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Dual frequency band annular probe for volumetric pulse-echo optoacoustic imaging

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Abstract

Optoacoustic (OA) pulse echo (PE) imaging is a hybridized modality that is capable of providing physiological information on the basis of anatomical structure. In this work, we propose a dual frequency band annular probe for backward mode volumetric PE/OA imaging. The performance of this design is evaluated based on the spatio-temporal impulse response, three dimensional steerability of the transducer and point spread function. Optimum settings for number of elements in each ring and maximum steering are suggested. The transducer design and synthetic array beamforming simulation are presented. The resolution performance and reconstruction capabilities are shown with the in-silico measurements.

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Keywords:Ultrasound imaging; Optoacoustic imaging; Transducer design;Phase array; Image reconstruction; Beamforming.

1. Introduction

Optoacoustic (OA) imaging is a hybrid imaging approach based on the photoacoustic effect, in which the slight temperature variation due to the deposition of laser pulse energy is followed by locally confined displacement. This transition between photothermal to thermoelastic generates a broad band acoustic pulse. The induced ultrasonic pressure then carries information about the physiology function of the tissue, based on the variation in optical properties. Attributing the anatomical structure of the tissue to the OA data is subjected to the ultrawide-band transducer (Oraevsky and Karabuto, 2003) and/or tomographic view for the transducer (Deán-Ben and Razansky, 2013). On the other side, the resolution of ultrasound (US) is a key feature that allows diagnosis for many anatomical abnormalities, yet the US contrast (bulk modulus) variation in soft tissues is only a few percent (Hill et al., 2005). The fusion of OA and US modalities enables delivering multifunctional complementary information when the simultaneous morphological and physiological studies are of interest. This includes preclinical studies, clinical early stage diagnosis, localization of the lesion, metabolism measurements and treatment monitoring. While US PE technique is transmitting and receiving the wave in the same range of frequency spectrum, the laser-induce OA pulse

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covers a wide spectrum, depending on the topology, morphology and optical/thermal properties of elastic properties of both local absorber and medium. Owing to the frequency response of the transducer, the received OA signal is partially obtained and that takes place with non-uniform amplitude. Consequently the image is reconstructed from a set of incomplete data. To radically address this problem, one way is to pursue a multi-frequency band approached (Chekkoury et al., 2013; Ku et al., 2004; Liu et al., 2008; Nikoozadeh et al., 2013) where the information from the edges and boundaries (rapid change in OA signal) of the absorber is expected from the transducer elements with the higher central frequency while transducers with lower central frequency render higher SNR and a better contrast for the main structures (slower change in OA signal). The ultrasonic transducer to a great extent determines the sensitivity, imaging depth, contrast and spatial resolution of this bimodality system. Heretofore, the commercially available phase array US transducers for volumetric imaging are square matrix apertures. High number of confined size elements, relative small size of the aperture, suppression of the weak OA signals in proximity of boundaries and difficulties in integrating the laser light into the probe (Chen et al., 2012) making the utilization of this geometry nontrivial for three dimensional PE/OA. To tackle simultaneously the aforementioned drawbacks, a dual frequency band annular ultrasonic array has been designed and evaluated utilizing numerical simulations. We showcase the advances and abilities of our proposed geometry in PE/OA backward imaging in terms of the acoustic pressure field and point spread function of both modalities.

2. Method and result

The performance of the PE/OA imaging system is highly governed by two main factors, namely the properties of the transducer and incorporating them into the reconstruction algorithm. Our interest in this paper is to analyze the influence of these factors with regard to the spatial impulse response (Jensen, 1999) of the proposed transducer which describes the performance of the imaging system (Mitsuhashi et al., 2014) and the point spread function of both modalities. These numerical studies performed with the Field-II program (Jensen, 1996). The effect of the spatial arrangement, the number and size and the spatial/temporal response of the ultrasonic transducers have been investigated separately for each modality, as the physics of these imaging system are dissimilar. The number, size and aspect ratio of transducer elements represent a non-trivial agreement between the performances of the imaging system in terms of spatial resolution, receive sensitivity and design complexity. In consideration of the OA imaging, to achieve a large angle of view and accordingly wide directional sensitivity, the element size must be less than the smallest wavelength producible by the transducer (Ashkenazi et al., 2009). The cost of such a point-like detector is either the small aperture size or high number of transducer elements where the first affects highly the spatial sensitivity field of the transducer and the later gives rise to the complexity of the design. On the other hand, to avoid grating lobes in ultrasound imaging conventional phase arrays require the inter-element spacing equal or less than half of the acoustic wavelength ($\lambda/2$) corresponding to the central frequency of the transducer. Nevertheless, owing to the less periodicity in circular geometry the inter-element spacing can be increased up to the acoustic wavelength (λ) (Ullate et al., 2006). Meanwhile, based on our empirical studies the aspect ratio of two allows a large surface for the aperture with negligible effect on the spatial resolution. Therefore, the effective aperture size can be increased with lower number of elements than the two dimensional matrix phase array. Moreover, the bandwidth of the transducer plays a crucial role in the performance of the imaging system. The broader bandwidth ameliorates the temporal response, hence enhances the axial resolution. The transducer frequency response influences the received information as well. In OA imaging, selecting the right frequency response is a trade-off between ideal operating frequency in terms of resolution (higher than 10 MHz) and deliverable contrast (lower than 5 MHz) (Liu et al., 2008). In our previous study we demonstrate this effect by comparing the results of two linear probes with different frequency responses in imaging the same sample (Vallet et al., 2014). In this work, through series of simulations we found that the transducer with 3 MHz central frequency enables the detector to obtain more contrast information while 7.5 MHz transducer provides a better resolution. In order to develop a PE/OA imaging system utilizing a hand held probe, we designed a dual annular ultrasonic transducer consist of 128 transceivers with central frequency of 7.5 MHz and 56 only receivers with central frequency of 3 MHz, both with 110% fractional bandwidth. The annular arrangement of the transducer elements simplifies the integration of different set of frequency band transducers. Besides, the annular geometry inherently provides a lumen (cylindrical cavity) for housing the light probe. In this way, not only a better light illumination for the laser light is provided (Wang et al., 2012) but a wider spectral coverage verifies the detection of high resolution data along with the contrast (Fig. 1.).

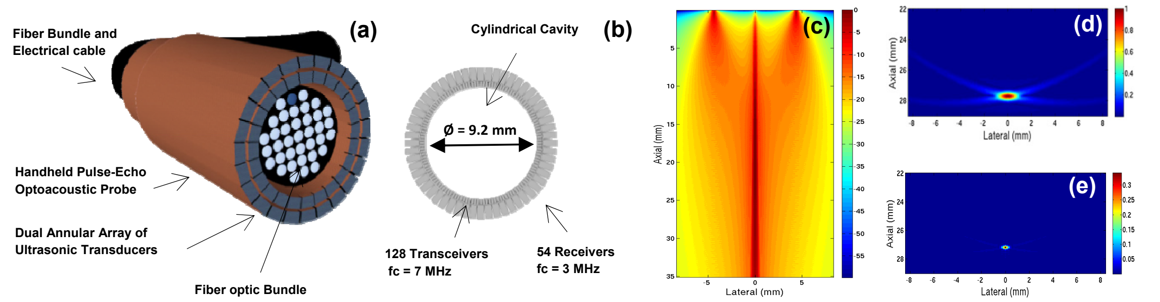

Fig. 1. The dual frequency-band annular array probe. (a), (b) the schematic of the transducer geometry (c) the 2D representation of SIR based sensitivity map of the transducer at transversal plane = 0, (d) and (e) image of an OA point source situated at (0,0,27) mm, reconstructed respectively from the array of reconstructed from the array of 56 element with 3 MHz central frequency (the outer ring) and 128 element with 7.5 MHz central frequency (the inner ring).

One important evaluation means of the transducer action is the spatial impulse response (SIR) of the transducer. This spatio-frequency parameter is held by the signal distortions associated with the finite dimension of transducer. Therefore the receive response of the transducer, or spatial sensitivity (Fig. 1. c), can be calculated by convolving SIR with the transducer impulse response (TIR). Likewise, in the transmit mode this spatio-temporal response combination describes how the pressure is being propagated from the transducer aperture. Thus the spatio-temporal response can describe the characteristics of the transducer. One of these properties is the ability of the transducer to steer and focus the transmit beam through a volume of interest. Fig. 2. depicts the beam steering property of the annular array in PE mode. It shows the possibility of steering the beam up to 30° with dynamic range around 32dB, which validates the annular array potentials for the volumetric ultrasound imaging. Using synthetic aperture focusing technique (SAFT), annular array can achieve the full aperture resolution for the PE mode (Norton, 2002). Fig. 3. is representing the performance of the annular probe with 128 transceiver elements in ultrasonic mode of imaging. The PE image of point scatterers (point spread function) positioned at the axial distance of 1 cm to 3 cm away from the transducer in the medium using SAFT reconstruction technique. Additionally, an adaptive weighted factor that counts for the properties of transducer has been employed to improve the quality of the deliverable images. As depicted in Fig. 3., the absence of grating lobes verifies the element size and aspect ratio.

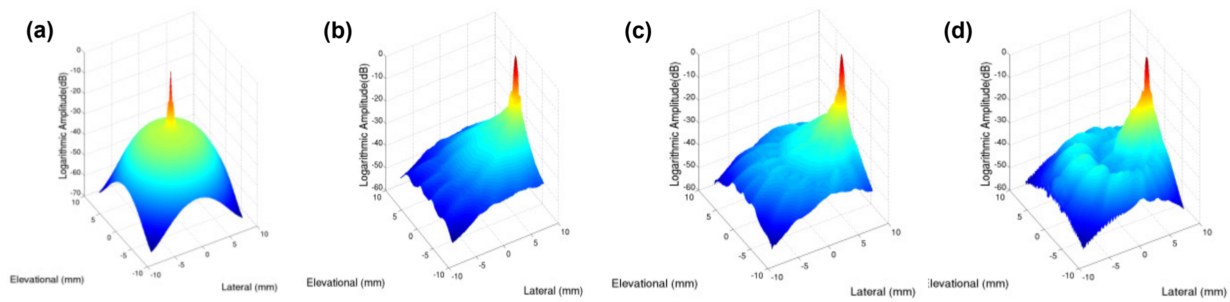

Fig. 2. The PE beam pattern of an annular array focused at (a) [0,0,12] mm (b) [0,9.2,30] mm (c) [0,9.2,20] mm (d) [0,9.2,10] mm. The simulation shows the steerability of the annular array by steering the acoustic emission beam at (a) 0°, (b) 15°, (c) 20°, and (d) 30° off axis.

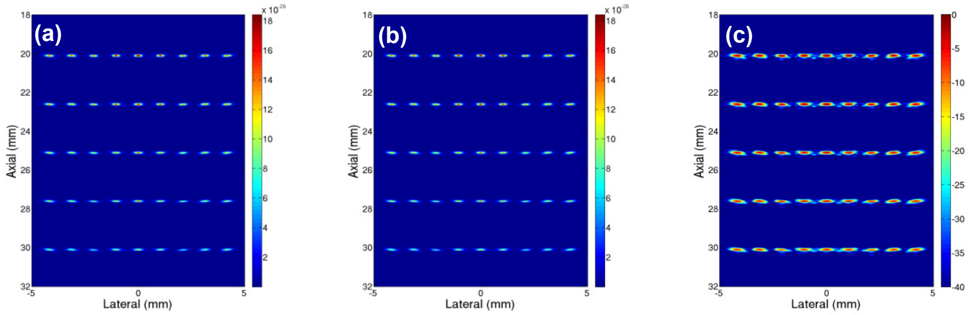

Fig. 3. The simulated PE images of point scatterers in the homogenous medium (a) SAFT, (b) weighted SAFT, (c) -40 dB logarithmic image of the weighted SAFT.

Synthetic aperture technique is known for ameliorating the lateral resolution by compounding set of low resolution images reconstructed from received acoustic wave. As compared to the PE, this technique provides a factor equal to the number of elements, less compounding data in reconstruction of OA image. Consequently, the OA images will include artifacts which if understood well, an adaptive weighting factor can be employed to alleviate this issue. The OA images are obtained with implementation of a weighted three dimensional synthetic aperture that incorporates the light propagation in the medium using an analytical model (Li et al., 2014). Our result (Fig. 4.) demonstrates the benefits of utilizing adaptive weighting factor to profoundly reduce these artifacts. Moreover, we include the SIR map to incorporate the spatially-dependent frequency response of the finite-sized elements.

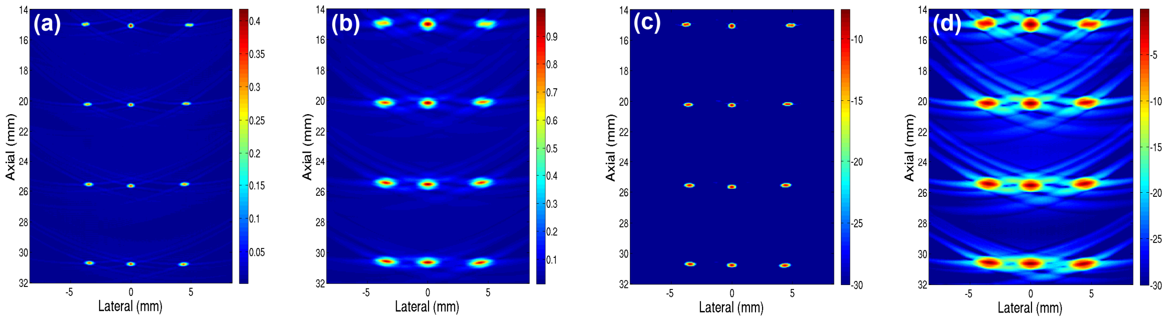

Fig. 4. Normalized weighted synthetic aperture image of OA point sources using (a) inner ring 128 elements with 7.5 MHz central frequency (b), outer ring 56 elements with 3MHz central frequency, (c) and (d) are logarithmic scale of (a) and (b) respectively.

3. Discussion

Annular array is expected to improve the volumetric imaging performance of such a bimodality system, thanks to its geometry. The circularly symmetrical response enables the volumetric imaging by rotating the B-mode image around the central axis. We demonstrated the avails of the dual frequency band annular probe in the OA PE imaging by elaborating the adaptive synthetic aperture algorithm. The frequency-amplitude dependent distortions and the effect of light propagation are incorporated with the reconstruction algorithm to minimize the quantification errors in the accuracy of deliverable data regarding the physiology of the medium. The circular arrangement provides additionally a cavity for accommodating the light probe, enabling perpendicular illumination, shortening the optical path to the absorber and gaining the less skin reflection. This work was inspired by the recent manifestations of CMUT technology in both design and improvement in ultrasound and OA imaging (Choe et al., 2012; Kshirsagar et al., 2013). However, for CMUT technologies, FieldII requires further considerations associated with the physics of CMUT transduction (Baek et al., 2010). We will include this effect in the future studies.

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