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● *Original Contribution*

CALIBRATED LINEAR ARRAY-DRIVEN PHOTOACOUSTIC/ULTRASOUND TOMOGRAPHY

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Abstract—The anisotropic resolution of linear arrays, tools that are widely used in diagnostics, can be overcome by compounding approaches. We investigated the ability of a recently developed calibration and a novel algorithm to determine the actual radial transducer array distance and its misalignment (tilt) with respect to the center of rotation in a 2-D and 3-D tomographic setup. By increasing the time-of-flight accuracy, we force in-phase summation during the reconstruction. Our setup is composed of a linear transducer and a rotation and translation axis enabling multidimensional imaging in ultrasound and photoacoustic mode. Our approach is validated on phantoms and young mice *ex vivo*. The results indicate that application of the proposed analytical calibration algorithms prevents image artifacts. The spatial resolution achieved was 160 and 250 μm in photoacoustic mode of 2-D and 3-D tomography, respectively. (E-mail: Milan.oeri@ibmt.fraunhofer.de) © 2016 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound tomography, Photoacoustic tomography, Transducer calibration, Linear transducers, Image artifacts, Combined imaging.**

INTRODUCTION

Linear ultrasound transducer for tomography

In biomedical research, tomographic imaging of the anatomy and physiology of small animals and human extremities is often performed using cost-intensive modalities, for example, magnetic resonance imaging, positron emission tomography and computed tomography (Lewis et al. 2002; Koba et al. 2011). In addition to their expense, however, these technologies are sometimes based on ionizing radiation and are not always sensitive to the imaging of vasculature. On the contrary, ultrasound imaging enables non-invasive, non-ionizing visualization of tissue and organs providing scalable resolution. Furthermore, full-view (*i.e.*, 360°) ultrasound (US) tomography enables isotropic spatial resolution through detection of a signal from a surface surrounding the target object and thus enhances the quality of reconstructed cross-sectional images of the investigated target. Tomographic US can be performed in either transmission or pulse-echo mode. Here, we focus on the latter configuration, which enables visualization of tissue interfaces based on the presence of acoustic impedance rather than attenuation maps.

Photoacoustic imaging

Photoacoustic (PA) tomography is an emerging imaging modality that can be combined with US to obtain additional information on the optical absorption of the same target object. The underlying principle is based on the conversion of absorbed light into acoustic waves that can be detected just as conventional ultrasound and is referred to as the *photoacoustic effect*. Thus, PA is capable of visualizing vasculature (Fournelle et al. 2009; Laufer et al. 2012; Zhang et al. 2006) and tumor angiogenesis (Ku et al. 2005) and has already made its way into pre-clinical studies of breast cancer diagnosis (Kruger et al. 2013; Piras et al. 2009).

Existing tomographic photoacoustic detection configurations are based on single elements (Sun et al. 2009) and curved (Brecht et al. 2009; Gamelin et al. 2008; Oraevsky and Karabutov 2000; Yang et al. 2009) or planar (Geateau et al. 2013; Kruger et al. 2003; Kuzhushko et al. 2004; Yin et al. 2004) arrangements.

Geometric detection approaches to tomography

Because *in vivo* studies require control of animal parameters (*e.g.*, motion, respiration), investigations should

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be as short as possible. Transducer arrays are, thus, more likely to be applied to tomography as parallel detection reduces acquisition times. Although tomographic and concave detection geometries address the radial propagation nature of acoustic waves, they remain custom-made and cost-intensive systems. Linear transducer arrays are commercially available and hence attractive for US and PA imaging. Medical linear ultrasound transducers were introduced for thermoacoustic tomography by Kruger et al. in 2003. A linear ultrasound transducer has been found to be suitable for a whole-body photoacoustic tomography system for small animal imaging (Geateau et al. 2013).

For tomographic imaging, the localization of transducer elements and the orientation of transducer arrays with respect to the center of the system are crucial. To date, several calibration methods or phantoms, such as wedge-pattern phantoms and wires (Abeyskera and Rohling 2011; Fenster and Downey 2000), acoustical trackers based on constrainment of emitter and receiver (Meyer and Biocca 1992) by coincident alignment and free-hand tracking methods based on optical or electromagnetic technologies (Arbel et al. 2004; West and Maurer 2004), have been used to align or calibrate acoustic detectors, for example, for 3-D freehand imaging (Mercier et al. 2005). However, these techniques can be cost intensive and lack the ability to determine the exact radial transducer array position and in-plane tilt (*x*/*y*-plane) in a tomographic setup, that is, with rotating probes or samples. Other calibrations are based on point-like phantoms and a manual, iterative adjustment of the transducer position. The position is varied until a certain criterion, for example, maximum amplitude, is passed (Brecht et al. 2009; Geateau et al. 2013). However, imprecise knowledge of the transducer positions, and especially of the tilt, yields inaccurate time-of-flight (TOF) assumptions, preventing an adequate phase-adjusted summation of signals during the reconstruction that degrades the image.

Analytical calibration algorithm I (2-D)

In a previous study (Oeri et al. 2015), we described the impact of transducer alignment on the image quality achieved and illustrated a calibration algorithm for ultrasound and photoacoustic tomography accurately delivering the actual radius r and transducer array tilt δ. The method is based on a system of linear equations (SLE) in which photoacoustic measurements from several angular positions are supplied as input (Fig 1, left). Owing to the misalignment of the transducer, the tomographic reconstruction of a small target yields an image artifact, where the signal information is distributed on a circular shape. Figure 1 (right) illustrates the obtained circular image artifact for a simulated transducer misalignment of 2°, an error in the radial distance of 1.5 mm and 18 angular positions (20° increments). A detailed description of the artifact, its derivation thereby and its impact on image quality is given by Oeri et al. (2015). The angular transducer position can be described by the combination of a rotation and translation matrix (R and T), in which the radial distance r and tilt δ cannot be measured precisely and thus remain unknowns (cf. Fig. 1). On that basis, we set up an overdetermined SLE of the form $Ax \approx b$ with respect to i different angular measurement positions to extract the tilt and radial distance:

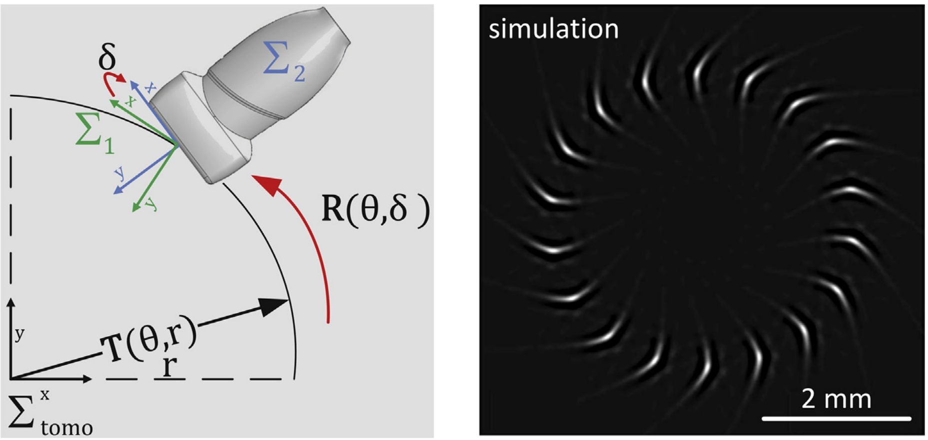

Fig. 1. Misalignment of transducer and image artifact. The transducer misalignment can be expressed by rotation and translation matrices (left), where a radial deviation and transducer tilt are present (left). Uncorrected transducer misalignment yields the circular distribution of signals fractions (right) that is used to derive the transducer tilt and actual radial distance.