HVM BIOFLUX
Human & Veterinary Medicine
International Journal of the Bioflux Society

The history and use of optical coherence tomography in ophthalmology

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Abstract. This paper presents the history and use of optical coherence tomography (OCT) in ophthalmology.
Key Words: optical coherence tomography, ophthalmology.

Rezumat. Această lucrare prezintă istoricul şi utilizarea tomografiei în coerenţă optică (OCT) în oftalmologie.
Cuvinte cheie: tomografia în coerenţă optică, oftalmologie.

Introduction. The application of optical technology in biology and medicine has a long and particular history (Schmitt 1999). Over the last 25 years, due to the growing application of the eye imaging for the diagnosis of ocular diseases, this field has recently grown significantly.

Optical coherence tomography (OCT) is an extension of optical coherence domain reflectometry (OCDR). OCT has attracted the attention of scientists working from the photonics field, out of a variety of techniques such as scanning laser polarimetry and confocal scanning laser ophthalmoscopy, because it is able to image and quantify microscopic details with high resolution (Schuman 2008).

The unique features of OCT make it a powerful imaging modality, which offers the greatest promise of delivering many fundamental research and clinical applications.

OCT had the most significant clinical impact in ophthalmology. OCT can provide quantitative information on retinal pathology and monitor disease progression in vivo that can't be obtained by any other method. Also, OCT can detect and diagnose early stages of disease before physical symptoms and irreversible vision loss to occur.

The latest technology in OCT included many changes that have improved axial and transverse resolution of the images and decreased the time necessary for image acquisition (Brezinski 2006).

OCT is a noninvasive, rapid and accurate, method applied in biomedical optics and medicine that uses low-coherence interferometry to determine the echo time delay and magnitude of backscattered light reflected off an investigated object.

This method can generate 3D images of the object internal structure such as the retina layers with very high axial resolution (3 - 12 μm) (Wojtkowski et al 2004 and 2005; Wollstein et al 2005; Ko et al 2005; Ţălu et al 2009).

OCT has been used most extensively for the diagnosis of diseases and disorders affecting the retina (Hee et al 1995; Zhu et al 2010). It has also been used successfully in the study of anterior segment of the eye because of its features on high resolution, non-contact, and easy anatomical interpretation (Arevalo 2008; Matonti et al 2009).

OCT technology was conceived in the Department of Electrical Engineering and Computer Science at Massachusetts Institute of Technology, USA (Cruz 2007).

In the laboratory of James G. Fujimoto, PhD, the first retinal imaging was done in 1989 by David Huang, MD, PhD, and Joel S. Schuman, MD and the data were reported in Science in 1991 (Huang et al 1991).

Eric Swanson, in 1993, designed the first clinical prototype ophthalmic OCT that was built in an engineering laboratory and installed at the New England Eye Center, Tufts - New England Medical Center, Tufts University School of Medicine in Boston, Massachusetts, USA. The ocular imaging of human subjects in vivo began in 1994 (Schuman 2008). The technology was ultimately sold on 1993 to Humphrey Instruments, a division of Carl Zeiss America™, which was later acquired by Zeiss.

Mr. Swanson, Dr. Puliafito, Dr. Schuman, Dr. Huang and Dr. Fujimoto created a start-up company in 1994 known as Advanced Ophthalmic Diagnostics (AOD) to transfer the technology to industry. In 1994 the technology was patented and subsequently transferred to industry to Carl Zeiss Meditec, Inc (Dublin, California). Clinical studies were performed between 1994 and 1995, and the first commercial available OCT, called OCT 1000, from Zeiss, was marketed in 1996 (Cruz 2007; Schuman 2008).

The 2nd-generation of the Zeiss instrument, resulting in OCT 2000, was introduced in 2000. The adoption of OCT proceeded slowly, with sales of only a few hundred units during a period of several years. The 3rd-generation, OCT 3 (Stratus OCT™) introduced in 2002, is considered the current standard for retinal imaging.

The first advanced OCT, known variously as Fourier domain OCT, SD-OCT, or hsHR-OCT, was commercially available in 2006. In contrast to the relatively slow TD-OCT market from 1993, Fourier Domain systems have moved relatively fast.

Measurements of axial eye length were the first biomedical applications of low-coherence interferometry (Fercher et al 1988). The first in vivo OCT images were presented by Fercher and associates (Fercher et al 1993) and later in 1995 the first images of retinal disease.

In 1994, Izatt and colleagues (Izatt et al 1994) presented the first imaging of the anterior eye. Subsequently, researchers have implemented for OCT the use of light wavelengths instead of time delay to determine the spatial location of reflected light. TD-OCT, the original OCT method, is based on the encoding of the location of each reflection in the time information relating the position of a moving reference mirror to the location of the reflection.

Spectral-domain detection technology (also named Fourier-domain detection technology based on the use of Fourier transformation of the frequencies of light reflected), acquires all information in a single axial scan through the tissue and detect all echoes of light from different delays simultaneously improving imaging speed. It is evaluated the frequency spectrum of the interference between the reflected light and a stationary reference mirror.

In 2002, Wojtkowski and colleagues (Wojtkowski et al 2001) presented the first SD-OCT ophthalmic scans where in vivo scans of the iris, lens, macula, and optic disc were all displayed. OCT has been mainly used in retinal imaging.

OCT can perform "optical biopsy", providing visualization directly and in real time, to guide microsurgical procedures minimally invasively in the eye and beyond. Also, OCT can monitor normal retinal function, the progression of retinal disease and other tissues characteristics.

Doppler OCT methods can provide informations about retinal blood flow (Wang et al 2011). Kagemann and colleagues (Kagemann et al 2007) used the spectral data of SD-OCT to assess blood oxygenation in retinal arteries and veins.

The emergence of ultrabroad bandwidth femtosecond laser technology has allowed the development of an ultra-high resolution OCT. Ultrahigh-resolution OCT was used in "optophysiology", to identify changes in the reflectance of certain layers of the in vivo retina following exposure to light and to improve the early diagnosis of various ophthalmic pathologies (Bizheva et al 2006).

OCT Techniques. OCT imaging is somewhat analogous to ultrasound B-mode imaging except that it uses light instead of sound, but as an optical echo technique has a higher resolution and does not require contact with the examined tissue.

OCT can be applied by two main methods: Time domain OCT (TD-OCT) and Spectral domain OCT (SD-OCT). Each method has its own distinct advantages and disadvantages (Brezinski 2006).

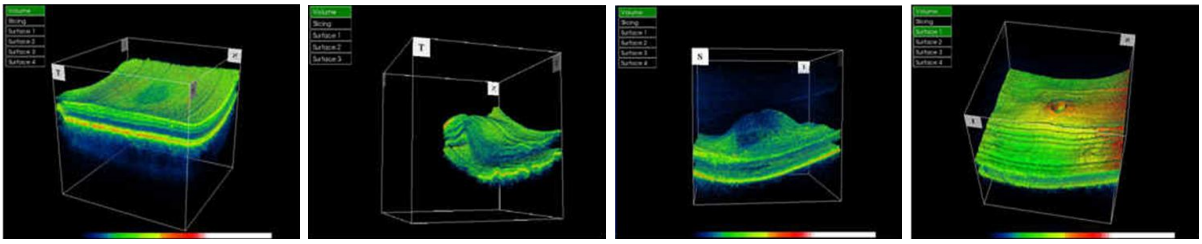
An imaging system has three scanning means, one to scan the object in depth and two others to scan it transversally. 1D scans are labeled as: A and T-scans, while 2D scans are labeled as B- and C-scans; A- and T-scans are 1D reflectivity profiles while B and C are 2D reflectivity maps or images (Podoleanu 2008).

TD-OCT produces two-dimensional images of the sample internal structure; the tissue-reflectance information in depth is gradually built up over time by moving a mirror in the reference arm of the interferometer.

SD-OCT can be implemented in two formats, Fourier domain (FD-OCT) and swept source (SS-OCT) (Podoleanu 2008).

SD-OCT units acquire entire A-scans in reflected light at a given point in tissue. Information on depth is transformed from the frequency domain to the time domain, without using a moving reference mirror obtain complete A-scans. The absence of moving parts allows the image to be acquired very rapidly - about 65 times faster than the older TD-OCT. The SD-OCT units has significantly better ability to detect and monitor of retinal diseases, because these ones have ultra high-speed scan rate, superior axial and lateral resolution, cross-sectional (2D) scan, 3D raster scanning and a high imaging sensitivity compared with the TD-OCT units. Also, the SD-OCT software allows many operations with 3D data relative to the traditional TD-OCT. The great number of scans done per unit time allows SD-OCT systems to generate 3D reconstructions, which can be further manipulated. Visualization of this data in 3D demonstrates subtle pathology that is not evident with traditional 2D images.

Some examples of the 3D FD-OCT imaging of the human retina performed by a Topcon 3D OCT-1000 unit (Japan, model 2007) are shown in Fig. 1 (Ţălu et al 2009).



a) b) c) d)

Figure 1. a) The normal macula; b) Central serous chorioretinopathy; c) Age-related macular degeneration; d) Epiretinal membrane with macular pseudohole.

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Received: 21 December 2010. Accepted: 10 April 2011. Published online: 12 April 2011.
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How to cite this article:
Ţălu Ş., Ţălu M., Giovanzana S., Shah R., 2011 The history and use of optical coherence tomography in ophthalmology. HVM Bioflux **3**(1): 29-32.