Optical Coherence Tomography (OCT) Imaging Technology

1st Ljubica Milanovic
Faculty of Engineering
University of Kragujevac
Kragujevac, Serbia
ORCID: 0000-0003-3488-031X

2nd Strahinja Milenkovic
Faculty of Engineering
University of Kragujevac
Kragujevac, Serbia
ORCID: 0000-0002-5822-4846

3rd Nenad Petrovic
Faculty of Medical Sciences
University of Kragujevac
Department of Ophthalmlogy
Kragujevac, Serbia
ORCID: 0000-0001-5449-2029

4th Nenad Grujovic
University of Kragujevac, Faculty of Engineering
Kragujevac, Serbia
ORCID: 0000-0002-8765-2196

5th Vukasin Slavkovic
University of Kragujevac, Faculty of Engineering
Kragujevac, Serbia
ORCID: 0000-0002-1103-6565

6th Fatima Zivic
University of Kragujevac, Faculty of Engineering
Kragujevac, Serbia
ORCID: 0000-0003-2509-187X

Abstract

This paper presents short review of the OCT technology concepts, including the recently emerging low-cost OCT devices. Technology concept of Fourier-domain OCT, based on spectral interferometry, is presented: spectral-domain OCT (SD-OCT) and swept-source OCT (SS-OCT). Technical properties of the recently developed low-cost OCT solutions are reviewed. Advanced OCT measurements in clinical ophthalmology are discussed, with relevant case studies. Further research directions that consider AI-based methods in OCT imaging is briefly presented.

Keywords— Optical Coherence Tomography (OCT); Imaging; Smart diagnostics; Fourier-domain detection; Spectral Domain Optical Coherence Tomography (SD-OCT)

I. Introduction

Optical coherence tomography (OCT) imaging technology is based on the application of the low-coherence light for capturing images at micro- and sub-micro-scale resolutions, including three-dimensional (3D) images [1]. OCT imaging technique uses the light waves, commonly with long wavelengths, to make cross-section images of the media that exhibits optical scattering. Light waves penetrate into the media down to several millimeters, and resulting scattering is correlated with some specific phenomena. OCT imaging is performed very quickly and very easy for the patient. This is well established non-invasive medical imaging technology in ophthalmology, but also in other biomedical areas [1–3]. OCT is mainly used in medicine for structural imaging of the eye structures [1, 2–5], in dermatology for skin cancer imaging and histological correlations [8], in vascular medicine in angiography, and for visualizing blood vessels [1, 4, 7, 9]. It is also used to detect neoplastic changes such as pulmonary [10], ovarian [11], urinary [12] and gastrointestinal [13, 14] pathologies.

Additionally, it can be used for nondestructive testing in industry [15–19], and recent developments of desktop and mobile OCT systems evolve in this direction also. OCT technology has been developed to aim at high-resolution imaging in polymer film evaluation [20], colloidal and latex drying process characterization [21] or fouling monitoring in membrane filtration systems [22], and even in examination of archeological artefacts and objects [23]. Modifications of the basic OCT technology solution resulted in specific OCT techniques, such as: Optical Coherence Tomography Angiography (OCTA), for visualization of blood vessels with resolution necessary for capillary imaging; Indocyanine Green Angiography (ICGA) that is used for choroid angiograms in ophthalmology; and Fluorescein angiography (FA) for imaging of the blood vessels and structures in the back of the eye.

OCTA has distinct advantages over ICGA and FA in the evaluation of retinal and optic nerve diseases. It provides noninvasive simultaneous 3D structural and blood flow information, allowing for comprehensive evaluation of disease presentation and progression. The visualization of pathologies that were previously difficult to diagnose, such as capillary dropout in different retinal plexuses in glaucoma and deep retinal (DR), occult and nonexudative choroidal neovascularization (CNV), and the rapid dynamics of CNV flow response to Anti–vascular endothelial growth factor (anti-VEGF) therapy [4]. OCTA is non-invasive, and provides volumetric scans that can be segmented to specific depths, uses motion contrast instead of intravenous dye, can be obtained within seconds, provides accurate size and localization information, visualizes both the retinal and choroidal vasculature, and shows structural and blood flow information in tandem [1]. Disadvantages of OCTA are its limited field of view, inability to view leakage, increased potential for artifacts (blinks, movement, vessel ghosting), and inability to detect blood flow below the slowest detectable flow [9].

OCT can also be used to detect potential disturbances in retinal architecture and could provide new insights into neuronal changes associated with psychosis spectrum disorders, with potential to elucidate the nature and timing of developmental, progressive, inflammatory, and degenerative aspects of neuropathology and pathophysiology, and to assist with characterizing heterogeneity and facilitating personalized treatment approaches [5].

The correlation between the retinal and choroidal thickness and volume along with choroidal vessel volume in children can be studied using OCT [6]. The retina, choroid and choroidal vessels can be automatically segmented by adequate algorithms [6]. Retinal and choroidal structural features, such thickness and volume can be simultaneously quantified from the OCT images [6].

Smart diagnostics is emerging in medicine [24]. Artificial intelligence (AI) has enabled automation of measurements [25]. However, in the case of OCT imaging, AI-based methods of diagnostics are still in research phases [26, 27].

This paper presents technology concept of the OCT, including the review of the recently emerging low-cost OCT devices. Advanced OCT measurements in ophthalmology are discussed, with relevant case studies. Further research directions that consider AI-based methods in OCT imaging is briefly presented.

II. Technology concept of OCT

OCT measurements are performed in a manner analogous to echo-based ultrasound imaging, but instead of a sound, optical techniques are used to measure the magnitude and echo time delay of the backscattered light [28].

There are several types of OCT imaging modalities. The first implementations of OCT, referred to as time-domain OCT, recorded backscattered reflectance profiles from the biological tissues by scanning the reference arm and demodulating to detect the envelope of the interference signal as a function of depth within the sample. The introduction of Fourier-domain detection significantly improved the technology by enabling faster imaging rate, as multiple depth signals are recovered simultaneously through a simple Fourier transformation of the interference signal, and without a need to physically sweep the reference arm [28].

Two main variations of the Fourier-domain OCT are used: spectral-domain OCT (SD-OCT) and swept-source OCT (SS-OCT). SD-OCT systems employ a broadband light source, by simultaneously delivering multiple wavelengths of the light onto the sample. SD-OCT includes spectrometer to spatially disperse the component wavelengths for detection using a high-speed line scan camera. SS-OCT, also referred to as optical frequency domain reflectometry, incorporates a narrow band laser with a rapidly tunable center frequency which enables frequency detection as a function of time, by using a single photodetector [28]. Schematic representation of the design concept of SD-OCT system is given in Fig. 1 [28].

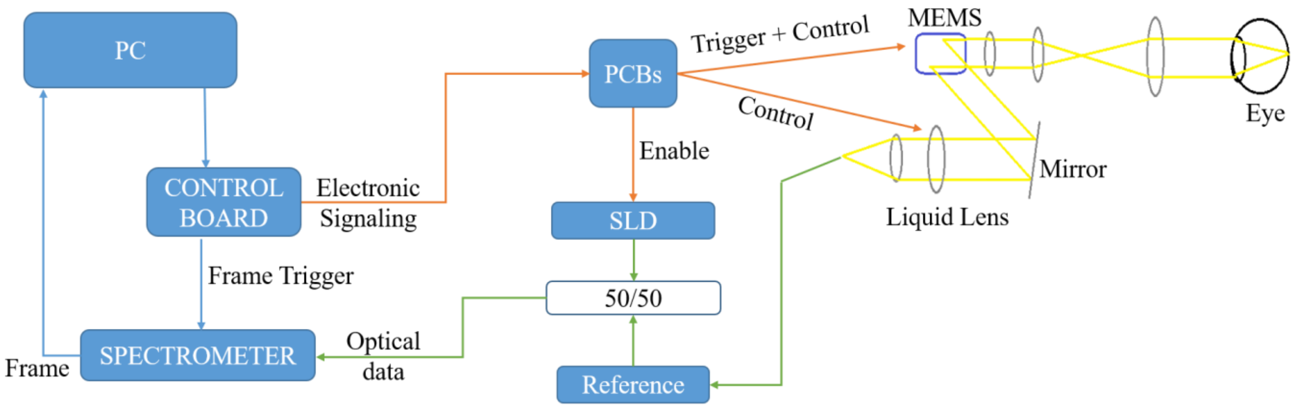

Fig. 1. Design concept of the SD-OCT system [18].

New direction in the development of OCT systems is focused on the low cost solutions [29]. Schematic view of the scanning mechanism within one low cost OCT device is given in Fig. 2. [29]. In this setup, the fiber pigtailed superluminescent diode (SLD) with open-loop thermoelectric cooling is used as the light source. The fiber optic output is connected to the scanning arm. The SLD has center wavelength of 830 nm and a full width at a half maximum bandwidth of 42 nm. The spectrometer design is similar to the previous one, with a parabolic mirror, a fold mirror, a transmission diffraction grating, and two stacked 150 mm focal length achromatic doublets in a loop configuration. A tall pixel CMOS sensor array consisting of 2048 pixels was used as the detector although only half of the array was utilized in order to increase A-scan line rate. The reference arm optics are setup in the adjustable-length lens tube to enable path-length adjustments to match that of the sample arm (Fig. 2) [29]. The scanning mechanism is based on the MEMS mirror and liquid lens. This combination allows independent scanning and dynamic focusing control to achieve the optimal spot size for each patient. The use of the liquid lens enabled focusing at multiple depths without a need to adjust imaging optics, thus allowing adjustments for different patients [29].

The OCT device is equipped with custom Windows-based software written in C# and C++. The user interface is displayed on the integrated touchscreen to allow simple system control and interaction to the user. The interface is configured to enable patient demographic input, selection of the scanning direction, and focus control. Once the image is acquired, the last 30 frames are retained in the buffer, allowing the operator to review them before saving both the processed and raw B-scans on the hard drive of the integrated PC. Synchronization between the scanner optics and the sensor array is affected by the master controller board in the main system body, which sends a trigger signal to the MEMS control board at the beginning of each lateral scan. The MEMS control board contains a digital-to-analog converter to generate an analog voltage that is amplified through a high-voltage rail to implement movement of the MEMS mirror. The spectrometer board consists of the embedded daughter board as the sensor interface and the board to digitize and send signals (B-scans) back to the PC through the USB 3.0 port. The PC receives and processes the frames before displaying images on the touchscreen through HDMI. Focusing is adjusted by the microcontroller on the scanner board, which alters the current through the liquid lens, by electrically shaping its spherical contour. The master controller board communicates to the SLD board through a serial peripheral interface, which sets the current needed to drive the light source [29].

Another approach that is used to achieve the low-cost OCT devices is to use the 3D printing to fabricate different OCT components, especially in the case of novel handheld devices. The application of 3D-printed parts allows the OCT system to be more compact and lightweight unlike machined aluminum parts that are used for the most of the commercial systems. Both the mini-PC and the touchscreen can be mounted in the 3D-printed body to allow easy user access, and to ensure the compactness. The fiber interferometer optics and printed circuit boards are contained within scanner housing. This concept offers a significant advantage in manipulation of the handheld scanner due to the possibility to combine the signals before the spectrometer, thus avoiding unwanted changes of the polarization state of the reference arm light relative to the light in the sample arm. Polarization of the light in the two arms can be optimized through geometric manipulation of the optical fibers before they are fixed in the scanner housing. Some of the main aspects for the handheld devices are the small size and low weight of the device, in order to enable easy manipulation with a device. Additional important aspect of the design is the chin rest for a patient, since that position need to enable maximum control and stability during retinal imaging [29].

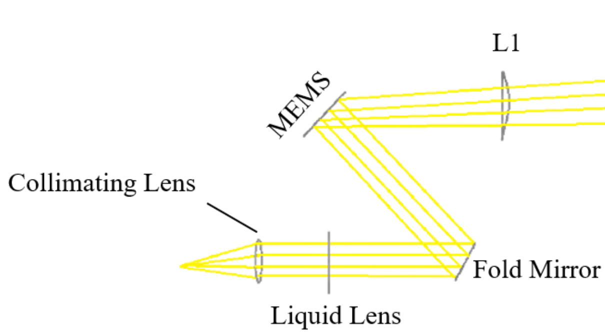

Fig. 2. Schematic view of the scanning mechanism in OCT arm [29]

The properties of the two currently existing low-cost OCT devices are given in Table 1, developed by Lumedica start-up. These systems are clinically applied and their tests showed comparable results to the large OCT systems, from aspects of the basic OCT measurements [29, 30]. Beside those devices showed in Table 1, other low cost OCT devices can be found at the market, such as Briefcase OCT system [31] with a price around $8000, but without specified technical properties, or Visotec Home care (no information regarding the price or technical details). Small OCT system is also developed by Notal Vision Home and it is still in development phase, not cleared for clinical use yet.

TABLE I. TECHNICAL PROPERTIES OF THE RECENTLY DEVELOPED LOW-COST OCT DEVICES [29]

Price	$7164	$5037
Center wavelength, nm	830	830
Bandwidth, nm	45	42
Number of pixels per A-scan	512	512
Scanner output power, μW	700	400-680
Imaging depth, mm	2.8	2.7
Axial resolution, μm	7	8
Lateral resolution, μm	17.6	19.6
A-scan rate, kHz	8.8	12.5
Sensitivity, dB	99.4	104
Working distance, mm	/	17.5
Scan range (X and Y), mm	7	6.6
Weight, kg	2.7	1.8
Volume, in^3	524.025	250

III. CASE STUDY OF THE OPTICAL COHERENCE TOMOGRAPHY (OCT) IN OPHTHALMOLOGY

OCT enables noninvasive, noncontact, transpupillary, optical in vivo imaging of the ocular structures. Spectral Domain Optical Coherence Tomography (SD-OCT) is the second generation of OCT that provides high-resolution images up to 5 μm of the different ocular tissues. In comparison to the first-generation Time Domain Optical Coherence Tomography (TD-OCT), SD-OCT is superior in terms of its capturing speed, signal to noise ratio, and sensitivity. In ophthalmology, the SD-OCT has been widely used in both clinical and research imaging.

Posterior segment evaluation with OCT allows visualization of the vitreous, retinal layers, retinal pigment epithelium (RPE) and the choroidal layers, as shown in Figures 3-6. Figure 3 shows the color mode of the OCT image of the normal retina with the numerical value of the total retinal thickness, as well as the thickness of the outer and inner retinal layers separately in the macular region. Figure 4 shows Cystoid Macular Edema with cystic spaces in retinal tissue. Figure 5 shows subretinal fluid in the center of macula lutea. Figure 6 shows subretinal fluid with multiple zones of the photoreceptors inner segment /outer segment (IS/OS) irregularity.

Each distinct retinal layer is visible on the OCT and corresponds well to histological studies. Image analysis using automated segmentation techniques is vital for extracting quantitative values that can be used to measure tissue layers thickness in order to detect structural damage and track disease progression. Certain types of retinal conditions can affect different retinal layers. For example, the retinal nerve fiber layer (RNFL) and retinal ganglion cell layer (RGCL) are affected in conditions like glaucoma. The inner retinal layers can be affected by retinal vascular disorders like diabetic retinopathy and retinal vascular occlusions. The outer retinal layers can become atrophy secondary to conditions that affect the RPE, for example in age-related macular degeneration. Soon after the introduction of OCT, the technique was also applied to the anterior segment of the eye. Ultra-high resolution anterior segment OCT may provide in vivo ‘histology’ images of the corneal layers with greater detail. OCT enables better understanding of glaucoma mechanisms via imaging of the aqueous outflow system and assessment of the anterior chamber angle. OCT of the tear film has improved understanding and treatment of dry eye disease.

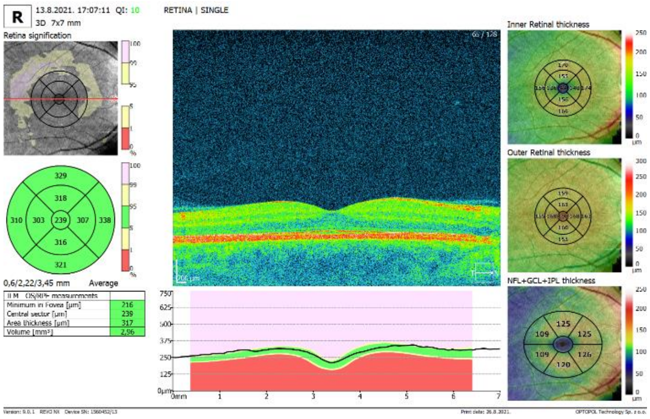

Fig. 3. Color mode of the OCT image of the normal retina

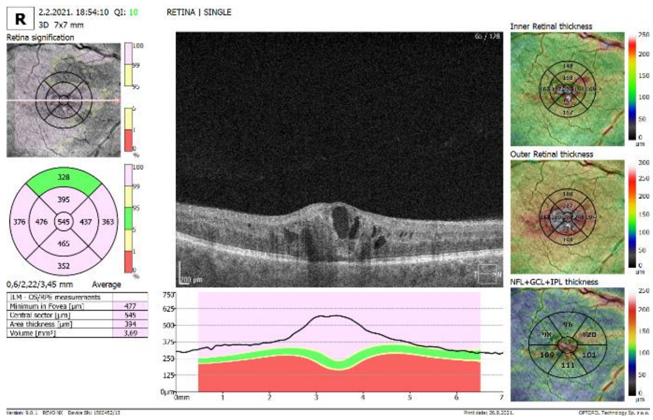

Fig. 4. OCT image of the Cystoid Macular Edema

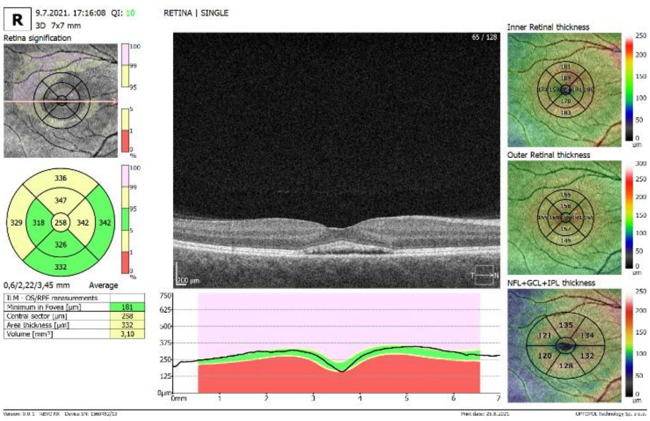

Fig. 5. OCT image: Subretinal fluid

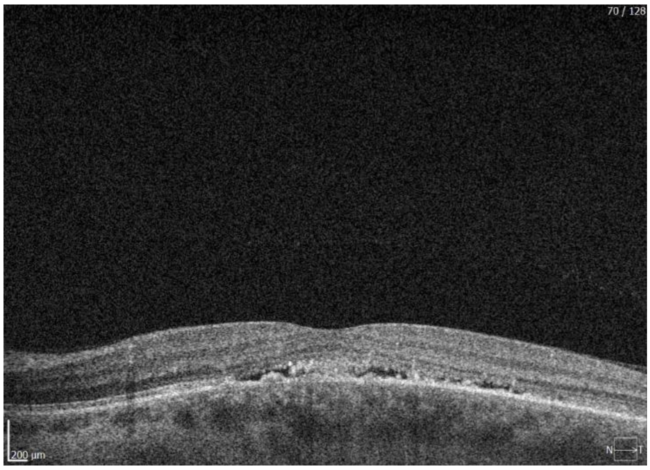

Fig. 6. OCT image: Subretinal fluid with photoreceptors IS/OS irregularity

New developments in ICT research, especially the development of artificial intelligence (AI) application in measurements promise the significant improvements in different measuring techniques, including OCT. For example, in cases of optic disc swelling, segmentation of projected retinal blood vessels from OCT volumes is challenging due to the swelling-based shadowing artifacts [7]. New AI-based methods are investigated for the OCT software processing. Simultaneous input of vessels-related data from multiple projected retinal layers can substantially increase vessel visibility, by using deep-learning-based approach to segment vessels involving the simultaneous use of three OCT en-face images as input [7]. The deep neural network can be trained from the imaging data of different patients with optic disc swelling to output a vessel probability map from three OCT en-face input images. The research results showed that in the case of OCT diagnostic with optic disc swelling, use of multiple en-face images enabled better vessel segmentation in comparison to the traditional use of a single en-face image [7]. AI-based methods for OCT imaging have already shown their advantages [5, 26, 27, 32, 33] and further research in smart diagnostics will enable better medical therapies.

IV. CONCLUSIONS

Optical coherence tomography (OCT) imaging technology has enabled high resolution in-depth imaging in several biomedical areas. OCT represents advanced diagnostic technology, especially in clinical ophthalmology. Fourier-domain detection has enabled high speed OCT high resolution imaging. Recent case studies of OCT images showed that this technology has become one of the most significant diagnostic tools for ocular structures that otherwise cannot be observed and accordingly treated, such as subretinal fluid conditions.

New developments in low-cost OCT solutions, including handheld devices are of the utmost importance for the wider use of OCT diagnostics in clinical medicine, and especially important for pediatric clinical ophthalmology. Technical properties of these low-cost OCT solutions are comparable with standard large OCT systems, from aspects of the basic functions. Considering the fact that OCT system incorporates custom software, recent research has been focused on application of AI-based methods in OCT imaging. Smart diagnostics and AI-based methods in OCT imaging are especially important for those eye conditions where simple OCT images cannot fully reflect the real condition, due to possible issues in software image processing (e.g., shadowing artifacts from subretinal fluid at optic disc swelling). Further research in smart diagnostics should greatly improve OCT technology and provide valuable assistance to clinicians.

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