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● *Original Contribution*

ASSESSMENT OF CODED EXCITATION IMPLEMENTATION FOR ESTIMATING HEAT-INDUCED SPEED OF SOUND CHANGES

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Abstract—Speed of sound (SoS) is an acoustic property that is highly sensitive to changes in tissues. SoS can be mapped non-invasively using ultrasonic through transmission wave tomography. This however, practically limits its clinical use to the breast. A pulse-echo–based method that has broader clinical use and that can reliably measure treatment-induced changes in SoS even under poor signal-to-noise ratio (SNR) is highly desirable. The aim of this study was to evaluate the implementation of coded excitations (CoEs) to improve pulse-echo monitoring of heat-induced changes in the SoS. In this study, a binary phase modulated Barker sequence and a linear frequency-modulated chirp were compared with a common Gaussian pulse transmission. The comparison was conducted using computer simulations, as well as transmissions in both agar–gelatin phantoms and *ex vivo* bovine liver. SoS changes were experimentally induced by heating the specimens with a therapeutic ultrasound system. The performance of each transmission signal was evaluated by correlating the relative echo shifts to the normalized SoS measured by through transmission. The computer simulations indicated that CoEs are beneficial at very low SNR. The Barker code performed better than both the chirp and Gaussian pulses, particularly at SNRs <10 dB ($R^2 = 0.81 \pm 0.06$, 0.68 ± 0.07 and 0.55 ± 0.08, respectively, at 0 dB). At high SNRs, the CoEs performed statistically on par with the Gaussian pulse. The experimental findings indicated that both Barker and chirp codes performed better than the Gaussian pulse on *ex vivo* liver ($R^2 = 0.80 \pm 0.15$, 0.79 ± 0.15 and 0.54 ± 0.17, respectively) and comparably on agar–gelatin phantoms. In conclusion, CoEs can be beneficial for assessing temperature-induced changes in the SoS using the pulse-echo method under poor SNR. (E-mail: haim@bm.technion.ac.il) © 2017 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Therapeutic ultrasound, Coded excitation, Speed of sound, Temperature, High-intensity focused ultrasound, Barker code, Thermometry.**

INTRODUCTION

Image-guided thermal ablation procedures have gained popularity is recent years. These therapeutic procedures include minimally invasive systems, such as radiofrequency, microwave and laser, and non-invasive systems based on high-intensity focused ultrasound (HIFU) (Goldberg et al. 2000). Real-time thermal monitoring of the procedure is an essential tool that would be required to attain the desired clinical outcome. Magnetic resonance imaging (MRI) can provide non-invasive thermal monitoring (McDannold 2005; Winter et al. 2016), but this is an expensive modality and access to its use is limited for the patient. Ultrasonic thermal monitoring could provide a cost-effective alternative with much higher temporal resolution. Indeed, quantification of the relationship between thermal changes and the acoustic properties of tissue has been the research topic of many studies (Miller et al. 2004; Souchon et al. 2005; Tra et al. 2012).

In that context, the speed of sound (SoS) is a valuable parameter that both is indicative of the state of the tissue and has high potential in real-time non-invasive temperature monitoring during thermal ablation procedures as it is very sensitive to temperature changes (Bamber and Hill 1979; Techavipoo et al. 2002). Hence, changes in SoS can be related to thermal changes induced in the studied tissue (Lewis et al. 2015). These temperature-induced SoS changes can be assessed directly (Azhari 2012; Jialiang et al. 1996) or indirectly by studying the changes occurring in detectable landmarks of the echo train signal (A-line). Echo strain (Miller et al. 2004) and echo shift (Amini et al. 2005; Maass-Moreno and Damianou 1996; Seip and

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Ebbini 1995) are some of the predominant ultrasonic mapping methods studied to view temperature-related changes. These changes, which manifest as temporal shifts of echo landmarks, are associated primarily with the changes in the local SoS. Additionally, they are also dependent on the local thermal expansion of the tissue. Nonetheless, it was reported that the echo displacement values caused by thermal expansion are relatively small when compared with the displacements caused by changes in the speed of sound (Maass-Moreno and Damianou 1996).

Speed of sound and its changes can be mapped noninvasively using ultrasonic computed tomography (UCT) (Li et al. 2009, 2011; Pratt et al. 2007), However, the need to measure through transmission (TT) waves practically limits the clinical use of UCT to the breast only. Pulse-echo, or B-mode, imaging offers a different solution to a broader spectrum of clinical applications. Hence, a pulse-echo–based method that can reliably measure the temperature-induced changes in SoS at deep tissue locations or in obese patients and under poor signal-to-noise ratio (SNR) conditions, for example, intra-cranial ultrasound, is highly desirable. One approach to pulse-echo assessment of SoS changes is the implementation of echo shift-based analysis. The quality of this analysis depends on the detectability of dominant features in the echo signals. Accordingly, reliable detectability of echo features depends mainly on the SNR and the axial resolution.

Tissue penetration and axial resolution are two opposing requirements of an ultrasonic imaging system, in general, and of echo shift analysis, in particular. As axial resolution is determined mainly by the frequency, high ultrasonic frequencies are desirable. However, attenuation increases with frequency, and this decreases the penetration into the imaged tissue. To overcome this problem of high attenuation, one may consider increasing the intensity of the transmitted wave, but this factor is limited by safety restrictions. Alternatively, one may implement high gain amplifications to the detected echo signals, but, under poor SNR conditions, this solution is also impractical as the noise is substantially amplified as well. Clearly, a method that would overcome these limitations is needed.

Coded excitations (CoEs) offer a potential solution to this problem. A CoE comprises a modulated signal that provides both a code and a carrier signal. There are primarily three different types of modulation paradigms: (i) amplitude, (ii) phase and (iii) frequency. CoE can be implemented by single transmission mode (Kamimura et al. 2015; Zhou et al. 2014) or multiple transmission modes, such as the Golay code (Chiao and Hao 2003; Nowicki et al. 2003; Pan et al. 2015). CoEs take advantage of long pulse durations, which allow an increased transmission energy without exceeding amplitude safety limits (Chiao and Hao 2005). The axial resolution is subsequently retrieved by implementing a compressive stage to the reflected echoes. Pulse compression increases the local intensity by compressing the total energy of the coded signal into a lobed signal and additionally removing the carrier. This pulse compression is commonly accomplished in signal processing by matched filtering. Matched filtering is indeed a useful filtering scheme, but as an unwanted side effect, it may contain large side lobes and, therefore, reduced pulse compression effectiveness. This undesired effect can be reduced by using alternative filtering approaches, such as complex baseband data after downsampling (Yoon et al. 2013) or inverse filtering.

The hypothesis is that coded excitations improve axial resolution and echo feature enhancement relative to the commonly used Gaussian pulse. In this way, SoS changes manifested as echo shifts can be more reliably detected under poor SNR conditions.

METHODS

The Barker code

The Barker code is a binary, phase-modulated signal. It comprises of a chain of N identical signal elements, also referred to as subpulses. The sign of each subpulse is assigned a positive (+) or a negative (–) value. There are seven possible Barker sequence lengths, and the sequence is optimized, by design, so that its autocorrelation function peak value equals N, the number of subpulses, whereas the side lobe level has values between +1 and −1 (Golomb and Scholtz 1965). The compression ratio is thus proportional to the length of the code; therefore, a longer Barker sequence provides better filtering results. Currently, the longest Barker code is 13 elements, and to maximize filtering results, this length was implemented.

The biphase modulation was carried out using sine waves centered on the central frequency of the transducers, at 5 MHz. By using a sine wave for the binary coding, high-frequency losses were minimized and the frequency bandwidth of the signal was better matched to that of the experimental system. The discontinuities stemming from the binary phase changes result in high-frequency energy losses. A full sine, or 2π cycle, was used for each binary value, or subpulse, in the code both to extend the total signal length and to increase the energy. The signal time duration for the Barker code was 2.6 µs. The Barker signal used here is illustrated in Figure 1.

The linear frequency-modulated chirp code

The chirp signal used here is a linear frequency-modulated (FM) signal. Mathematically, the chirp is expressed as

$$S(t) = A \cdot \cos\left\{2\pi\left[\left(f_0 - \frac{B}{2}\right)t + \frac{B}{2T}t^2\right]\right\} \quad 0 \le t \le T \quad (1)$$