Ultrasound in Med. & Biol., Vol. 44, No. 2, pp. 303–310, 2018

0301-5629/$ - see front matter

https://doi.org/10.1016/j.ultrasmedbio.2017.10.003

● *Original Contribution*

EVALUATING THE BENEFIT OF ELEVATED ACOUSTIC OUTPUT IN HARMONIC MOTION ESTIMATION IN ULTRASONIC SHEAR WAVE ELASTICITY IMAGING

Yufeng Deng,* Mark L. Palmeri,* Ned C. Rouze,* Clare M. Haystead,† and Kathryn R. Nightingale*

* Department of Biomedical Engineering, Duke University, Durham, North Carolina; and † Department of Radiology, Duke University Medical Center, Durham, North Carolina

(*Received* 26 *April* 2017; *revised* 2 *October* 2017; *in final form* 3 *October* 2017)

Abstract—Harmonic imaging techniques have been applied in ultrasonic elasticity imaging to obtain higher-quality tissue motion tracking data. However, harmonic tracking can be signal-to-noise ratio and penetration depth limited during clinical imaging, resulting in decreased yield of successful shear wave speed measurements. A logical approach is to increase the source pressure, but the *in situ* pressures used in diagnostic ultrasound have been subject to a *de facto* upper limit based on the Food and Drug Administration guideline for the mechanical index (MI <1.9). A recent American Institute of Ultrasound in Medicine report concluded that an *in situ* MI up to 4.0 could be warranted without concern for increased risk of cavitation in non-fetal tissues without gas bodies if there were a concurrent clinical benefit. This work evaluates the impact of using an elevated MI in harmonic motion tracking for hepatic shear wave elasticity imaging. The studies indicate that high-MI harmonic tracking increased shear wave speed estimation yield by 27% at a focal depth of 5 cm, with larger yield increase in more difficult-to-image patients. High-MI tracking improved harmonic tracking data quality by increasing the signal-to-noise ratio and decreasing jitter in the tissue motion data. We conclude that there is clinical benefit to use of elevated acoustic output in shear wave tracking, particularly in difficult-to-image patients. (E-mail: yufeng.deng@duke.edu)

Key Words: **Elevated acoustic output, Shear wave elasticity imaging, Mechanical index, Liver, Harmonic imaging.**

INTRODUCTION

Ultrasonic elasticity imaging methods have been developed over the last two decades to estimate tissue stiffness, which is often associated with underlying pathological conditions (Shiina et al. 2015). An increase in tissue stiffness can be caused by the presence of fibrotic tissue, as occurs in liver cirrhosis, or by an increase in tissue cellular density, as typically occurs with cancer. A number of ultrasonic elasticity imaging techniques have been proposed, including acoustic radiation force impulse (ARFI) imaging (Nightingale et al. 2002) and shear wave elasticity imaging (SWEI) (Sarvazyan et al. 1998). These methods use long-duration focused ultrasound beams to induce tissue motion and standard ultrasound imaging techniques to track the resulting tissue motion. ARFI imaging measures on-axis tissue displacement to determine relative differences in tissue stiffness. SWEI monitors tissue motion at locations offset from the ARFI excitation to determine the propagation speed of the induced shear wave, which is related to the shear modulus of the material.

Tissue harmonic imaging (THI) has been widely used in diagnostic ultrasound since the late 1990s because it improves image quality compared with fundamental B-mode imaging mode. THI relies on non-linear acoustic wave propagation, which generates harmonic signals as the transmitted sound wave travels through biological tissues. An ultrasound harmonic image is created from the harmonic signal instead of the transmitted fundamental signal. Compared with fundamental imaging, THI is reported to create higher-quality images with respect to lesion visibility and diagnostic confidence (Thomas and Rubin 1998), because of decreased side lobe energy (Christopher 1997, 1998) and decreased reverberation clutter (Bradley 2006; Pinton et al. 2011). However, second harmonic pressure amplitude is generally 10–20 dB lower than the corresponding fundamental pressure (Desser and Jeffrey 2001). Therefore, THI can be both signal-to-noise ratio

Address correspondence to: Yufeng Deng, Department of Biomedical Engineering, Duke University, 1427 CIEMAS, Box 90281, Durham, NC 27708. E-mail: yufeng.deng@duke.edu

(SNR) and penetration depth (PD) limited during clinical imaging, resulting in decreased diagnostic utility (de Moura Almeida et al. 2008; Klysik et al. 2014; Schuh et al. 2011).

Tissue harmonic imaging techniques have been applied in tissue motion tracking in ultrasonic elasticity imaging methods to obtain higher-quality tracking data using the benefits of *in vivo* harmonic imaging (Amador et al. 2016; Doherty et al. 2013; Hurlburt et al. 2007). The ability to detect a shear wave signal is dependent largely on ultrasound image quality, which is susceptible to artifacts such as phase aberration and reverberation clutter. Harmonic tracking reduces the reverberation clutter in tissue displacement estimates, thus improving the tracking data quality (Doherty et al. 2013). Harmonic tracking has been reported to improve SWEI measurements in myocardial tissue (Song et al. 2013) and in human livers (Amador et al. 2016). On the other hand, similar to B-mode THI, harmonic tracking has the challenge of low SNR and low penetration depth. The low SNR in harmonic tracking can lead to higher jitter, that is, the magnitude of the uncertainties in ultrasonic displacement estimation. On the basis of the Cramér-Rao lower bound (CRLB), a theoretical lower limit of the jitter in ultrasonic correlation-based time delay estimation can be expressed as (Walker and Trahey 1995)

$$\text{Jitter} \geq \sqrt{\frac{3}{2f_c^3\pi^2T\left(BW^3+12BW\right)}\left(\frac{1}{CC^2}\left(1+\frac{1}{SNR}\right)^2-1\right)} \quad (1)$$

where f_c is the center frequency, T is the correlation window length, BW is the fractional bandwidth, CC is the correlation coefficient between the signals and SNR is the electronic signal-to-noise ratio. Because of the limited harmonic signal amplitude, CC and SNR can be lower for harmonic tracking, which can result in higher jitter. Herein, we test the hypothesis that using an elevated mechanical index (MI) in harmonic tracking will increase the SNR of the harmonic signal, thus reducing jitter magnitude and increasing the measurement success of ARFI and SWEI imaging.

The acoustic output of diagnostic ultrasonic imaging systems in the United States has been subject to a *de facto* upper limit by the Food and Drug Administration (FDA) based on the mechanical index (MI <1.9) (Center for Devices and Radiological Health (CDRH) 1994). The MI is defined as

$$\text{MI} = \frac{p_{r.3}\left(z_{MI}\right)}{\sqrt{f_c}} \quad (2)$$

where $p_{r.3}\left(z_{MI}\right)$ is the attenuated (derated using an attenuation coefficient [α] of 0.3 dB/cm/MHz) peak-rarefactional pressure, z_{MI} is depth from the transducer to the plane of the maximum attenuated pulse-intensity integral (which generally occurs near the focal depth (Center for Devices and Radiological Health (CDRH) 1994) and f_c is the center frequency of the transmitted wave (International Electrotechnical Commission [IEC] 2010). The MI guideline is intended to minimize the potential risk of inertial cavitation induced by diagnostic ultrasound examinations. The MI is commonly further limited by commercial ultrasound vendors when a 20%–30% safety buffer is applied to reduce the number of production transducers requiring quality assurance testing (American Institute of Ultrasound in Medicine/National Electrical Manufacturers Association [AIUM/NEMA] 1998; Ziskin 2003); as a result, most current commercial scanners use a maximum MI between 1.3 and 1.6. However, the FDA MI guideline for diagnostic ultrasound systems was based on substantial equivalence with commercial products on the market prior to 1976, rather than on the scientific evidence of bio-effects. A recent report from the AIUM concluded that exceeding the recommended maximum MI given in the FDA guidance up to an estimated *in situ* value of 4.0 could be warranted without concern for increased risk of cavitation in non-fetal tissues without gas bodies (Nightingale et al. 2015).

Our group has previously investigated the benefit of using elevated acoustic output in the ARFI excitation in shear wave imaging (Deng et al. 2015). A clinical study was performed to evaluate hepatic SWEI measurement success as a function of push pulse energy using two MI values (1.6 and 2.2) over a range of pulse durations. The results indicated that the rate of successful SWS estimation is linearly proportional to the magnitude of the push energy. A higher push energy results in higher tissue displacement, which in turn leads to higher SNR of the tracking data. On the other hand, in our experience, the success of ultrasonic shear wave imaging depends largely on the ability to accurately track tissue motion. The impact of using elevated MIs in tissue motion tracking was not separately evaluated because of hardware limitations in the previous study.

In the work described in this article, we examined the use of elevated acoustic output in harmonic motion estimation in SWEI. This study evaluated SWS estimation yield and jitter amplitude for SWEI sequences using identical push beams and either a typical MI value of 1.4 or an elevated MI value of 2.4 for motion tracking.

METHODS

Data acquisition sequence and calibration

Group SWS was measured with a modified Siemens Acuson S2000 ultrasound scanner (Siemens Healthcare, Ultrasound Business Unit, Mountain View, CA, USA) and a 4C1 curvilinear array. The push and track pulses for each