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Differential ultrasonic imaging for the characterization of lesions induced by high intensity focused ultrasound

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Abstract

High intensity focused ultrasound (HIFU) is an effective technique for noninvasive local creating coagulative necrotic lesions in deep target volumes without damage to the overlaying or surrounding tissues. It is very important to detect and evaluate lesions generated by HIFU during treatment procedures. This study describes the development of several differential ultrasonic imaging techniques to characterize lesions based on estimation of relative changes in tissue properties derived from backscattered RF data. A single, spherical HIFU transducer was used to produce lesions in soft tissues. The RF signals were recorded as outputs from a modified diagnostic ultrasound system. After some preprocessing, the integrated backscatter values, which can be used as an indicator of the microstructure and backscattering property of tissues, were calculated before and after HIFU treatment. The differential integrated backscatter values were subsequently used to form images revealing the lesion areas. The differential attenuation imaging with the same RF data was also performed, which has been proposed by a few researchers. The results of the differential integrated backscatter imaging were compared with that of the differential attenuation imaging and the former method offers some advantages over the latter method. The two methods above are both based on spectrum analysis and would spend much computational time. Therefore, some simple digital differential imaging methods, including absolute difference (AD), sum absolute differences (SAD), and sum squared differences (SSD) algorithms, were also proposed to detect HIFU-induced lesions. However, these methods cannot provide the information of the degree of tissue damage. Experiments in vitro bovine muscle and liver validated the method of differential integrated backscatter imaging for the characterization of HIFU-induced lesions. And the AD, SAD, and SSD algorithms can be implemented in real-time during HIFU therapy to visualize the lesions.

Keywords: High intensity focused ultrasound; Differential ultrasonic imaging; Integrated backscatter

1. Introduction

High intensity focused ultrasound (HIFU) is currently being investigated to treat localized tumors in ablation therapy and has been applied clinically in China. The technique can focus the energy precisely on the target volume and make the temperature rise sharply without damage to the overlaying or surrounding tissues [1]. However, monitoring imaging technique for HIFU treatment has not been developed adequately even though medical imaging technology has made great progress.

Various methods have been proposed to monitor and evaluate HIFU-induced lesions during the therapy. MRI, CT and US are three imaging methods available to noninvasively monitor HIFU therapy progress. Ultrasound-based techniques are promising for its low costs and giving more mechanical compatibility. The most obvious method entails the use of conventional B-mode ultrasound images, which generally shows the variation in echogenicity in the HIFU-treated area [2]. Unfortunately, there is no correlation between the degree of backscattering and the degree of tissue damage. Changes in tissue properties, such as

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attenuation, speed of sound, nonlinearity and elasticity have been measured at the site of the HIFU-induced lesion and methods to detect these changes have been reported [3–6].

Ultrasonic integrated backscatter (IBS) has shown the potential to provide the information of micro-architecture in tissue, which may be altered after tissue destroyed by HIFU therapy [7]. And cavitation effects may also modify the scattering and propagation of ultrasound in the tissues. The aim of this study is to characterize the lesions by measuring localized variations in tissue IBS. And differential IBS imaging technique was compared with the differential attenuation imaging which was proposed by other researchers. Moreover, this paper describes several simple digital differential imaging methods including absolute difference (AD), sum absolute differences (SAD) and sum squared differences (SSD) algorithms to identify the HIFU-induced lesions, which may be applied in real-time.

2. Materials and methods

2.1. Instrumentation setup

A 1.2 MHz HIFU transducer (Imasonic Inc., France) with an aperture diameter of 140 mm and a focal depth of 120 mm was driven by a power amplifier (AG1016, T&C Power Conversion Inc., Rochester, NY). A modified diagnostic ultrasound system consisting of one 128-element linear array imaging probe with a center frequency of 5 MHz (DP9900, Mindray Inc., China), was used to capture the RF signals backscattered by the tissue and digitize the RF signals at a sampling rate of 25 MHz. The output digital signals were sampled through a high speed DIO data acquisition card (PCI-7300A, Adlink Technology Inc., TW) and stored in the hard drive of a PC for offline processing. The overall system block diagram of the experimental setup is shown in Fig. 1.

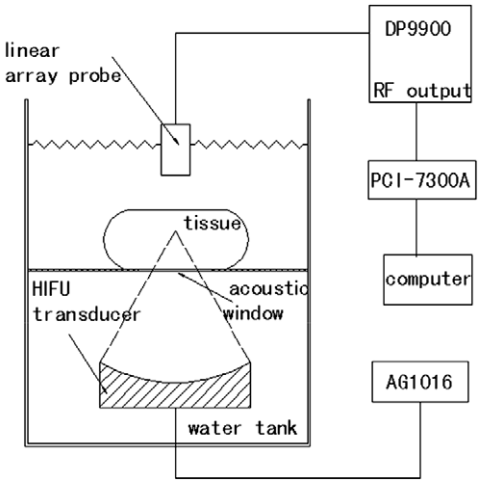

Fig. 1. Experimental setup.

2.2. Tissue preparation and experiment parameters

Fresh ex vivo bovine muscle and liver samples were used in the experiments. The samples were placed in a vacuum chest for 20 min prior to the experiments to ensure that they were thoroughly degassed. The HIFU transducer, the B-mode imaging transducer, and the tissue samples were all immersed in the degassed water during the experiments. Low-power and long-time irradiations were adopted in this study to avoid serious cavitation and ensure the predictability of the results. The beef samples were irradiated for 40 s with electric power of 60 W with the focus locating at the distance of 20 mm from the surface of the tissues. The exposure time, electric power and depth of the liver samples were 60 s, 50 W and 10 mm respectively. RF signals were recorded before and after HIFU treatment from identical positions of the tissue samples.

2.3. Data analysis

The mathematical description of the differential imaging method candidates is given below.

Differential integrated backscatter imaging

$$DI = \log(IBS_a) - \log(IBS_b)$$

$$IBS_a = \int_{f_0-\Delta f/2}^{f_0+\Delta f/2} \frac{P_a(f)}{P_0(f)}\mathrm{d}f, \quad IBS_b = \int_{f_0-\Delta f/2}^{f_0+\Delta f/2} \frac{P_b(f)}{P_0(f)}\mathrm{d}f$$

Differential attenuation imaging

$$DI = \mathrm{slope}(\Delta P(f))$$

$$\Delta P(f) = 10 \cdot \log_{10} P_a(f) - 10 \cdot \log_{10} P_b(f)$$

Digital differential imaging

$$\mathrm{AD} : DI(z,x) = |S_a(z,x) - S_b(z,x)|$$

$$\mathrm{SAD} : DI(z,x) = \sum_{i=-\frac{n-1}{2}}^{\frac{n-1}{2}} |S_a(z+i,x) - S_b(z+i,x)|$$

$$\mathrm{SSD} : DI(z,x) = \sum_{i=-\frac{n-1}{2}}^{\frac{n-1}{2}} [S_a(z+i,x) - S_b(z+i,x)]^2$$

where $P_b(f)$, $P_a(f)$ are the power spectrum of acoustic signal backscattered by the tissue before and after HIFU treatment respectively, $P_0(f)$ is the power spectrum of reference echo. $S_b(z,x)$, $S_a(z,x)$ refer to the RF echo. z is the depth, x is the transverse direction of image. f_0 is the center frequency and Δf is the bandwidth of the imaging probe.

3. Results and discussion

Fig. 2(a) and (b) show the B-mode images of an in vitro beef sample before and after HIFU treatment respectively. And Fig. 2(c)–(g) are corresponding differential images applied with the various algorithms we proposed. Although the information of HIFU-induced lesions is more obvious in differential images, other tissues are almost