by ultrasound. Studying the choroid may help us gain insight into the pathogenesis of several diseases such as AMD, CSC, glaucoma, posteriorly located choroidal tumors, and PCV among others.

1. Introduction

The choroid plays an important role in the structure and function of the normal eye. Most of the ocular blood flow is accounted for by the choroidal circulation. In fact, the choroid has one of the highest blood flow rates in the entire body. In addition, the choroid supplies oxygen and nutrients to the outer retinal layers.[1] An understanding of the pathophysiological changes that occur in the choroid is of paramount importance in understanding disease of the posterior segment of the eye.

Despite advances in imaging technology, adequate visualization of the choroid is still lacking. Traditional imaging modalities used to study the choroid such as indocyanine green angiography (ICGA) and B scan ultrasonography have limitations with regard to image resolution and measurement accuracy.

Optical coherence tomography (OCT) is a non-invasive, noncontact transpupillary imaging modality that has revolutionized ophthalmic clinical practice. It utilizes light to image tissue using low coherence interferometry.[2] Time domain OCT does not image the posterior choroid and sclera adequately. Current commercially available spectral domain (SD)-OCT systems may be modified to allow adequate choroidal imaging.

2. OCT choroidal imaging

There are a few strategies that may improve choroidal OCT imaging, namely bringing the choroid closer to the zero delay line using SD-OCT using a light source with a longer wavelength or using swept source OCT.

During SD-OCT imaging, a beam of low coherence light from a superluminescent diode is split through a beam splitter into a sample and a reference beam. Light from the sample beam is directed toward the tissue of interest, in this case the posterior segment of the eye, and depending on the composition of the internal tissue structures, the sample beam will be reflected towards the detector with different echo time delays. The reference beam is reflected from a reference mirror towards another detector. Both reflected beams of light are compared and combined into an interference pattern by a modified Michelson interferometer, called the spectral interferogram or spectrometer.[2,3] Fourier equations transform this spectral interferogram into two OCT

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mirror images. The screen of the OCT instrument only depicts one of these images. By convention, the image depicted places the vitreous at the top of the screen and the choroid towards the bottom of the screen. In this position, the vitreous is at the peak of the OCT sensitivity curve and closer to the zero delay line.[4,5] When an OCT instrument is positioned closer to the eye, the inverted mirror image is obtained and the choroid approaches the zero delay line. This inverted mirror image has more information from the deep choroid than the normal noninverted image (Fig. 1). Eye tracking and image averaging capability are important features that improve the signal-to-noise ratio with resulting improvement of visualization of the choroid. In order to obtain the best quality image, it is important to try to keep the image straight and to keep the inverted image close to the top of the screen. Spaide and collaborators [4,5] coined the term enhanced depth imaging (EDI) to describe this novel choroidal OCT imaging technique using the Spectralis (Heidelberg Engineering, Heidelberg, Germany) OCT system. The most recent Spectralis software version makes EDI even more user friendly by incorporating EDI into the scanning protocols. Therefore, all the operator needs to do is press the EDI button, and the software automatically inverts the image. Image averaging, eye tracking, high-speed scanning, and low speckle noise produce high-quality choroidal images with the EDI mode in the Spectralis OCT.

Most commercially available OCT systems use a light source of approximately 800 nm, which penetrates the choroid and sclera poorly. Both the photoreceptor and retinal pigment epithelium (RPE) layers scatter the 800-nm light signal, resulting in a weak signal from the choroid (Fig. 1). An investigational OCT device that uses a light source of 1060 nm has been developed. The longer wavelength of the light source permits a higher penetration and visualization of the choroidoscleral interphase allowing accurate measurement of the choroidal thickness.[6]

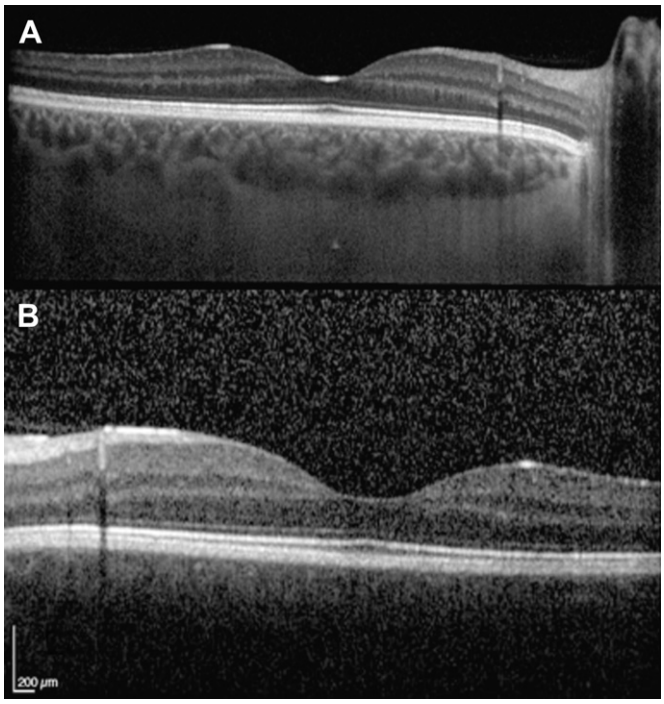

Fig. 1. Comparison between conventional Spectralis optical coherence tomography (OCT) scanning and enhanced depth imaging (EDI) OCT scanning of the macula of the same patient. (A) EDI-OCT showing choroidal details and the choroidal scleral interphase. (B) Conventional OCT showing no choroidal details.

Swept source OCT is another device that uses a frequency swept laser with a narrowband light source that is rapidly tuned over a broad optical bandwidth that enables the measurement of interference at different optical frequencies or wavelengths sequentially over time.[7] No spectrometer or line camera is needed for the Fourier transformation. This increases the imaging speed up to 300,000 axial scans per second and allows a deeper penetration of the sampling beam.

Choroidal imaging and thickness measurements have been reported with several commercially available OCT systems including the Cirrus (Carl Zeiss Meditec Inc, Dublin, CA), Topcon 3DOCT 2000 (Topcon Corporation, Tokyo, Japan), Optovue RTVue (Optovue Inc, Fremont, CA), Bioptigen (Bioptigen Inc, Research Triangle Park, NC, USA) and the Heidelberg Spectralis.[4,5,8] Not all machines are created equally. For instance, the Cirrus OCT system lacks eye tracking ability, and hence the averaging of the images is less likely to improve the signal-to-noise ratio. Furthermore, with Cirrus, it is unclear where the image is placed within the sensitivity curve.[9] As a matter of fact, with the Cirrus it is important not to bring the choroid to the zero delay line since image inversion with the Cirrus software results in images of very low quality.[8] Lin et al[10] compared the choroidal thickness, visualization of the choroido-scleral junction, and visibility of the large outer choroidal vessels across several SD-OCT systems using upright and inverted images. They reported that the most favorable modes to visualize choroidal details were Spectralis in either EDI or inverted mode, Bioptigen in the inverted mode and Cirrus in upright mode. They also stated that choroidal thickness cannot be compared between machines because of different conversion factors.[10]

3. Choroidal thickness in normal eyes

There is currently no automated segmentation software that is commercially available to measure the choroidal thickness. Therefore, once the EDI-OCT image is obtained, the choroidal thickness needs to be measured manually by using calipers to measure the distance from the outer border of the RPE to the inner surface of the sclera (Fig. 2). Investigators have recently unveiled an

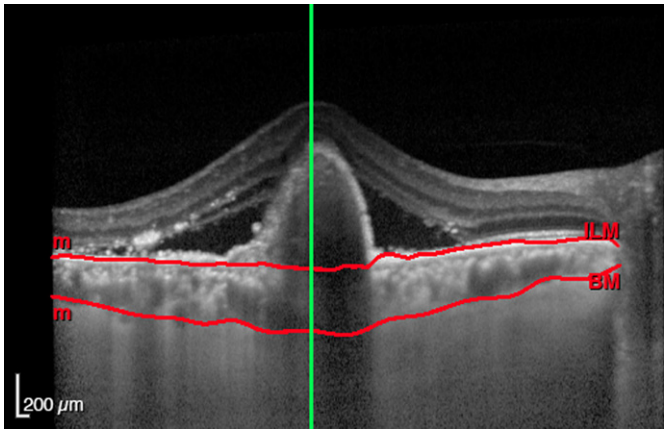

Fig. 2. There is currently no automated segmentation software available to measure the choroidal thickness in the Spectralis machine. Therefore, once the EDI-OCT image is obtained, the choroidal thickness needs to be segmented semi-automatically using the built-in automated retinal segmentation software on the Spectralis SD-OCT. By using the software of the Heidelberg spectralis we have manually moved the lines of the ILM to the RPE and the RPE to the chorioscleral junction. The retinal boundary reference lines placed by the built-in automated segmentation software were moved to the choroidal boundaries. BM = Bruch's membrane; EDI-OCT = enhanced depth imaging-optical coherence tomography; ILM = internal limiting membrane; RPM = retinal pigment epithelium; SD-OCT = spectral domain-optical coherence tomography.