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Temperature monitoring by channel data delays: Feasibility based on estimated delays magnitude for cardiac ablation

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ABSTRACT

Ultrasound thermometry is based on measuring tissue temperature by its impact on ultrasound wave propagation. This study focuses on the use of transducer array channel data (not beamformed) and examines how a layer of increased velocity (heat induced) affects the travel-times of the ultrasound backscatter signal. Based on geometric considerations, a new equation was derived for the change in time delay as a function of temperature change. The resulting expression provides insight into the key factors that link change in temperature to change in travel time. It shows that velocity enters in combination with heating geometry: complementary information is needed to compute velocity from the changes in travel time. Using the bio-heat equation as a second source of information in the derived expressions, the feasibility of monitoring the temperature increase during cardiac ablation therapy using channel data was investigated. For an intra-cardiac (ICE) probe, using this "time delay error approach" would not be feasible, while for a trans-esophageal array transducer (TEE) transducer it might be feasible.

1. Introduction

Atrial fibrillation is a pathophysiology characterized by irregular contraction of the atrium. For some patients, thermal ablation may be the treatment of choice. As described in [8], ablation serves to create an isolated substrate, hindering the propagation of electrical activation signals. Complete electrical isolation is achieved by creating a continuous isolation line (typically around the pulmonary veins) by heating the atrial wall to reach a temperature of at least 50 °C [8,16] transmurally [17]. Monitoring the temperature distribution by ultrasound during the ablation procedure could help ensure adequate ablation as well as avoid complications related to overheating. Many approaches have been proposed for tracking temperature with ultrasound, including Change of Backscatter Energy [26,3,4,10,14,27,32], Thermal Strain Imaging [25,19,22,12,30], decorrelation imaging [15], thermal expansion [28] or the use of shear waves [1,2,21].

As described by [22], ablation monitoring can be performed using Thermal Strain Imaging (TSI), a method evaluating the apparent tissue strain, caused primarily by differences in local sound speed (due to heating) and to some extent (neglectable under 50 °C [22]) by thermal expansion of the heated tissue. The temperature change is then linked to the measured "strain" with the help of a calibration curve, as done in [34]. The same authors have demonstrated the feasibility of using thermal strain and a custom-made ablation catheter to monitor cardiac radiofrequency ablation [23]. Thermal strain is limited by the need for a baseline image, and therefore only provides relative temperature change indications.

In this paper we analyze the feasibility of using ultrasound travel times to estimate the temperature perturbation. There are potential benefits of using such channel data. One avoids the need for a baseline reference image since the travel time delay errors can be analyzed without such a reference. The ultrasound channel data is also very sensitive to delay changes and even fractions of a wavelength delays can potentially be estimated from such data.

The content of the present paper is twofold. Firstly, we derive a method to evaluate the impact of an area of higher sound speed on the travel time of ultrasonic echoes to individual elements of the probe. The new formalism is based on the classic travel time equations to compute how a change in velocity lead to a change in travel time for a scattering point at a certain depth. This is well-known, but not very useful, since the scatter depth is unknown; only the two-way travel time to the scattering point is known and ultrasound scanners use an assumption about the velocity to compute the beam forming delays. A change in the velocity between the scatter and the probe will thus change the apparent

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depth. To derive an equation that can be used in practice we used a parametrization of the expression in terms of travel time (or apparent depth). The apparent change in depth by a change in velocity is then included in such a way that we can compute the resulting delay as a function of element-offset without knowing the real depth. The newly derived equation therefore provides insight into how a change in velocity lead to a change in travel time. It further shows that the change in travel time depends on a perturbation term which is a function of the relative velocity perturbation in combination with the geometry of the heated region. As a consequence, one can only estimate the perturbation term from travel time changes and need additional information to further estimate the change in velocity.

The main goal is to provide insight into the fundamental effects and is not an attempt to provide a complete solution. Adding too much complexity would mask the fundamental effects so in the derivations we utilize some strong assumptions and simplifications like plane-layered velocity change and use of a linear relationship between tissue temperature and the resulting velocity. Despite these assumptions we believe that the analysis provides new insight into the potential use of channel data for such analysis and that the result will help further work in this field.

In the second part, we apply the method in the specific context of radio-frequency ablation of the atrium to evaluate the possibility of a thermometry method based such perturbations. To do so, we set the study under similar hypotheses as TSI, namely that the effect of heat on the propagation speed of ultrasound in the tissue is dominant over the physical thermal dilation in the considered range of temperatures [22].

2. Materials and methods

Heat affects the sound speed of biological tissues [5], directly impacting the travel times of the ultrasonic waves. This section presents the travel time equations to the receiving elements as functions of the dimensions of an aberrating layer and the depth attributed to the echo by the receive beamformer.

2.1. General geometrical considerations

In the geometry illustrated by Fig. 1, the echo of interest originates distal to a layer of higher sound speed, at a distance z_{true} from

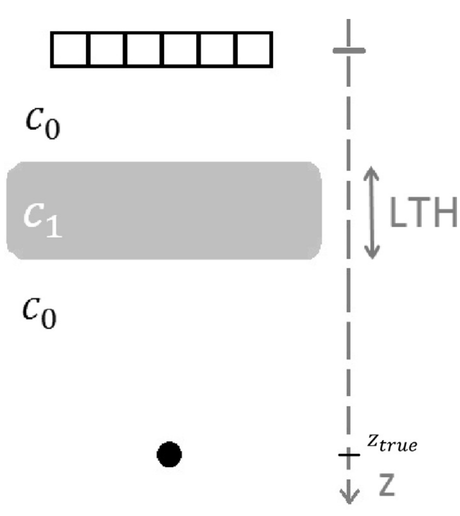

Fig. 1. Schematics of the studied setup: a strong reflector is imaged by a linear array through a layer (thickness *LTH*) of different sound speed than the rest of the medium (sound speed c_1 vs c_0). The array transducer is represented by the grid-like structure above the layer.

the transducer. The layer sound speed c_1 and background sound speed c_0 are such that $c_1 = c_0 + \Delta c$.

As the background medium's sound speed is equal to the speed assumed by the beam former, the relationship $z_s = c_0 t/2$ defines the conversion of the arrival time t of an echo to a depth z_s.

Using simple time-of-flights equations and geometry, z_{true} can be expressed as a function of z_s as follows:

$$z_{true} = z_s\left(1 + \frac{LTH}{z_s}\frac{\frac{\Delta c}{c_0}}{1+\frac{\Delta c}{c_0}}\right), \tag{1}$$

In a similar way, discretizing the layer into N layers of the same thickness Δz so that $\sum_{i=1}^{N}\Delta z_i = N\Delta z$ and $c_i = c_0 + \Delta c_i$, Eq. (1) becomes:

$$z_{true} = z_s\left(1 + \frac{\Delta z}{z_s}\sum_{i=1}^{N}\frac{\frac{\Delta c_i}{c_0}}{1+\frac{\Delta c_i}{c_0}}\right). \tag{2}$$

A reduced parameter Δ and its counterpart Δ_{eq} were introduced to simplify the notations:

$$\Delta = LTH\frac{\frac{\Delta c}{c_0}}{1+\frac{\Delta c}{c_0}}. \tag{3}$$

$$\Delta_{eq} = \Delta z\sum_{c_i\neq c_0}\frac{\frac{\Delta c_i}{c_0}}{1+\frac{\Delta c_i}{c_0}}. \tag{4}$$

Eq. (4) represents the cumulative effect of a collection of layers reduced to an equivalent single layer of thickness Δz and sound speed $\sum_{c_i\neq c_0}\frac{\Delta c_i}{c_0}\Big/\left(1+\frac{\Delta c_i}{c_0}\right)$.

2.2. Perturbed travel times

The time for an echo reflected at z_{true} to reach an element on the aperture of the probe can be then formulated using Δ (resp. Δ_{eq}) and z_s. Ray-bending was neglected as sound speed changes were expected to be small (see Section 3).

$$t(x) = \frac{z_s}{c_0}\sqrt{1+\left(\frac{x}{z_s\left(1+\frac{\Delta}{z_s}\right)}\right)^2}. \tag{5}$$

with x being the lateral offset between the vertical trajectory and the element receiving the echo.

A Taylor development of Eq. (5) around $\Delta = 0$ was performed given that $\Delta c \ll c_0$ (and consequently $\Delta \ll 1$):

$$t(x) \simeq t|_{\Delta=0} - \frac{1}{c_0}\frac{\left(\frac{x}{z_s}\right)^2}{\sqrt{1+\left(\frac{x}{z_s}\right)^2}}\Delta. \tag{6}$$

While $t|_{\Delta=0}$ represents the "normal" (i.e. with no layer) arrival time, the first order term in Eq. (6) is a scaling factor, so:

$$t(x) \simeq t|_{\Delta=0} + \mathcal{C}(x/z_s, c_0)\Delta \tag{7}$$

where $\mathcal{C}$ depends on the beam forming sound speed, and the ratio between the offset x and the scanner-assumed depth z_s. This ratio is close to the F-number ($F^{\#}$) of the acquisition as by definition, $F^{\#} = z_s/a$ where a is the probe aperture (x is a fraction of a).

Assuming that $x = a/2, \mathcal{C}$ can be written as:

$$\mathcal{C}(F^{\#}, c_0) = -\frac{1}{c_0}\frac{\left(\frac{1}{2F^{\#}}\right)^2}{\sqrt{1+\left(\frac{1}{2F^{\#}}\right)^2}} \tag{8}$$

The resulting hyperbolic curve is presented in Fig. 2.