Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 6 Issue 12, December - 2019

A Review of the LED-supported Photoacoustic System

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ARTICLE INFO

Article history
Received: Nov. 20th, 2019
Revised: Dec. 21st, 2019
Accepted: Dec. 24th, 2019
Published: Dec. 31st, 2019

Abstract— **Photoacoustic systems have been used in several areas of medicine, including cardiac, intravascular, neurological disorder, and small animal studies. Photoacoustic systems are a type of hybrid medical imaging system, using optical and ultrasound systems. Therefore, photoacoustic systems can provide the mutual advantages of high contrast and axial resolutions due to the light and ultrasonic transducer devices. Lasers are a type of standard transmitting source in photoacoustic systems; however, lasers are somewhat bulky, expensive, and consumptive of large amounts of power. Therefore, light emitting diodes (LEDs) have recently been introduced as photoacoustic sources because they are low-cost and compact light sources with easier frequency tuning capability. Hence, photoacoustic systems using LED light sources are useful for manufacturing fast, real-time photoacoustic systems. In this review article, LED-supported photoacoustic systems are summarized and discussed.**

Keywords—Light emitting diode, Ultrasound systems, Photoacoustic systems

I. INTRODUCTION

There are several imaging modalities in the field of medical imaging, such as X-ray, magnetic resonance imaging (MRI), positron emission tomography (PET), computed tomography (CT), ultrasound, and optical modalities [1-3]. Each medical imaging technique has its own advantages and disadvantages, such as penetration depth, sensitivity, and imaging resolution [4-6]. Therefore, hybrid medical imaging techniques such as MRI-guided high-intensity focused ultrasound, PET-CT, and PET-MRI have been developed to overcome the disadvantages of individual methods [3, 7].

Ultrasound systems have been used to diagnose the structure of targets in the skin, eyes, breasts, and blood vessels [3, 8, 9]. Optical systems have been used to analyze physiological and biological information of blood vessels and eyes [7, 10]. Types of the hybrid methods using optical and ultrasound systems are called photoacoustic, optoacoustic, or thermoacoustic systems [11]. For medical applications, optoacoustic systems have been used widely in a variety of areas of medicine, such as small animal and cardiac-vascular imaging, intravascular diseases, and brain-related disorders, because they are useful for obtaining the structure and identifying the oxyhemoglobin and de-oxyhemoglobin information of the desired target [11]. For neurology applications, Alzheimer's and Parkinson's diseases, brain tumors, development errors, and trauma can be investigated using photoacoustic systems [12]. For animal studies, drug delivery and gene therapy are possible applications [13, 14]. Compared to ultrasound-only systems, photoacoustic systems use two independent sources or devices [15]. The major devices in the optoacoustic system are light sources and ultrasound (ultrasonic) transducers as transmitting and receiving components, respectively [16]. Therefore, optoacoustic systems can offer the mutual advantages of high optical contrast and acoustic resolution provided from optical and ultrasound sources, respectively [17, 18]. However, laser source intensity is typically hundreds of times less than ultrasound source intensity because of the scattering characteristics of the light sources [19, 20]. The next section provides an overview of photoacoustic systems and technical reviews of both laser-supported and light emitting diode (LED)-supported photoacoustic systems.

II. MATERIALS AND METHODS

A. *Overview of photoacoustic systems*

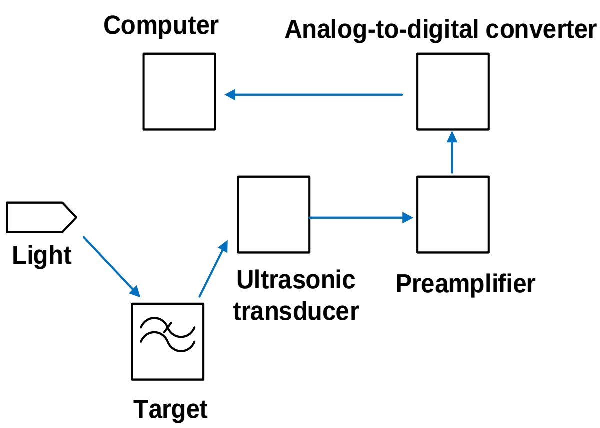

Fig. 1. *Basic configuration of photoacoustic systems.*

For the optoacoustic system, the transmitting sources are light or radio frequency sources, such as a laser, LED, or radio frequency or microwave source [21]. The receiving sources are ultrasonic transducers [21]. These sources could be single elements or array-type elements, depending on the application. The light transmitted from the light sources is projected into the desired target [22]. Figure 1 shows the basic configuration of a conventional photoacoustic system.

First, light is delivered to the target. Next, signals from vibrating thermal expansion that are converted into acoustic signals are generated from the desired target [23]. The ultrasonic (acoustic) signals are detected by the ultrasonic transducer, which can transform them into electrical signals [24]. Afterward, weak electrical signals are amplified by the preamplifier, variable-gain amplifier, or time-gain compensation amplifier with additional tunable low-pass or band-pass filters before the analog signals are converted to digital signals in the analog-to-digital converter [24]. The processed electrical signals can be displayed on a computer screen to reconstruct the photoacoustic target image [25, 26].

Photoacoustic systems can be divided into three major categories [21]. The first is photoacoustic tomography systems, which are traditional photoacoustic systems [21]. The second is the optical resolution photoacoustic system. The lateral resolution of this system is limited by the optical sources and optical devices [27]. Therefore, the optical resolution is dependent on the optical wavelength and aperture sizes of the optical systems [28]. The third is acoustic resolution photoacoustic systems. The acoustic resolution of these systems is dependent on the ultrasound transducer [11]. To improve the acoustic resolutions of these systems, focused ultrasound (ultrasonic) transducers are normally used to receive echo signals from the desired target and thus improve sensitivities [21]. Single or array-based ultrasonic transducers can be used to acquire the echo signals with a mechanical or electrical scanning motor [21]. To deliver the light to the desired targets, an optical lens, prism, or mirror needs to be utilized to change the light direction [29]. To cover the whole organ of a small animal or human being, an additional mechanical motor system that can rotate to control the light sources would be required [30].

There are two different types of laser or LED light sources, continuous and pulse types. For photoacoustic systems, the pulsed-type laser or LED light source is typically used because continuous-type light sources can permanently destroy the tissues [11]. Otherwise, ultrasonic transducers with mechanical motor systems are utilized for coverage.

B. Laser-supported photoacoustic system

Lasers have been used as a transmitting light source in photoacoustic systems. The lasers are coherent and sufficiently powerful light sources to produce acoustic signals from the desired target [31]. In the photoacoustic systems using a laser light source, YAG, sapphire, dye, and Q-switch sources have been used widely. These laser sources need to provide several millijoules of energy with a sub-nano-second pulse duration to excite the biological tissues and obtain the echo signals [32]. These kinds of laser sources can generate such light and use optical lenses such as concave lenses, ground glasses, mirrors, conical lenses, and optical condensers [21, 33].

Wavelengths between 500 and 900 nm are used to visualize the eye and tissue areas because of their relatively good penetration depth [33]. Photoacoustic systems using 755 nm wavelength light and 64 element transducer arrays have provided small animal imaging for whole body areas [34]. Photoacoustic systems using 532 nm light have revealed images of the cerebral surface of the skull [32]. Systems using 1200 nm light have shown a coronary artery stent in tissue phantoms [35]. Additionally, using the wavelength of 1210 nm, Intravascular images have been achieved for human coronary arteries [36]. These types of laser sources are quite bulky and expensive light sources, typically used in pre-clinical or laboratory experiments. Additionally, the pulse repetition rate of the laser is sometimes less than 1 kHz, which cannot obtain medical imaging very quickly [11]. These types of experimental configurations in photoacoustic systems are not suitable for ultra-fast medical imaging. Therefore, LED-supported photoacoustic systems have been introduced.

C. LED-supported photoacoustic system

The LED-supported photoacoustic system has been introduced recently to overcome the technical issues of the laser-supported photoacoustic system, such as cost and tunable capability. Compared to the laser-supported photoacoustic system, for which laser tuning is not easily controlled by the electronic systems, the LED-supported photoacoustic system can be tuned easily by the LED control board [37]. Compared to the laser, the LED light source amplitude is easier to change, even though the LED energy is not very high [37]. Each different LED, such as the red (around 620 nm), green (around 530 nm), and blue (460 nm) LED, is used to obtain the images. Compared to laser sources, LED sources are safe and relatively inexpensive. The pulse repetition rate of LED sources can be changed using the LED control board such that the pulse repetition rate can be increased to the several MHz level if necessary.

Several LED-supported photoacoustic systems have been developed. High-power LED diodes were used to demonstrate the capability of obtaining mouse ear vasculature imaging [38]. Multiple-wavelength LEDs have also been used in photoacoustic systems because each LED with a different wavelength has its own unique optical absorption characteristics. To use multiple wavelengths (e.g., 455, 505, 617, and 660 nm), optical fibers have been used to combine the LED light sources, but they can lose LED light intensity [39]. Photoacoustic systems using LED arrays and ultrasound probes have been developed to obtain ultrasound, photoacoustic, and combined ultrasound and photoacoustic images [40].

The first commercially developed LED-supported photoacoustic system (the AcousticX, PreXion Corp. Tokyo, Japan) was shown. This LED-supported photoacoustic system, which uses several LED arrays with 850 nm wavelength light, can provide real-time imaging [41]. In this system, each 36 individuals of the LED array produces 200 µJ of energy. The pulse repetition frequency of the electrical systems is between 1 and 4 kHz. The pulse duration of the electrical systems is between 30 and 100 ns. The operating frequency of the linear ultrasonic transducer array is around 9 MHz. The intensity of the LED arrays can be similar to that of single laser light sources, which have energy levels of several millijoules.

LED-supported portable photoacoustic systems have recently been implemented due to their light weight and low cost [42]. Because of these advantages, LED-supported photoacoustic systems, as opposed to laser-supported photoacoustic systems, can be large-volume imaging modalities for use as a clinical tool [38]. For handheld LED-supported photoacoustic systems, several experiments have been demonstrated using blood-mimicking phantoms, in-vivo imaging, and metal needles [41]. In the experiments, relatively comparable performances could be achieved when using LED arrays. However, the LED array cannot be more useful than a single laser source due to low intensity of each LED source [41, 42]. Additionally, the electrical systems that support the LED array can be more complex to implement. However, due to recent developments in semiconductor technology, these types of technical issues can be resolved accordingly [43, 44]. Therefore, LED-supported photoacoustic systems could be promising candidates for a compact and cost-effective pre-clinical and clinical imaging modality.

III. CONCLUSION

This manuscript provided a brief review of the LED-supported photoacoustic systems from the perspective of medical imaging. In comparison with laser-supported photoacoustic systems, LED-supported photoacoustic systems have been introduced, compared, and investigated. The photoacoustic systems are a type of hybrid medical imaging system that uses light as the transmitting source and an ultrasonic transducer as the receiving source. The light transmitting source may be a laser, microwave, or LED source. Therefore, these photoacoustic systems are useful for a variety of medical diagnostic applications, such as in cardiology, neurology, oncology, and animal studies, because the light is useful for obtaining physiological and biological information. The ultrasonic transducer is useful for acquiring structural information about the desired target in small animals and human beings. To cover whole organs in human beings, mechanical motor systems to move the LED sources or ultrasonic transducers are required.

Conventional photoacoustic systems using continuous- or pulsed-type laser sources with wavelengths between 400 and 1200 nm have been developed for cardiovascular imaging, small animal imaging, intravascular disease imaging, and brain-related disorder diagnosis. The first commercial photoacoustic systems are available for pre-clinical applications. Compared to the laser, the LED is an economical, relatively safe, compact, and portable light source. Frequency tuning of LED sources is somewhat easier than tuning of laser sources because the frequency tuning is controlled by electrical systems. Therefore, it is useful to develop compact and inexpensive photoacoustic systems for pre-clinical and clinical real-time medical imaging applications. Compared to lasers, LED sources are divergent light sources that may require an additional electrical system for implementation in LED-supported photoacoustic systems. Additionally, several optical lenses may be used to rotate or change the direction of the LED light sources. Compared to a laser source, the LED has low light intensity. To increase the sensitivity, LED arrays could be practical solutions, such as in commercially available photoacoustic systems. Additionally, recent developments in semiconductor technology could overcome some of the associated technical issues. Therefore, LED-supported photoacoustic systems could be excellent candidates for one type of commercially available medical imaging modality.

ACKNOWLEDGMENTS

This research was supported by Kumoh National Institute of Technology (2019-104-123).

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