Available online at www.sciencedirect.com
SCIENCE DIRECT
Progress in Retinal and Eye Research 25 (2006) 325–353
Progress in RETINAL AND EYE RESEARCH
www.elsevier.com/locate/prer

Retinal assessment using optical coherence tomography ☆

Rogério A. Costa[a,*], Mirian Skaf[b], Luiz A.S. Melo Jr.[b], Daniela Calucci[a], Jose A. Cardillo[a], Jarbas C. Castro[c], David Huang[d], Maciej Wojtkowski[e]

[a]*U.D.A.T.—Retina Diagnostic and Treatment Division, Hospital de Olhos de Araraquara, Rua Padre Duarte 989 ap 172, Araraquara, SP 14801 310, Brazil*
[b]*Glaucoma Section, Hospital de Olhos de Araraquara, Araraquara, SP, Brazil*
[c]*Instituto de Física de São Carlos—USP, São Carlos-SP, Brazil*
[d]*Department of Ophthalmology, University of Southern California, Los Angeles, CA, USA*
[e]*Institute of Physics, Nicolaus Copernicus University, Torun, Poland*

Abstract

Over the 15 years since the original description, optical coherence tomography (OCT) has become one of the key diagnostic technologies in the ophthalmic subspecialty areas of retinal diseases and glaucoma. The reason for the widespread adoption of this technology originates from at least two properties of the OCT results: on the one hand, the results are accessible to the non-specialist where microscopic retinal abnormalities are grossly and easily noticeable; on the other hand, results are reproducible and exceedingly quantitative in the hands of the specialist. However, as in any other imaging technique in ophthalmology, some artifacts are expected to occur. Understanding of the basic principles of image acquisition and data processing as well as recognition of OCT limitations are crucial issues to using this equipment with cleverness.

Herein, we took a brief look in the past of OCT and have explained the key basic physical principles of this imaging technology. In addition, each of the several steps encompassing a third generation OCT evaluation of retinal tissues has been addressed in details. A comprehensive explanation about next generation OCT systems has also been provided and, to conclude, we have commented on the future directions of this exceptional technique.

Keywords: Artifacts; Cross-sectional; Fourier domain; Glaucoma; Interferometer; Macula; Macular map; Measurement; Nerve fiber layer; Optic disc; Optical coherence tomography (OCT); Photoreceptor; Retinal boundary; Retinal thickness; Spectral

Contents

Abbreviations: A-scan(s), axial scan(s); HRL, highly reflective layer; OCT, optical coherence tomography; RNFL, retinal nerve fiber layer; RPE, retinal pigment epithelium; RTA, retinal thickness analyzer; SLD, superluminescent diode

☆Supported in part by Fundação de Amparo à Pesquisa do Estado de São Paulo, FAPESP Grant no.: 98/14270-8, and by Grant no.: KBN 4T11E02322.

*Corresponding author. Tel./fax: +55 16 3331 1001.
E-mail address: roger.retina@globo.com (R.A. Costa).

1350-9462/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.preteyeres.2006.03.001

1. History of optical coherence tomography (OCT): conception of the idea

OCT was first developed by David Huang and colleagues in James Fujimoto's laboratory at the Massachusetts Institute of Technology (MIT) and published in a 1991 *Science* article (Huang et al., 1991). The Fujimoto's laboratory was specialized in femtosecond lasers at the time. These are lasers that emit pulses of only several tens of femtosecond (million billionth of a second) and can be used to measure the delay of light reflected from tissue structures with near micron precision. Because femtosecond lasers were too bulky and expensive for routine clinical use, Huang worked on an interferometer system that could use a cheap and compact diode light source to measure the time-of-flight of light with the same precision. He realized then that this technique, called optical coherence domain reflectometry, could be the basis of a new imaging technology with unprecedented potential for non-invasive imaging of retina and other tissues with micron resolution. This new technique was coined optical coherence tomography because it relied on measuring the coherence of light reflected from tissue structures and generates cross-sectional images, or tomographs.

The initial retinal OCT experiment that Huang conducted with Joel Schuman, an ophthalmologist then at Harvard, took several hours to acquire a single image. To improve the imaging speed, Fujimoto recruited Eric Swanson, then working on optical communications at MIT Lincoln Laboratory. With Swanson's crucial assistance, it was first developed an efficient fiber-optic OCT system that was fast enough for clinical testing (Swanson et al., 1993). The first clinical tests of retinal scanning were conducted by Carmen Puliafito's group that was then at the Massachusetts Eye and Ear Infirmary, Harvard Medical School. The encouraging results lead to commercialization of the technology in the mid-1990s by Humphrey Instruments, Inc. (since acquired by Carl Zeiss Meditec, Inc). The latest Zeiss Stratus OCT system (third generation OCT or OCT3) is now used by thousands of ophthalmologists for the management of macular diseases and glaucoma.

2. Basic physical principles

Clinical examination using the slit lamp has been used for several years as the main instrument for retinal structural assessment. Meanwhile, many other imaging techniques have been developed to examine cross-sectional retinal morphology. The confocal scanning laser ophthalmoscope (cSLO) forms retinal images by sequentially collecting reflections from laterally and longitudinally well-defined retinal volumes. Several cSLO images taken with sequential focal depths can generate three-dimensional information on the distribution of retinal reflectivity for topographic and tomographic assessments (Huang, 1999). The longitudinal resolution of a cSLO, however, is limited to ~300 μm due to the available numerical aperture through the pupil and ocular aberrations (Bartsch and Freeman, 1994). Cross-sectional measurements of the retina can be achieved in the clinical setting as well by the instrument coined retinal thickness analyzer (RTA). The RTA employs the principle of optical triangulation to provide direct measurement of the retinal thickness with an estimated accuracy of 20–30 μm (Zeimer et al., 1989). The instrument projects a narrow slit of 543 nm He–Ne laser light onto the retina and calculates the distance between the reflections that correspond to the vitreoretinal and chorioretinal interfaces. Although recent advances in this instrumentation have enabled rapid multiple optical sectioning of neighboring retinal regions to generate a retinal thickness map (Zeimer et al., 1996), information is restricted to fundus (macular) regions of 2×2 mm and limited qualitative data can be extracted from such imaging methodology.

Optical coherence tomography (OCT) is based on the imaging of reflected light. But unlike a simple camera image that only has transverse dimensions (left/right, up/down), it resolves depth. The depth resolution of OCT is extremely fine, typically on the order of 0.01 mm or 0.4 thousandth of an inch. This provides cross-sectional views (tomography) of internal tissue structures similar to tissue sections under a microscope, without disturbing the tissue as in histology. Thus, OCT has been described as a method for non-invasive tissue "biopsy."