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● *Original Contribution*

HYBRID PHOTOACOUSTIC/ULTRASOUND TOMOGRAPH FOR REAL-TIME FINGER IMAGING

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Abstract—We report a target-enclosing, hybrid tomograph with a total of 768 elements based on capacitive micromachined ultrasound transducer technology and providing fast, high-resolution 2-D/3-D photoacoustic and ultrasound tomography tailored to finger imaging. A freely programmable ultrasound beamforming platform sampling data at 80 MHz was developed to realize plane wave transmission under multiple angles. A multiplexing unit enables the connection and control of a large number of elements. Fast image reconstruction is provided by GPU processing. The tomograph is composed of four independent and fully automated movable arc-shaped transducers, allowing imaging of all three finger joints. The system benefits from photoacoustics, yielding high optical contrast and enabling visualization of finger vascularization, and ultrasound provides morphologic information on joints and surrounding tissue. A diode-pumped, Q-switched Nd:YAG laser and an optical parametric oscillator are used to broaden the spectrum of emitted wavelengths to provide multispectral imaging. Custom-made optical fiber bundles enable illumination of the region of interest in the plane of acoustic detection. Precision in positioning of the probe in motion is ensured by use of a motor-driven guide slide. The current position of the probe is encoded by the stage and used to relate ultrasound and photoacoustic signals to the corresponding region of interest of the suspicious finger joint. The system is characterized in phantoms and a healthy human finger *in vivo*. The results obtained promise to provide new opportunities in finger diagnostics and establish photoacoustic/ultrasound-tomography in medical routine. (E-mail: marc.fournelle@ibmt.fraunhofer.de) © **2017 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Photoacoustic tomography, Ultrasound imaging, System design, Capacitive micromachined ultrasound transducer technology, Finger imaging, Rheumatoid arthritis.**

INTRODUCTION

Rheumatoid arthritis

Rheumatoid arthritis (RA) is a disease with a prevalence of 1%–2% worldwide (Gibofsky 2012). This chronic disease affects the finger joints and causes swelling, deformation and even destruction. When treated late, RA may lead to immobility of the fingers or hand. Several investigations prove that the diagnosis of arthritis at an early stage and subsequent treatment increase the potential to prevent further damage (Breedfeld 2011; Huscher et al. 2006; Tsakonas et al. 2000). These studies illustrate that inflammatory processes and, thus, an intense proliferation of blood vessels in the region of the affected finger joints are related to RA. Another abnormality that may help to identify RA is the swelling of the joints caused by hypertrophy of the synovial layer (Raza et al. 2005).

Imaging of finger vasculature

To date, ultrasound (US), radiography and magnetic resonance imaging (MRI) have been used to visualize both the finger bones and the synovium. However, US imaging by itself is less suitable for visualizing small vessels, and it does not achieve adequate contrast in soft tissue. Doppler US can estimate the increased blood flow caused by proliferation, but is highly user dependent. Cost-intensive MRI usually involves the application of contrast agents to provide sufficient resolution of vasculature (Vasanth et al. 2010). Other imaging systems such as positron emission tomography and radiography suffer from ionization and minor sensitivity to vascularization.

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Visualization of the vasculature, in particular, has high potential in facilitating the early detection of RA, because proliferating vessels are a characteristic symptom of the outbreak of the disease. RA diagnosis may therefore benefit from photoacoustic tomography (PA), also called optoacoustic tomography, an emerging imaging technology that provides optical absorption maps of tissue. Hemoglobin is a major absorber of the applied optical energy. The phenomenon of the photoacoustic effect is the conversion of the absorbed energy into propagating ultrasound waves that can be detected by acoustic detectors non-invasively. Although PA profits from established ultrasound detection technology and has proven to be capable of imaging the vascular anatomy of the human hand (Deán-Ben and Razansky, 2013; Niederhauser et al. 2005; Zhang et al. 2011), ultrasound adds information on bone eruptions, the joint interspaces and the synovium (Backhaus et al. 2001). Together, these technologies address the shortcoming of existing imaging modalities, because they enable low-cost, user-independent, high-resolution (US) and high-contrast (PA) finger joint imaging.

System design considerations

Various studies have reported that photoacoustic/ultrasound tomography (PAUS) enables the visualization of blood vessels in human fingers (Ermilov et al. 2012; Sun et al. 2009; van Es et al. 2014). Although Sun et al. (2009) concentrated on the correlation of inflammatory regions to the finger joints of patients suspected of having osteoarthritis (OA), Ermilov et al. (2012) illustrated the visualization of major blood vessels by studying time series during hypothermia. Daoudi et al. (2014) developed a PAUS device based on a portable ultrasound system and a linear 128-element transducer integrating laser diodes for OA signal generation. However, because such linear arrays only a limited view (roughly 30°), the proposed system is restricted to combined imaging of superficial structures facing the transducer.

In the past few years, several attempts have been made to counter limited view artifacts, which occur with objects that are not fully enclosed by the detector. as is the case with commercially available linear transducer arrays. Tomography, in which data are collected from different views, has proven to enable the artifact-free reconstruction of cross sections of the human finger. Technically, the applied tomographic geometries range from systems based on single-element detectors (Liu et al. 2016; Xi and Jiang 2015), to linear arrays (Ermilov et al. 2016) or concave transducers (van Es et al. 2014) to hand-held concave probes (Merčep et al. 2015) that are rotated partly or by 360° around the investigated object.

Van Es et al. (2014) were the first to report high-quality photoacoustic tomography of the finger blood vessels *in vivo* providing a spatial in-plane resolution of 100 μm. Tomographic images were obtained by rotating a 32-element, curvilinear array (spanning 85°) and applying multiple fiber bundles to illuminate the distal (DIP) and peripheral (PIP) interphalangeal joints of a volunteer. The imaging time for one slice is reported to be roughly 1 min. By translation, volumetric data of the investigated finger could be acquired (10 slices [0.5 mm]). Xi and Jiang (2015) used two, coincidentally arranged focused transducers and multiple fiber bundles in a circular scanning system with a diameter of 19 mm to fairly visualize inner structures as the tendons and phalanx of a female finger within a limited, active imaging area of 5.5 mm (radius). The total scan time for 50 slices (240 μm) was reported to be 5 min at a pulse repetition frequency (PRF) of the laser system of 20 Hz. A similar geometry, but with two unfocused ultrasound transducers, was developed by Liu et al. (2016) to provide multispectral, dual-modality imaging (PAUS) with enhanced image quality. Although blood vessels were imaged clearly in the photoacoustic mode at four wavelengths, the US images reveal significantly decreased contrast of tissue structures such as the tendons and phalanx. However, complementary information could be obtained from the PA images. The acquisition time for a single slice obtained from 240 positions at an angular step size of 1.5° was stated to be 2–3 min.

Although the aforementioned systems successfully produced tomographic PA images (partly in a hybrid combination with US), they impeded real-time imaging, a key limitation to their application in routine medical practice. Recently, Merčep et al. (2015) addressed this drawback by designing hand-held concave probes (40-mm radius) spanning 135° (256 elements) and 270° (512 elements) with integrated fiber bundles, enhancing the coverage of the investigated object. An advanced synthetic transmit aperture (STA) beamforming algorithm, together with a compounding technique, was found to reduce sidelobe artifacts, yielding high-quality images of the cross section of a human PIP joint *in vivo*. Volumetric images were obtained by moving the probe along the finger. Although the obtained images revealed complementary information on the hyperperfusion (PA) and structures as skin, bone and larger vessels (US), a small section of the investigated objects (∼45°) could not be covered by the transducer and thus was not imaged well in both modes. The framework developed provides GPU-accelerated image reconstruction, yielding images (200 × 200 pixels) within less than 100 ms (US) and 40–278 ms (PA) depending on the algorithm used.

Although the aforementioned systems assumed a constant speed of sound (SOS) supposedly resulting in