Introduction

Biomedical optical imaging technology and applications: From basic research toward clinical diagnosis

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Biomedical optical imaging technologies are playing an indispensable role in basic research and clinical diagnosis owing to their superior spatial resolution, rich imaging contrasts, and non-ionizing properties of the light radiation. Biomedical optical imaging technologies rely on the interaction of light with biological tissues, the subject of biomedical optics, to provide contrast to reveal the features of interest of a sample. When interacting with biological tissues, the properties of the incident photons like amplitude/intensity, phase, polarization states, and wavelength may be modified by scattering, absorption, tissue birefringence, fluorescence, and nonlinear effects. All these changes of the light properties may provide specific contrasts for imaging the structure or function of biological tissues.

Optical coherence tomography (OCT)[1–5] and photoacoustic tomography (PAT)[6–10] are two representative novel optical imaging technologies that can provide high-resolution (micrometer scale) three-dimensional (3D) structural and functional imaging of biological tissues. OCT is a low-coherence interferometry-based optical imaging technology that uses coherence gating to achieve depth resolution. Conventionally, OCT uses a Michelson interferometer, either optical fiber-based or in free space, illuminated with a broadband light source to get the interference signal between the backscattered light from a sample in the sample arm and the reflected light from the reference arm. Although first invented in 1991,[1] time-domain OCT was not well accepted in the clinics until the invention of the spectral-domain OCT (SD-OCT), which was reported first in 1995 and well recognized since 2003.[2,3,11–13]

There are different branches of OCT technology for imaging different bio-parameters by using different contrast mechanisms. Conventional OCT images the structure of biological tissues by using the signal intensity contrast, which depends on the optical boundaries formed by regions with different optical properties.[14,15] Polarization-sensitive OCT,[16,17] including Mueller-matrix OCT and Jones-matrix OCT,[18–21] images the polarization properties of a sample like amplitude and orientation of birefringence. Optical Doppler tomography[22–24] or Doppler OCT images the flow speed of moving particles like the red blood cells inside a blood vessel. OCT angiography (OCTA)[25–27] is a recently developed technology to image the structures of the blood vessels with sensitivity high enough to image the capillaries, which uses the moving-induced decorrelation of the interference signals as contrast. Optical coherence elastography (OCE)[28,29] is a new branch of OCT to measure the mechanical properties of biological tissues by taking advantage of the high spatial resolution of OCT to measure the small displacement induced by pressure.

OCT has found clinical and preclinical applications in various medical fields such as ophthalmology,[30–37] cardiology,[38–40] neurology,[41–43] gynecology,[44,45] dermatology,[46–48] dentistry,[49,50] developmental biology,[51] urology,[52–54] gastroenterology,[55–57] etc. OCT has been used to measure the oxygen saturation in blood vessels by extracting the spectral information in the interference signals.[58–60] OCT can provide molecular contrasts in a multimodal imaging system to quantify the concentration of molecules like rhodopsin and lipofuscin in the retina.[61–65] OCT was used to measure the intrinsic signals of the photoreceptors.[66,67] Currently, OCT has established its role in the forefront in ophthalmology for the diagnosis and monitoring progression of all kinds of retinal diseases. The clinical applications of OCT in other medical fields are also under investigation.

In this thematic issue, we have gathered research and mini-review articles in the fields of PS-OCT, OCE, OCTA, and novel applications of OCT. The paper by Yao and Duan[68] presented a review on the recent developments of high-resolution 3D optical tractography using Jones-matrix PS-OCT. Tractography is a specialized imaging technology that can reveal the detailed fiber architecture of fibrous tissues. Recent developments have demonstrated the feasibility of extracting the depth resolved local optic axis from PS-OCT measurements using Jones-matrix calculus. The obtained optic axis data can then be used to construct 3D tractography in a variety of tissues including heart, skeletal muscle, cartilage, and artery. This new tractography technology is also termed optical polarization tractography.

Qian et al.[69] presented a new method of evaluating the posterior eye elasticity in vivo by using a shaker-based OCE. They validated the technique by imaging both phantoms and rabbit eyes in vivo. Su et al.[70] reported their investigations on retinal neurovascular responses to transcorneal electrical stimulation (TES). By using SD-OCT to measure the intrinsic optical signal (IOS) and the blood flow parameters, they were able to record simultaneously the neural and vascular responses of the retina to TES in vivo. They have found that TES mainly induced neural responses in the retina while no significant vascular responses were evoked. These results provided insights to the mechanism of retinal neurovascular coupling in response to TES. Yao et al.[71] reviewed the current progress of quantitative OCTA, which extracts quantitative measures of the vasculature parameters from OCTA images, including blood vessel tortuosity, blood vessel caliber, blood vessel density, vessel perimeter index, fovea avascular zone area, FAZ contour irregularity, vessel branching coefficient, vessel branching angle, branching width ratio, and choroidal vascular analysis. These quantitative measures are proved to be useful for the diagnosis of various retinal diseases.

PAT is a scalable imaging technology, which has two major branches: photoacoustic microscopy (PAM) and photoacoustic computed tomography.[6] PAT uses the photoacoustic effect to generate an image. When illuminated by pulsed or intensity-modulated laser light with a wavelength within the absorption spectrum of a sample, the absorbed light energy is converted to heat, inducing a transient temperature increase. Upon thermal relaxation, an ultrasonic wave is generated, which can be detected by using an ultrasonic transducer. The time-of-flight of the detected ultrasonic wave tells the depth information of the origin of the wave, thus the location of the absorber, e.g. the red blood cells in a blood vessel. The lateral resolution of PAM can be either the size of the light focus in the superficial region (the ballistic scattering regime) or the size of the ultrasonic focus in deeper regions where the incident light is diffused (optical quasidiffusive or diffusive regime). The majority of PAT technologies have been intensively studied for preclinical imaging of animal models.

Zhang et al.[72] investigated the technical feasibility of transrectal PAT for prostate cancer imaging by using ICG as a contrast agent, light illumination from an LED array via the urethral track, and a commercial linear array ultrasonic transducer. They conducted experiments on a clinically relevant ex vivo model including whole human prostates harvested from radical prostatectomy. Their imaging results showed that tubes containing ICG solution at different concentrations could be detected at different positions in the prostate within a 2 cm range from the urethral wall, an imaging range that can possibly cover the entire prostate.

In the paper of Kim et al.,[73] new updates to improve the clinical usability of a real-time clinical photoacoustic and ultrasound imaging system were reported. These updates allow optimization of all imaging parameters while continuously acquiring the photoacoustic and ultrasound images in real-time. The updated system has great potential to be used in a variety of clinical applications such as assessing the malignancy of thyroid cancer, breast cancer, and melanoma.

In the article of Karthikesh and Yang,[74] technologies of photoacoustic image-guided interventions were reviewed. They reviewed the potentials of photoacoustic imaging in guiding active and passive drug deliveries, photothermal therapy, and other surgeries and therapies using endogenous and exogenous contrast agents including organic, inorganic, and hybrid nanoparticles, as well as needle-based biopsy procedures. The advantages of photoacoustic imaging in guided interventions were discussed.

Dadkhah and Jiao[75] reported a PAM-based multimodal imaging technology, which integrated PAM, OCT, OCTA, and fluorescence microscopy in a single platform. The reported system was able to image complementary features of a biological sample by combining different contrast mechanisms.

In addition to the OCT and PAT technology and their applications, this thematic issue also features articles that use novel optical imaging as a key technology for research. Li et al.[76] investigated application of intrinsic nonlinear optical imaging such as two-photon excited autofluorescence and second harmonic generation (SHG) microscopy to quantitatively assess chondrocyte viability in articular cartilage. Lu et al.[77] applied time-lapse near-infrared light microscopy to monitor the spatiotemporal dynamics of the IOS responses in freshly isolated retinas activated by visible light stimulation. Nesmith et al.[78] reported the use of optical method to map the electromechanics in intact organs. Massett et al.[79] used SHG and total internal reflection fluorescence microscopy to investigate the loss of smooth muscle α-actin effects on mechanosensing and cell-matrix adhesions.

In summary, although only covered a limited number of optical imaging technologies and their applications, this thematic issue would help us perceive the power and significance of optical imaging technologies in clinical diagnosis and biomedical research. This thematic issue will also help attract future publications of biomedical optical imaging related articles in Experimental Biology and Medicine.

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