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● *Original Contribution*

THERMAL SAFETY SIMULATIONS OF TRANSIENT TEMPERATURE RISE DURING ACOUSTIC RADIATION FORCE-BASED ULTRASOUND ELASTOGRAPHY

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Abstract—Ultrasound transient elastography is a new diagnostic imaging technique that uses acoustic radiation force to produce motion in solid tissue *via* a high-intensity, long-duration "push" beam. In our previous work, we developed analytical models for calculating transient temperature rise, both in soft tissue and at a bone/soft tissue interface, during a single acoustic radiation force impulse (ARFI) imaging frame. The present study expands on these temperature rise calculations, providing applicable range assessment and error analysis for a single ARFI frame. Furthermore, a "virtual source" approach is described for temperature and thermal dose calculation under multiple ARFI frames. By use of this method, the effect of inter-frame cooling duration on temperature prediction is analyzed, and a thermal buildup phenomenon is revealed. Thermal safety assessment indicates that the thermal dose values, especially at the absorptive bone/soft tissue interface, could approach recommended dose thresholds if the cooling interval of multiple-frame ARFI elastography is too short. (E-mail: yunbo.liu@fda.hhs.gov) Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology.

Key Words: **Transient temperature rise, Ultrasonic heating, Radiation force elastography, Exposure regulation, Acoustic output, Acoustic radiation force impulse.**

INTRODUCTION

Acoustic radiation force impulse (ARFI)-based ultrasound transient elastography produces localized motion in solid tissue *via* high-intensity, long-duration push beams (Parker et al. 2011; Sarvazyan et al. 2010). This new diagnostic imaging method has been applied to broad categories of disease examination and surgical interventions in the past decade (Garra 2011). For example, clinical diagnostic applications include liver cirrhosis, breast lesions, vascular pathology and potential thermal ablation monitoring (Burnside et al. 2007; de Korte et al. 2000; Sandrin et al. 2003; Zhang et al. 2008).

Current thermal safety models for estimating ultrasound-induced temperature increase and corresponding thermal indices calculate the steady-state (tens to hundreds of seconds) temperature rise based on temporal-average acoustic intensity (American Institute of Ultrasound in Medicine [AIUM]/National Electrical Manufacturers Association [NEMA] 2004). Although such calculations are valid for short-duration diagnostic pulses, they may not accurately model the actual temperature rise under ARFI elastography caused by the higher-intensity, longer-duration push pulses. This is especially true at a highly absorptive bone/soft tissue interface. Therefore, special attention needs to be paid to a thermal safety evaluation specific to elastography, and various ARFI-induced temperature studies have been conducted in the past decade. For example, under different ARFI push beam sequences and focal configurations, Palmeri and Nightingale (2004) simulated the temporal and spatial temperature field using the finite element method (FEM) and validated the results with embedded thermocouple measurements in porcine muscle *in vitro* (Palmeri et al. 2004). Nitta et al. (2012) numerically evaluated the ARFI temperature elevation in tissue models (with and without bone) using the 2-D bio-heat transfer equation by considering ultrasound absorption, thermal conduction and blood perfusion. Also, because higher ARFI frame rates can result in increased tissue heating, optimization of elastography acquisition sequences has been conducted, both numerically and

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experimentally, to mitigate thermal safety concerns (Bouchard et al. 2009; Fahey et al. 2006). Direct temperature measurement using a thermal test phantom has been reported to be an effective alternative to the thermal index calculation for elastography thermal safety evaluation (Skurczynski et al. 2009).

On the basis of thermal models described in AIUM/NEMA (2004) and the International Electrotechnical Commission (IEC, 2007, 2010), we previously developed mathematical models using numerical analysis and theoretical derivations to evaluate the transient temperature rise from a single long ARFI push burst (up to hundreds of milliseconds) for both bone surface and soft tissue (Herman and Harris 2002; Herman and Myers 2003; Nell and Myers 2010). Through the use of finite-element simulations, the heating effect at a bone/soft tissue interface caused by ARFI-type pulses also was studied and compared with a conventional "time-average" model (Myers 2005). These studies indicated that tissue temperature may increase by as much as 10°C, raising safety concerns even though the acoustic output was still within the Food and Drug Administration's recommended maximum output exposure level for diagnostic ultrasound. To better understand and apply these models, the current work focuses on a more detailed analysis of the relevant mathematical conditions, such as burst duration and beam diameter. Further, a "virtual source" approach is described that provides a convenient and efficient method for temperature profile simulation during multiple-burst/frame ARFI elastography imaging. A simulation based on this "virtual source" method is presented that compares temperature rise profiles induced by different inter-frame cooling durations using clinically relevant ARFI parameters and imaging sequences. Compared with the conventional steady-state temperature calculations using temporal-average intensity, the "virtual source" calculation reveals a temperature buildup effect caused by an insufficient cooling interval. This type of analysis can provide a useful thermal safety evaluation tool when designing a multiple-frame ARFI imaging strategy.

For elastography thermal safety evaluation, the time-temperature profiles obtained through the transient temperature models were used in a t_{43} thermal dose assessment (Sapareto and Dewey 1984). In line with the analysis in O'Brien et al. (2008), the thermal dose at a bone/soft tissue interface under multiple ARFI frame acquisitions was calculated and compared under different inter-frame cooling intervals.

Overall, the aim of the study described here was to develop a protocol for thermal safety evaluation based on the transient temperature calculation, both in soft tissue and at a bone/soft tissue interface, during single or multiple repeated ARFI imaging frames. The numerical methods and results presented in this work, including calculation examples, applicable range calculation, accuracy assessment, virtual source analysis and thermal dose evaluation, can facilitate the thermal safety evaluation process for a variety of ARFI-based elastography imaging sequences and ultrasound exposure parameters.

METHODS AND RESULTS

An example ARFI imaging sequence that is used for theoretical analysis is illustrated in Figure 1. Each individual ARFI push/excitation pulse has a specific pulse duration (PD) and derated spatial-peak pulse-average intensity, $I_{\mathrm{SPPA.3}}$. The excitation pulse is repeated at a frequency $\mathrm{PRF_P}$ to form a pulse burst. The ARFI burst has a temporal-average burst intensity of I_{B} and total duration of t_{B}. This burst duration, together with a cooling period, will form one complete ARFI imaging frame/acquisition ($t_{\mathrm{frame}} = t_{\mathrm{B}} + t_{\mathrm{cooling}}$). This individual imaging frame could be repeated at a frequency of PRF_{B} with a temporal-average intensity $I_{\mathrm{SPTA.3}}$ during the entire ARFI image acquisition process. Given the relatively large thermal time constants of tissue, the fine (*i.e.,* microsecond-scale) structure of the individual ARFI pulses constituting an ARFI burst are not thermally significant. Rather, it is the burst intensity, I_{B}, that is important in determining the transient temperature rise.

Table 1 lists the ultrasound and thermal parameters, along with their symbols, units and representative values, that are used to illustrate the transient temperature rise calculation. These parameter values do not correspond to any specific clinical or research device, but are intended to be representative of radiation force-based elastography applications. On the basis of the ARFI imaging sequence and parameters presented in Figure 1 and Table 1, several related ultrasound parameters are calculated:

$$I_{\mathrm{B}} = I_{\mathrm{SPPA.3}} \cdot \mathrm{PD} \cdot \mathrm{PRF_P} = 200 \cdot 0.0005 \cdot 100 = 10\ \mathrm{W\ cm^{-2}} \tag{1}$$

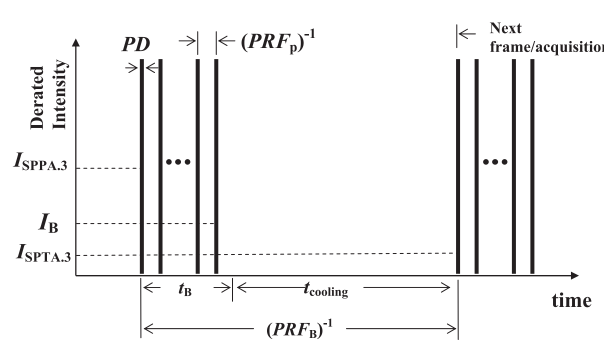

Fig. 1. Acoustic radiation force impulse push burst sequence. Intensities are not to scale.