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On the assessment of time-shift variations from backscattered ultrasound for large temperature changes in biological phantoms

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Abstract

This work reports the assessment of time-shifts (TS) from backscattered ultrasound (BSU) signals when large temperature variations (up to 15 ºC) were induced in a gel-based phantom.
The results showed that during cooling temperature is linear with TS at a rate of approximately 74 ns/ºC. However during a complete heating/cooling cycle, the relation is highly non-linear.
This can be explained by the fact that during cooling the temperature distribution is more uniform. Another problem to report is that TS is very sensitive to external movements.

Keywords: Non-invasive temperature estimation, temperature models, time-shift estimation, ultrasound.

1. Introduction

A broader acceptance of thermal therapies is constrained by the inexistence of reliable temperature estimators. In a first approximation, temperature can be assessed invasively. However the disadvantages of invasive temperature estimation raise the necessity to apply non-invasive methods. Non-invasive temperature estimation (NITE) methodologies are based on the extraction of temperature-dependent features from available signals. In the case of ultrasound techniques, four features, extracted from the backscattered signals, were claimed to have potential for NITE. These features are: medium attenuation coefficient [1], time-shifts (TS) [2], spectral component shifts [3], and backscattered energy [4]. Among these features, the one that has been receiving a high attention is TS, because is claimed that it is a monotonic function of temperature, and is also intrinsically independent of the transducer on usage. Theoretical and experimental studies were performed and consistent results were obtained for temperature

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variations up to 10 ºC. Previous reported models based on TS were based on linear relationships, in which a-priory medium constant had to be determined and afterwards the obtained shifts were transformed into temperature estimates. Besides the high quality results so far obtained, applications on in-vivo environments require an improved knowledge of the TS variations.

This paper reports the assessment of TS from BSU signals when large temperature variations were induced. These variations consider stand-alone cooling phases and complete heating/cooling phases in a gel-based phantom. Temperature changes up to 15 ºC where induced and studies performed in the collected signals. The induction of large temperature variations is an essential step to understand TS behavior, and then to develop feasible TS-based in-vivo estimators.

In Section 2 the description of the experimental setup developed is performed. The methodology employed to extract TS is exposed in Section 3. The obtained results and their discussion are presented in Section 4. In Section 5, the conclusions are presented.

2. Experimental Setup

The developed phantom is a mixture of (in % of weight): 86.5 of water, 11 of glycerin and 2.5 of agar-agar. In order to obtain acoustic information from the medium, 1% of the water weight in graphite powder was added to the mixture. This mixture is based on the one presented in [5], and has acoustical properties similar to human muscle. The phantom was used in the experimental setup presented in Fig. 1.

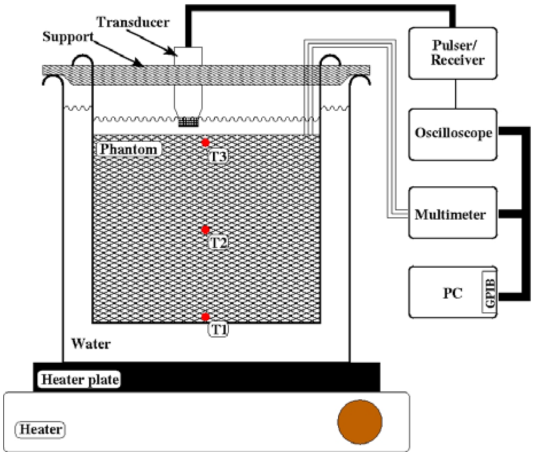

Fig.1 Experimental setup. T1, T2 and T3 refer to thermocouples 1, 2 and 3, respectively.

Two Pyrex Beckers compose the phantom heating system. A smaller Becker (1000 ml) contains the phantom. The bigger one (2000 ml) contains degassed water and acts like a thermal capacitor, preventing abrupt temperature changes and improving a uniform phantom heating. In order to measure temperature, three thermocouples were placed inside the phantom.

The first one (T1) was placed close to the bottom of the smaller Becker, a second one (T2) was placed in the middle of the phantom. The third thermocouple measures temperature at the top of the phantom, *i.e.*, close to the transducer. The thermocouples were connected to a cold junction compensated multiplexer, that is part of a digital multimeter (2700/7700, Keithley). The acquisition of BSU signals was performed by using a 5-MHz transducer (V310SU, Panametrics-NDT), driven by a pulser/receiver (5800pr, Panametrics - NDT). The analog BSU signals from the pulser/receiver were digitalized by an oscilloscope at 50 MHz. At each 10 seconds, the three temperature values and one digitalized BSU signal were collected and saved for future use in a personal computer. The computer interfaces the oscilloscope and multimeter through a GPIB bus. An example of typical collected signals is presented in Fig. 2.

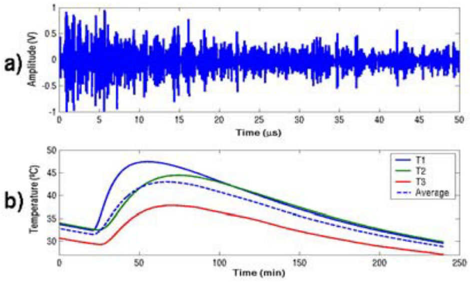

Fig.2 Collected signals: a) a BSU signal, and b) the temperature signals along a complete experimental trial. T1, T2 and T3 refer to thermocouples 1, 2 and 3, respectively. The dotted line represents the average temperature.

3. Time-shifts computation

The way that time-shifts (TS) are obtained is also an important aspect; direct determination, i.e. looking directly at the digitalized (sampled) signals, can result in insufficient resolution. For small temperature changes, subsample delays happen, and, thus, TS should be estimated instead of obtained directly. For subsample TS estimation, the most popular method encompasses the computation of a pattern-matching function, which is typically the normalized correlation function. Subsample estimation is then possible by defining an analytic function based on the sampled pattern-matching function. Then, analytical methods, such as derivatives can be applied to the continuous pattern-matching function, to obtain the delays between signals. In this work the strategy presented in [6] was applied. It is referred that the proposed algorithm offers an excellent performance at a reduced computational cost. It is claimed that this approach significantly outperforms other algorithms in terms of jitter and bias over a broad range of conditions. The algorithm start by considering two signals s1[n] and s2[n], with size N and M, respectively, being M<N. The bigger one (s1[n]) is called the reference signal, and is processed to determine an analytical representation using cubic splines. Then s2[n] is overlapped N-M times and the sum of the squared errors (SSE) computed for each overlap. In each of them, the time value that minimizes the related SSE function is called the "local TS estimate". Placing all the local estimates in a vector (ΔL(.)), the global estimate is obtained by considering the element that has a value between 0 and 1. This means that the discrete TS is given by the position (k) in the vector where a value between 0 and 1 is observed, and the subsample delay is obtained considering the value stored in ΔL(k). The overall TS estimate is given by summing the discrete estimate plus the subsample estimate, i.e., TS=ΔL(k)+k. In the case that ΔL(.) has multiple values between 0 and 1, the true delay is obtained considering the element that corresponds to the minimum SSE. In the current work the reference signal is the first BSU collected at the beginning of a measurement trial. The sampled signals are the other BSU signals collected along an experiment trial, undergoing shifts due to temperature. TS are considered positive if the echoes in a signal come sooner than in the reference signal, and negative otherwise, as exposed in Fig. 3.

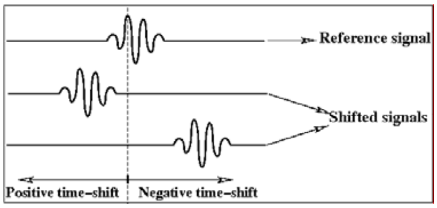

Fig.3 Protocol applied in the determination of TS signals.

4. Results and discussion

After data acquisition, TS signals were computed with the algorithm explained in Section C. As referred previously, TS were computed in signals from complete heating and cooling trials and in signals where only-cooling was considered.

The average temperature, computed TS waveform, and TS/temperature scatter-plot, related with an only-cooling phase are in Fig. 4.

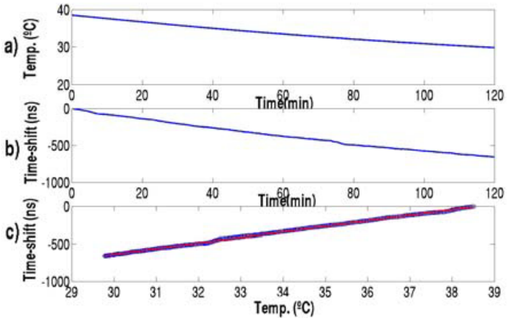

Fig.4 Temperature in comparison with computed time-shifts, during an only-cooling phase. a) average temperature; b) computed time-shifts; and c) scatter-plot time-shift/temperature. The red curve is obtained after a linear least square fit. The curve slope is 74.4 ns/ºC approximately.

After a linear least-square fit to the data points presented in Fig. 4c, a ratio of 74 ns/ºC was obtained, as represented by the red curve. It can be said that temperature is linear with temperature (in that range). A correlation coefficient of 0.99 between the red curve and the data points was obtained.

In Fig. 5 the average temperature, computed TS waveform, and TS/temperature scatter-plot, related with a complete heating and cooling trial is presented. It can be seen that it is no longer a purely linear relation.

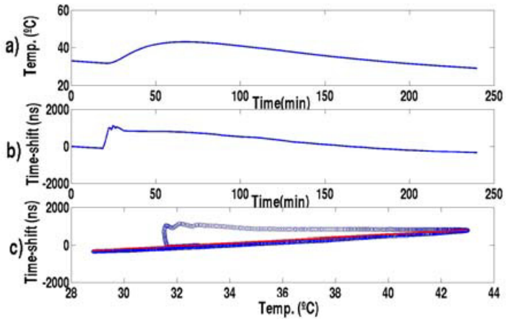

Fig.5 Temperature in comparison with the computed time-shifts, during a heating and cooling trial. a) average temperature; b) computed time-shifts; and c) scatter-plot time-shift/temperature. The red curve is obtained after a linear least square fit. The curve slope is 74.7 ns/ºC approximately.

Looking at the TS/temperature scatter plot (Fig. 5c) it can be said that the behavior observed during heating is different from cooling. For the same temperature value different TS values are observed. This behavior can be explained by the fact that during cooling, the temperature distribution is more uniform, resulting in more reproducible TS estimates. Another problem is that TS are very sensitive to external movements. A small movement in the experiment can induce large TS variations, given that we are working at a nanoseconds scale. In the case of this work, the phantom system is placed over a heater. As heating occurs the metal of the heater plate dilates elevating the phantom, and, thus inducing erroneous time-shifts. In the same way, when the heater is switched off, the metal plate contracts, and the phantom is moved down, inducing again erroneous shifts. It is possible to see this phenomenon by observing Fig. 6. The oscillation visible between 40 and 60 minutes, in Fig. 6b, is due to the dilation and contraction of the heater plate. The heater has a self-regulating system, based on a thermostat that switches it on/off.

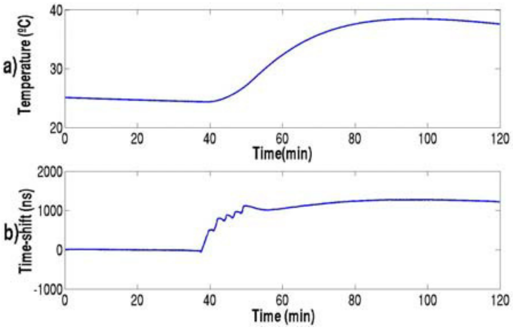

Fig.6 Temperature in comparison with the computed time-shifts, during a heating and cooling trial. a) average temperature; b) and computed time-shifts.

5. Conclusion

This paper is on the assessment of time-shifts induced by large temperature changes in a biological phantom. The TS/temperature relation can be considered linear when the medium is cooling. However considering a heating and cooling trial the relation is highly non-linear. This is mainly due to the high sensibility of TS to external movements, originated by the dilation/contraction of the heater system. This high sensibility raises the necessity of using movement correction algorithms. The rule is that care must be taken when assuming generalized linear relations between temperature and time-shifts.

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