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● *Original Contribution*

ULTRASOUND THERMAL MAPPING BASED ON A HYBRID METHOD COMBINING PHYSICAL AND STATISTICAL MODELS

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Abstract—Non-invasive temperature measurement of tissues deep inside the body has great potential for clinical applications, such as temperature monitoring during thermal therapy and early diagnosis of diseases. We developed a novel method for both temperature estimation and thermal mapping that uses ultrasound B-mode radio-frequency data. The proposed method is a hybrid that combines elements of physical and statistical models to achieve higher precision and resolution of temperature variations and distribution. We propose a dimensionless combined index (CI) that combines the echo shift differential and signal intensity difference with a weighting factor relative to the distance from the heat source. *In vitro* experiments verified that the combined index has a strong linear relationship with temperature variation and can be used to effectively estimate temperature with an average relative error $<5\%$. This algorithm provides an alternative for imaging guidance-based techniques during thermal therapy and could easily be integrated into existing ultrasound systems. (E-mail: cwhuang@cycu.edu.tw and wenshiang@gmail.com)

Key Words: **Temperature, Ultrasonic imaging, Physical model, Statistical model.**

INTRODUCTION

In recent years, high-temperature thermal therapy has risen in popularity as an effective technique for use in cancer treatment (Denbow et al. 2000; Eggener et al. 2007; Henderson et al. 2010; Hill and Ter Haar 1995; Hwang et al. 2010; Kennedy et al. 2004; Sherar et al. 2003). The intent in high-temperature thermal therapy is to raise the temperature of a targeted tissue volume, typically in excess of 48°–50°C and up to 100°C (Diederich 2005), to produce lesions in the tissue. Although high-temperature thermal therapy has many potential applications, it still suffers from some limitations in practical use. One major obstacle is the lack of a real-time, non-invasive multi-dimensional temperature monitoring method that can be conveniently incorporated into the thermal therapy system.

An ideal thermal therapy system should provide surgeons with real-time imaging and updated temperature profile estimates so that they can better understand the effects of the thermal therapy, and make suitable decisions regarding thermal dosimetry. Temperatures are routinely measured with invasive thermometer probes (*e.g.,* thermocouples) in clinical applications; however, only few discrete points can be measured using this method. Additionally, thermometer probes might interfere with the operation, resulting in artifacts in the imaging data. The metal tips of the probes may also over-heat during thermal therapy, resulting in inaccurate temperature estimation. The most serious problem with invasive temperature monitoring is probably the risk of facilitating metastasis by needle tracks, which can have fatal consequences (Jaskolka et al. 2005; Yamauchi et al. 2011).

To meet the standards of present and future heating technologies, a clinical method is required that can accurately measure 3-D temperature distributions (*i.e.,* ±0.5°C) within volumes of 1 cm^3 (Arthur et al. 2003).

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A non-invasive method for determining volumetric temperature distributions during hyperthermia treatments would greatly enhance the ability to heat tumors at therapeutic levels and help to achieve tumor control. Currently, magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound are used to guide ablation probes and to monitor the extent of ablation (Amini et al. 2005; Bohris et al. 1999; Chung et al. 1999; Hahn et al. 1997; Merkle et al. 1999; Varghese et al. 2002).

Each of the techniques mentioned has its advantages and limitations. MRI-based non-invasive temperature estimation methods have good heating field localization capabilities and can operate in quasi real time, but have limited temperature resolution (on the order of 2°C) and are costly to implement. For real-time computed tomography guidance, in addition to the radiation, which is potentially harmful to both patients and physicians, the major concern is that the large quantity of contrast agent used limits the number of scans that can be performed. Major advantages of using ultrasound include its relatively low cost, real-time data collection and signal processing, deep penetrative ability and compatibility with the ultrasound technology that generates the therapeutic beam.

Different ultrasound techniques have been suggested for use in estimating temperature change. Acoustic parameters that are dependent on temperature can be found, measured and calibrated according to variations in temperature. Generally speaking, these approaches can be divided into two categories: physical model-based and statistical model-based approaches. In physical model-based approaches, temperature distributions are estimated *via* changes in the physical acoustic parameters, such as ultrasonic speed (Amini et al. 2005; Maass-Moreno and Damianou 1996; Maass-Moreno et al. 1996; Seip and Ebbini 1995; Simon et al. 1998; Varghese et al. 2002), backscattered power (Anand and Kaczkowski 2008; Anand et al. 2007; Arthur et al. 2003, 2005) and attenuation coefficient (King et al. 2011). However, the relationships between temperature itself and variations in the physical acoustic parameters it induces are complex to develop *in vitro*, and they cannot be described easily by analytical equations. In addition, thermal expansion in the heated field also affects the ultrasound echoes.

In statistical model-based approaches, B-mode image processing techniques are used to estimate temperature changes by analysis of the ultrasound image textures (Novak et al. 2001; Pousek et al. 2006; Yang et al. 2010). The relationship between tissue temperature and the correspondent B-mode texture features, particularly for gray-scale ultrasonography, has been investigated, with results demonstrating that the mean gray-scale tendency is non-linear at different temperature phases and quite vulnerable to hysteresis (Pouch et al. 2010; Su et al. 2006).

The specific limitations of each model could be overcome by combining features of these two models (Liu et al. 2011). In the study described here, we developed a hybrid method incorporating both physical and statistical models to estimate temperature variation and distribution. The physical model is based on the differential of the echo shift with respect to the ultrasound traveling distance; the statistical model is based on the relationship among radiofrequency (RF) data intensity variations. We propose a dimensionless index—the combined index (CI)—to estimate the temperature variation.

Heating experiments in porcine muscle were performed to illustrate the precision of the proposed hybrid method *in vitro*. Experimental data indicated that the combined index was suitable for temperature estimation up to ~60°C. Within the suitable temperature range, the combined index displayed a linear relationship with temperature variation. Our results suggested that the hybrid method provides reasonable precision over a wider range of temperature estimates than possible with previous methods (Ju and Liu 2010; Miller et al. 2002, 2005). In addition, we explored the relationship between combined index variation rate and distance from the heat source. The resultant regression function was used to conduct temperature mapping for ablation experiments.

METHODS

Physical model

Assume that the distribution of sound in a tissue sample is a function of temperature T and axial depth z and can be written as $c(z, T)$, where $z = 0$ at the interface between the transducer and the tissue. The round-trip transit time $t(z)$ of a pulse echo reflected from a point z in the tissue at base temperature T_0 is

$$t_0(z) = 2\int_0^z \frac{1}{c(\zeta, T_0(\zeta))} d\zeta \tag{1}$$

where $c(\zeta, T_0(\zeta))$ is the speed of sound at $z = \zeta$ and $T = T_0$, and $d\zeta$ is a differential distance.

Once the temperature in the medium changes, the temperature distribution, $T(z)$, can be decoupled into the terms base temperature, T_0, and local temperature variation, $\delta T(z)$, induced by an external heat source, as described by the equation $T(z) = T_0 + \delta T(z)$ (Liu et al. 2009). To account for thermal expansion in the propagating medium, the differential distance, $d\zeta$, can be replaced by

$$d\zeta|_{T=T_0+\delta T} = (1+\alpha(\zeta)\delta T(\zeta))d\zeta|_{T=T_0} \tag{2}$$

where $\alpha(\zeta)$ is the thermal expansion coefficient of the medium at depth ζ.