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Imaging of human peripheral blood vessels during cuff occlusion with a compact LED-based photoacoustic and ultrasound system

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ABSTRACT

Non-invasive imaging plays an important role in diagnosing and monitoring peripheral artery disease (PAD). Doppler ultrasound imaging can be used for measuring blood flow in this context. However, this technique frequently provides low contrast for flow in small vessels. Photoacoustic imaging can allow for the visualization of blood in small vessels, with direct contrast from optical absorption of hemoglobin. In this work, we investigate the potential applications of a compact LED-based photoacoustic (850 nm) and ultrasound imaging system for visualizing human peripheral blood vessels during cuff occlusion. Each measurement comprised three stages. First, a baseline measurement of a digital artery of a human finger from a volunteer without a diagnosis of PAD was performed for several seconds. Second, arterial blood flow was stopped using an occlusion cuff, with a rapid increase of pressure up to 220 mm Hg. Third, the occlusion cuff was released rapidly. Raw photoacoustic and ultrasound image data (frame rate: 70 Hz) were recorded for the entire duration of the measurement (20 s). The average photoacoustic image amplitude over an image region that enclosed the digital artery was calculated. With this value, pulsations of image amplitudes from the arteries was clearly visualized. The average photoacoustic image amplitude decreased during the increase in cuff pressure and it was followed by a rapid recovery during cuff release. With real-time non-invasive measurements of peripheral blood vessel dynamics *in vivo*, the compact LED-based system could be valuable for point-of-care imaging to guide treatment of PAD.

Keywords: Photoacoustic imaging, Ultrasound imaging, LED, Peripheral artery disease

INTRODUCTION

Peripheral artery disease (PAD) is prevalent clinical manifestation of systemic atherosclerosis that is underdiagnosed. Ankle–brachial index (ABI) is a common method for diagnosis of PAD based on non-invasive blood pressure measurements. However, a review by Xue et al. [1] from 8 studies comprising a total of 2043 patients concluded that the sensitivity of ABI varied from only 15% to 79%, and that it was particularly low in elderly patients and diabetics.

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Doppler ultrasound (US) is also used to diagnose PAD, as it can provide information about blood flow [2]. However, detecting blood flow in small vessels with Doppler US is often challenging.

Photoacoustic (PA) imaging is a hybrid imaging modality that is based on the detection of ultrasound signals from optically absorbing tissue chromophores using pulsed excitation light [3]. PA imaging has been shown to image deep vascular structures with high spatial resolution and sensitivity [4]. Using a linear array probe for US detection, PA imaging can be combined with US imaging to provide complementary functional, molecular and structural information of tissue [5-9]. However, conventional excitation light sources for PA imaging are often expensive and bulky, and as such they are often impractical from the standpoint of clinical translation.

In this study, we investigated the capabilities of a light emitting diode (LED)-based PA and US imaging system for providing diagnostic information of human peripheral vessels. To obtain a preliminary indication of the system's clinical potential, a digital artery from a human volunteer was imaged at a frame rate of 70 Hz during cuff occlusion. Subsequent image analysis revealed that the system successfully recorded the rapid response of the digital artery to cuff occlusion and release.

MATERIALS AND METHODS

1.1 The imaging system

The dual modality imaging system (AcousticX, CYBERDYNE Inc, Tokyo, Japan) [10] was based on a linear-array US probe for ultrasound detection with LED arrays as excitation light source. The US imaging probe was similar to a clinical linear array US probe (128 transducer elements, 9 MHz central frequency, 0.3 mm inter-element spacing). PA and US imaging was performed in an interleaved manner. Excitation light for PA imaging was provided by two arrays of LEDs attached to opposite sides of the imaging probe, and illuminated an area of 50 mm × 7 mm on the sample surface (Figure 1). Each LED array provided a pulse energy of 200 µJ at 850 nm. The pulse repetition frequency and duration could be tuned over ranges of 1- 4 kHz, and 30 ns to 100 ns, respectively. Raw channel data from all 128 channels were digitized simultaneously at 40 MS/s for PA imaging and 20 MS/s for US imaging. Image reconstruction (PA and US) was performed using an in-built, GPU-based Fourier-domain algorithm and PA and US image overlays were displayed online in real-time.

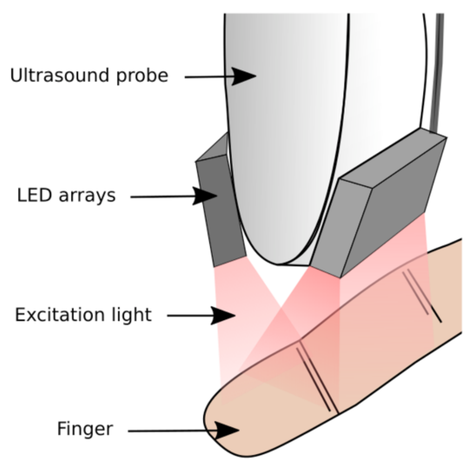

Figure 1. Schematic illustration of the photoacoustic and ultrasound imaging probe and the measurement configuration. A digital artery of the index finger of a human volunteer was imaged in water.

1.2 Imaging digital artery during cuff occlusion.

A digital artery in the index finger from a human volunteer without a diagnosis of PAD was imaged during cuff occlusion and release of the brachial artery. Each measurement, which comprised three stages, was performed with the imaging probe and the finger in water. First, the digital artery was visually identified with the guidance of real-time PA and US imaging and a baseline measurement was performed for *ca*. 5 s. Second, arterial blood flow was stopped using an occlusion cuff at the brachial artery with a rapid increase of pressure up to 220 mmHg. Third, the occlusion cuff was released by rapidly opening the pressure valve. Raw PA and US channel data were recorded at a frame rate of 70 Hz for the entire duration of the measurement (20 s). PA image reconstruction was performed offline with a frequency-domain algorithm implemented in the k-Wave toolbox [11]. The average PA image amplitude over an region that enclosed the digital artery was calculated at each time point.

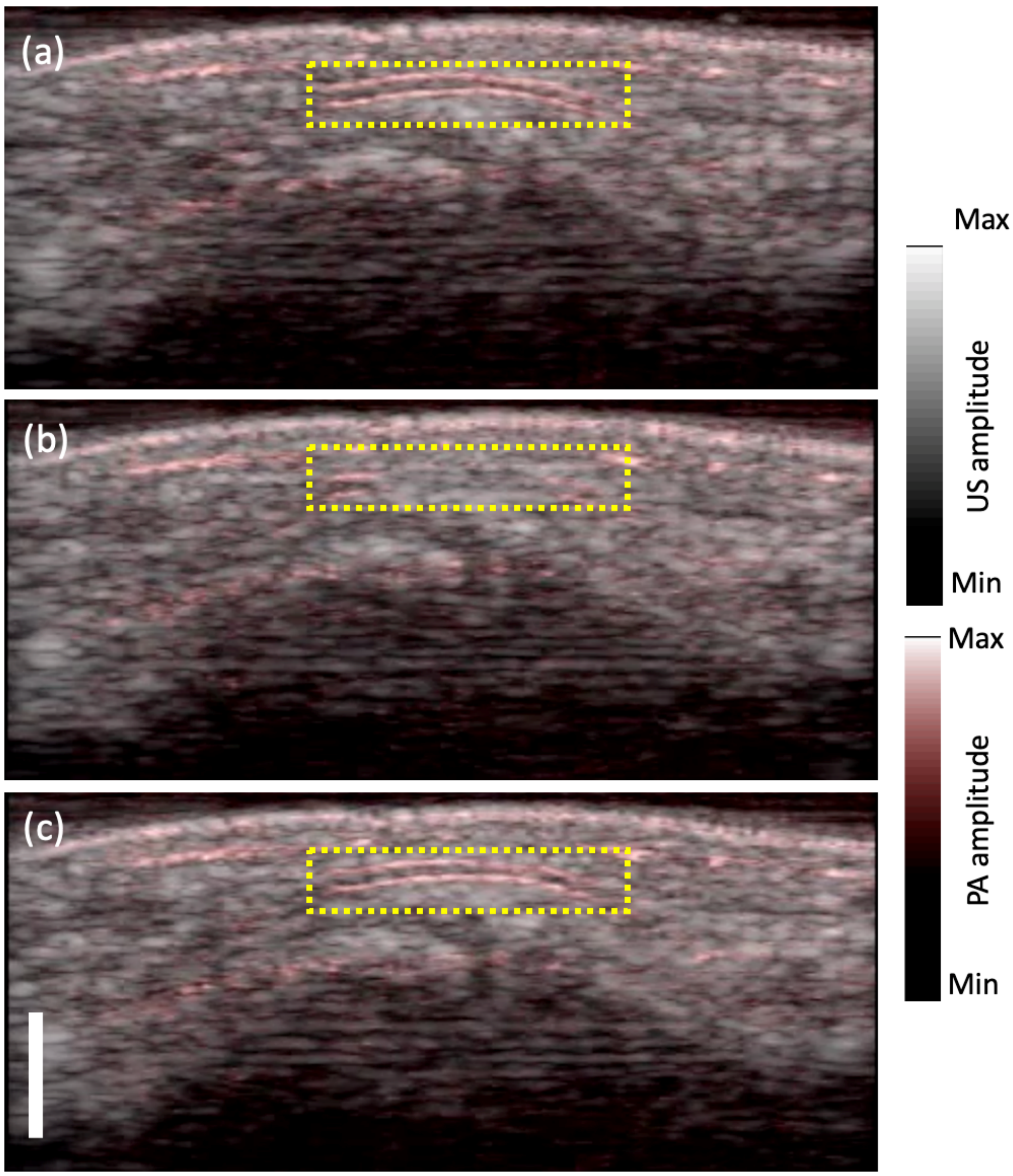

Figure 2. Photoacoustic (PA) and ultrasound (US) image overlays of a digital artery of the index finger of a human volunteer before (a) and after cuff occlusion (b), and after recovery (c). A region-of-interest (ROI) surrounding the digital artery is indicated with a yellow dashed box (left). The image region corresponding to the depth range of 0 to 5 mm, where there was water for ultrasonic coupling, was cropped. Scale bar: 5 mm. Images are displayed in a logarithmic scale with dynamic ranges of 45 dB and 60 dB for PA and US images, respectively.

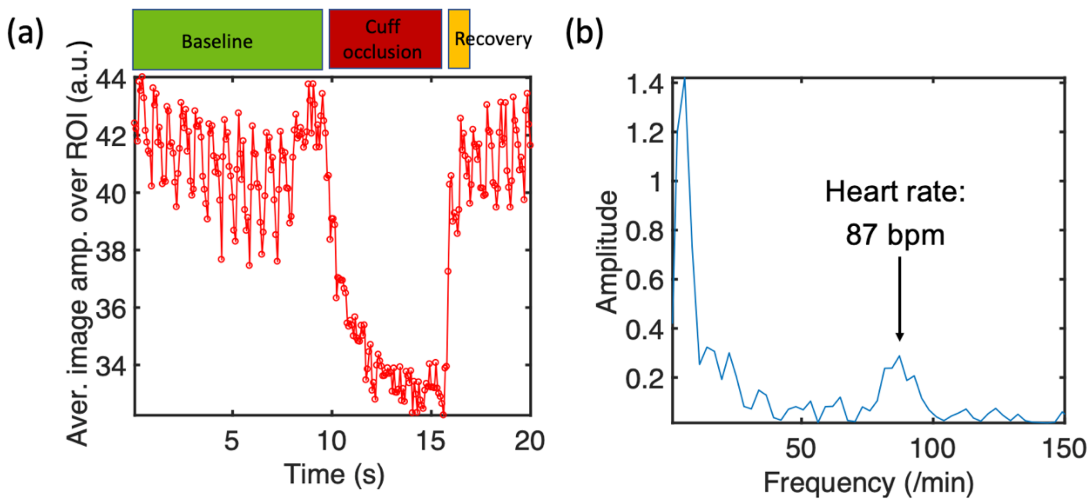

Figure 3. (a) Average photoacoustic image amplitude over an image region that enclosed the digital artery (dashed yellow box in Figure 2) for all acquired images. The coloured boxes indicate the durations of the three measurement stages including Baseline, Cuff occlusion and Recovery. (b) Fourier transformation of the curve in (a) revealed a heart rate of 87 beats per minute (bpm).

RESULTS AND DISCUSSION

During the baseline measurement, US imaging provided anatomical information of the index finger, such as the skin surface, and the finger joint. PA imaging provided visualization of superficial blood vessels including the digital artery, which was identified by the image amplitude pulsations (Figure 2a). During cuff occlusion, PA signal from the digital artery disappeared with increasing cuff pressure (Figure 2b), and recovered rapidly when the cuff was released (Figure 2c).

The average photoacoustic image amplitude over a region-of-interest enclosing the digital artery (dotted box in Figure 2) for each time point is shown in Figure 3(a). Pulsations signals were clearly visible during the baseline measurement and after recovery from cuff occlusion. This average value decreased rapidly when the cuff pressure was increased. PA imaging was able to record the fast recovery of the digital artery after the release of the cuff. Fourier transformation (Figure 3a) revealed a heart rate of 87 beats per minute (Figure 3b). The observed periodicity of the PA signal from the digital artery could arise from several factors, and further study is needed to provide a full explanation. A recent study by Bok et al. pointed to the effects of aggregation/non-aggregation of red blood cells throughout the cardiac cycle on PA signal amplitudes and wavelength-dependencies [12].

In this work, we demonstrated that the LED-based photoacoustic / ultrasound imaging system provided sufficient depth and resolution for imaging digital vessels. This preliminary study indicates that the system could be useful to study the rapid responses of the digital artery to cuff occlusion and release, by providing clinically relevant parameters such as vessel diameter, heart rate, and recovery time from cuff occlusion.

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