TEMPERATURE DETECTION BASED ON NONPARAMETRIC STATISTICS OF ULTRASOUND ECHOES

MICHAŁ BYRA, BARBARA GAMBIN

Institute of Fundamental Technological Research
Pawińskiego 5B, 02-106 Warsaw, Poland
mbyra@ippt.pan.pl, bgambin@ippt.pan.pl

Different ultrasound echoes properties have been used for the noninvasive temperature monitoring. Temperature variations that occur during heating/cooling process induce changes in a random process of ultrasound backscattering. It was already proved that the probability distribution of the backscattered RF (radio frequency) signals is sensitive to the temperature variations. Contrary to previously used methods which explored models of scattering and involved techniques of fitting histograms to a special probability distribution two more direct measures of changes in statistics are proposed in this paper as temperature markers. They measure the "distance" between the probability distributions. The markers are the Kolmogorov Smirnov distance and Kulback-Leiber divergence. The feasibility of using such nonparametric statistics for non-invasive ultrasound temperature estimation is demonstrated on the ultrasounds data collected during series of heating experiments in which the temperature was independently registered by the classical thermometer or thermocouples.

INTRODUCTION

Two types of thermal treatment of human soft tissue should be supported by the temperature field monitoring. The first is the local hyperthermia, wherein elevating the temperature to 43°C results in the defensive biochemical reaction of cells, namely the production of so-called heat shock proteins (HSP). HSPs are the chaperones and they "fix" the affected proteins, which are observed, for example in the Alzheimer's disease. Such temperature range does not cause irreversible changes in living cells. The second is radiofrequency ablation therapy (thermoadlation), which involves thermal destruction of tissue ill parts. It requires raising the temperature above 43°C. The special ultrasonic heating transducers can be used in the both of these treatments, in the first therapy low-intensity focused ultrasoun (LIFU) is used, and in the second, high intensity focoused ultrasound (HIFU). It is clear that the quality of both therapies is associated with the current control of the temperature field, i.e. the volume of the heated area and the level of temperature. For several years, studies are being conducted on the possibility of non-invasive precise monitoring of the temperature field by registering the variations in backscattered ultrasound field, see [1], [2] and references therein. The statistical properties of the backscattered signal amplitude depend on the scatterers reflectivities and their geometrical distribution. Because both of this features can change during heating some statistical chracteristics should be sensitive on temperature variations. In the papers [3] and [4] this idea were explored. Firstly, the signals were subjected to band-pass filtering around the transmit frequency and compensation of attenuation were performed. Then the random amplitude data had been fitted to different probability distributions, which are commonly used to describe the nature of the scattering from soft tissues, cf.[5], [6], [7], particularly the Rayleigh distribution, Nakagami and K-distribution had been studied. We found that the statistical properties of amplitudes are very sensitive to the methods of attenuation compensation, and thus also the statistical parameters of the probability distributions are dependent on such data preprocessing. Despite this the shape parameters of the K and Nakagami distributions had been proposed as temperature markers. To become independent of the data processing , we decided to perform statistical analysis at another basis. The only signal filtering, we have done is to limit the bandwidth of received echoes to the nearest range of the transmit frequency. Then, after calculating the amplitudes of the signals the changes in their statistics caused by heating and cooling will be measured in the most direct way by „distances" between the probability distribution functions. In such a way we omit the determination of a class of the distribution and besides it is unnecessary to evaluate the goodness of fittings to choosen distribution . We have used two different measures of „distance" between distributions , namely Kolmogorov-Smirnov distance and Kullback Leiber divergence. Further, the analysis is performed to demonstrate why this measures can be used as markers of temperature variations. The paper is organized as follows. In Section 1 the brief description of performed experiments is given. Section 2 contains main results and final remarks are given in Section 3.

1. EXPERIMENTS

Two types of tissue mimicking materials were used in experiments, namely the PVA-c (polyvinyl alcohol - cryiogel) sample and the AGO (Agar-Oil) samples, details of the experiment are given in [8]. The PVA-c sample was heated by the water bath. The temperature of the bath increased linearly from 20.6 ^{0}C to 48.8 ^{0}C within the one hour. Next the heating were switched off and after the next two hours temperature decrease to 25.8 ^{0}C. RF signals were registered by means of ultrasound (ULTRASONIX SonixTOUCH, British Columbia, Canada) with the linear transducer L14-5/38 at a frequency of 8 MHz. RF signals were recorded every half minute (361 times) during the one hour of heating and two hours of cooling.

The heating of AGO (Agar Oil) samples were performed with the use of the spherical ultrasonic transducer (central frequency 2.2 MHz, diameter 44 mm, 44.5 mm focal length, area S = 15.2 cm2) during 10 minutes. The temperature within the sample was firstly recorded by thermocouples along the beam axis during the heating and additionally by 10 minutes of cooling. Secondly, the imaging transducer registered frames every 5 sec during 20 minutes of the same heating/cooling process as in the first case. The same imaging system as in the PVA-c experiment was used but additionaly the synchronization in time had been been done of the heating and imaging transducers to preserve the imaging process from the acoustic noise possibly coming from the heating beam. The sampling rate (sampling frequency) was 40 MHz and imaging frequency was 8 MHz. The measurements were repeated for two heating power of the heating transducer, the power of 4 W and 6 W. The measured by thermocouples temperature range was from 20°C to 48°C.

2. MEASURES OF DISTANCE BETWEEN STATISTICAL DISTRIBUTIONS

In what follows as a random one dimensional variable the amplitude values of FR signals in the fixed moment of time is understood. The Rf signals are backscattered from a square areas with 3mm x 3mm, which are marked in Figures 1 and 2 as different ROI's (region of interest) located in different places of samples. The empirical histogram from every ROI in a fixed time moment of the heating process was determined. The aim of this contribution is to demonstrate that defined below two measures of distance between two distributions, namely the random amplitude in the starting point of the thermal process and the distributions of the random amplitude for every succesive time moments of process, both calculated from the same region of the sample, can be used as an excellent temperature marker. The first nonparametric statistics is the Kolmogorov-Smirnov distance (KS statistics) which is a distance between the two empirical distributions, computed as the maximum absolute difference between their cumulative curves. To determine this distance at first the cumulative distribution function from the empirical histograms should be calculated. The second distance is the Kullback-Leibler divergence(or the relative entropy). It is the most commonly used measure of the dissimilarity between two probability distributions. For discrete probability distribution P and Q, the Kullback–Leibler divergence (KL statistics) of Q from P is defined to be

$$D_{\mathrm{KL}}(P\|Q) = \sum_i P(i)\,\ln\frac{P(i)}{Q(i)}. \tag{1}$$

The above expression means that KL divergence is the expectation of the logarithmic difference between the probabilities P and Q, where the expectation is taken using the probabilities P. KL distance it is not a distance in the typical (metric) sense, because of lack of symmetry and triangle inequality, and so it can be used in places where the directionality is meaningful. KL distance were calculated from empirical distribution function estimated by the kernel density estimation method with the Gauss kernel.

3. RESULTS

"Distances" between initial statistics of signal amplitude from the statistics of amplitudes in succesive time moments of thermal process were calculated with MATLAB. On the Fig. 1 ROI areas are indicated on B-mode images for the PVA-c sample left, and the AGO sample right, respectively. The echo amplitude from this area formed the data which were used for calculations.

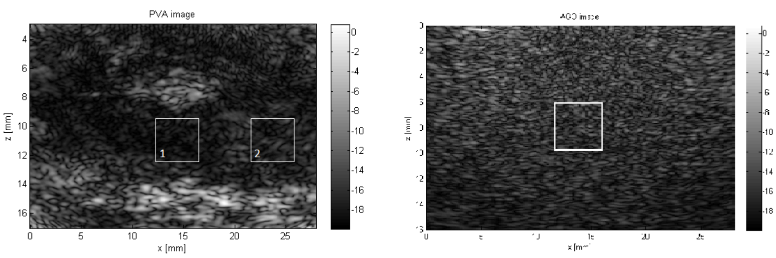

Fig. 1. The USG image of PVC-c sample with marked two ROI's, ROI1 located centrally and ROI2 close to the sample side, left, the USG image of AGO sample with fixed ROI located near the center of the sample, right.

KS distance between the probability distribution function of echo amplitude recorded at the initial moment and consecutive probability distribution function in the next moments of thermal process creates a time-variable map of ”warming-up” of material PVA-c sample. For illustration, in Fig. 2 and Fig. 3 the maps in ROI1 and ROI2 in the 5 minutes after the start of the process, after 1 hour of heating, that is, the maximum increase in heating and after a further two hours of cooling are shown.

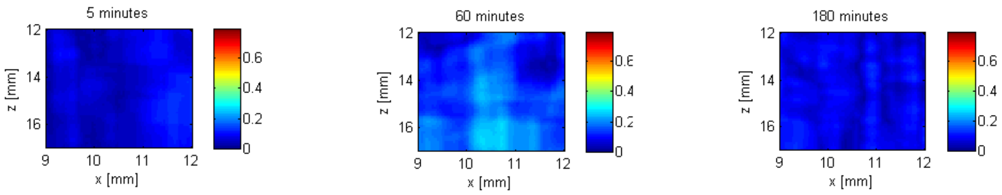

Fig. 2. The map of KS distances calculated for PVA-c sample in centrally located ROI1 for 3 different time moments of thermal process, from left to right 5 minutes after staring of heating, 60 minutes later and 180 minutes later.

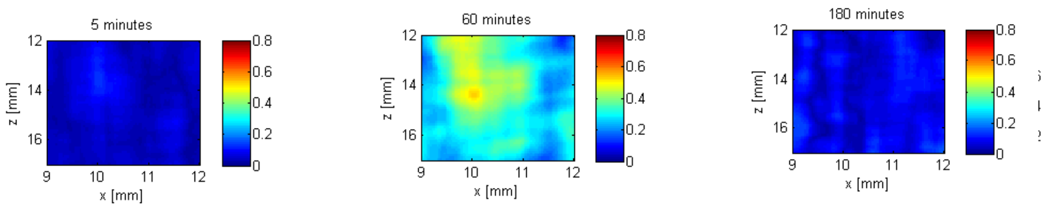

Fig. 3. The map of KS distances calculated for PVA-c sample in close to the side located ROI2 for 3 different time moments of thermal process, from left to right 5 minutes after staring of heating, 60 minutes later and 180 minutes later.

It should be noted that the magnitudes of the KS distance depend on the position of the ROI in the sample . ROI1 centrally located shows a much smaller increase of KS distance than the ROI2 lying closer to the edge of the sample. As the temperature was measured by recording the water bath temperature and the structure of the material PVA-c is a highly heterogeneous there is a high probability that in such a low temperature range, despite a relatively long time heating probably the sample volume does not warm up out uniformly. In Fig. 4 the comparison of KS distance as a function of time with the time-varying to the measured by thermometer temperature variations of the water bath is depicted.

Like the KS distance KL divergence was calculated in the time of the whole process of heating / cooling. Fig. 5 compares the relationship betweeen changes of KL divergence magnitude with changes in temperature level in the water bath during the process. For further comparison linear regression was used to calculate directional coefficients for temperature and non-parametric statistics variations.

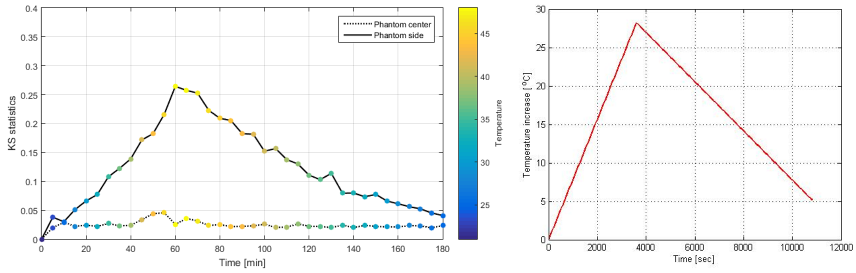

Fig. 4. The KS distance variations, left, and water bath temperature variations during process, right.

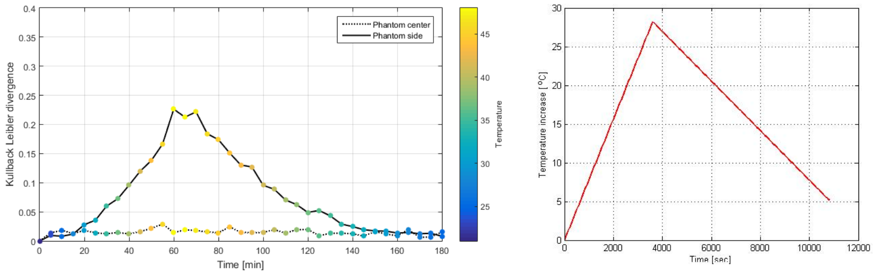

Fig. 5. The KL distance variations, left, and water bath temperature variations during process, right.

Having in mind that the process of heating and cooling performed with the AGO samples is complety different it was interesting to show that the same measures, namely KS and KL distances proposed in this contribution play a role of temperature estimators qualitativly even better than in the first experiments. Let us underline that the heating process goes in AGO sample experiment 6 times quicker than previouslly - only 10 minutes and the source of temperature rise was concentrated inside the sample - acoustic focused beam - not at the boundary of the sample as it was in PVA-c experiment. In Fig. 6 and Fig. 7 the variable in time distances KS and KL are compared with curves of temperature time dependence measured by thermocouples during the whole process of AGO sample heating/cooling.

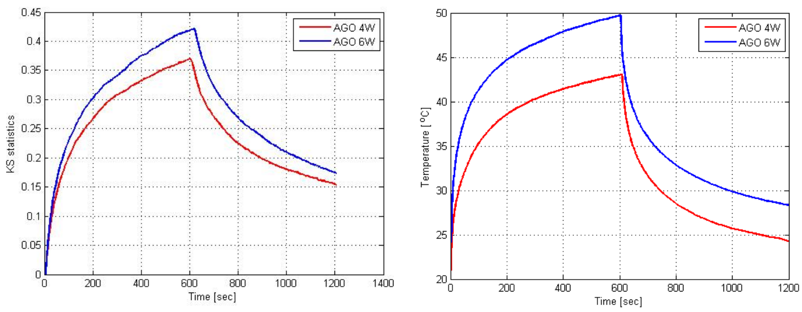

Fig. 6. The KS distance variations, left, and the temperature registration by thermocouples during process, right, for two different powers of heating.

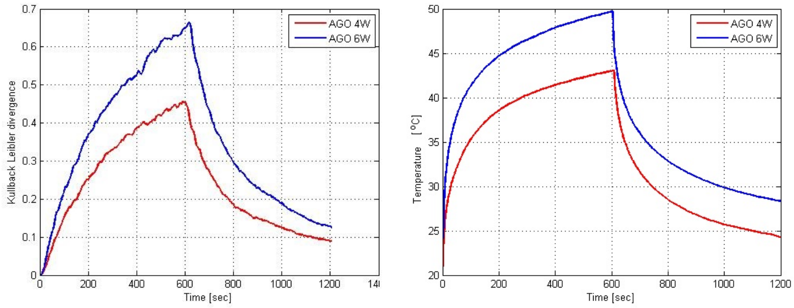

Fig. 7. The KL divergence variations, left, and the temperature registration by thermocouples during process, right, for two different powers of heating.

4. FINAL REMARKS

Linear regressions were calculated for the rise and fall of the temperature of the PVA-c sample for the measured experimental curve and the curves obtained from introduced here both measures of distibutional distances. Obtained directional coefficients of the straight lines has the same signs so the rise and the fall in temperature and KS and KL distances tooke place in the same period of time but, what is even more interesting the rate of temperature variations coincides. It means thet the ratio of the heating rate to the cooling rate is the same (with accuracy up to 3%) for calculated by the distibutional distances and experimentaly measured temperature.

In the AGO sample experiments the KS and KL distances as functions of time are strongly nonlinear. But in this thermal process temperature variations measured by thermocouples exhibit also strong nonlinearity. The culculated and experimental curves are very similar. Particularly, the maximum values of all curves calculated for KS distance and KL divergence in both experiments accurately correspond to the maximum temperatures determined from the experimental curves. To sum up the KS distance and KL divergence between probability distributions of echo amplitude in different thermal processes can be used as temperature markers.

ACKNOWLEDGMENT

The paper was partially supported by the National Science Centre (2011/03/B/ST7/03347).

REFERENCES

[1] Xiaonan Geng et al., Comparison of ultrasound temperature imaging with infrared thermometry during radio frequency ablation, Jpn. J. Appl. Phys., 53, 047001, 2014.

[2] Hao-Li Liu et al, A unified approach to combine temperature estimation and elastography for thermal lesion determination in focused ultrasound thermal therapy, Phys. Med. Biol.56, 169, 2011.

[3] B. Gambin, O. Doubrovina, Statistical properties of wavelet transform coefficients of backscattering signal from soft tissues and their phantoms, Hydroacoustics, Vol. 16, 59-66, 2013.

[4] E. Kruglenko, B. Gambin, RF signal amplitude statistics during temperature changes in tissue phantoms, Hydroacoustics, Vol. 17, 115-122, 2014.

[5] Quantitative Ultrasound in Soft Tissues, Eds. J. Mamou, M. L. Oelze, Springer 2013.
[6] H. Piotrzkowska, J. Litniewski, E. Szymańska, M. Lewandowski, A. Nowicki, Statistics of envelope of high frequency ultrasound signal backscattered in human dermis, Hydroascoustic, Vol. 13, 205—214, 2010.
[7] F. Destrempes, G. Clouthier, A critical review and uniformized reprezentation of statistical districution modeling the ultrasound echo envelope, Ultrasound in Med.& Biol., Vol. 36, 7, 1037–1051, 2010.
[8] B. Gambin, E. Kruglenko, Temperature measurement by statistical parameters of ultrasound signal backscattered from tissue samples, Acta Physica Polonica A, (in press).