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The Effect of Temperature Change on Backscattered Ultrasound Power

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Abstract

The temperature dependence of the power received by an ultrasound transducer from the backscatter of an interrogating pulse is dependent on how certain ultrasonic tissue characteristics (speed of sound, attenuation and backscatter coefficient) change with temperature. A theoretical parametric analysis showed that the temperature dependence of the backscatter coefficient dominates the variation of the received power with temperature. According to this analysis the power received by the transducer could either increase or decrease depending on the type of tissue and the inhomogeneities within the tissue. We have confirmed this experimentally *in vitro*. By capturing the RF signal from a single A-mode scan we have been able to identify individual scatterers and follow these scatterers as signals were obtained at temperatures from 37ñ50 °C. The change in energy of these scatterers can increase or decrease with temperature and is for the most part monotonic. Typically we have seen a change of between 5 and 15 dB in backscattered energy over the temperature range of 37ñ50°C. The envelope of a collection of scatterers can be used to infer the temperature of the tissue by analyzing the statistics of the collection. We found that the standard deviation of backscattered power increased monotonically with temperature and was accurately approximated by a second-order polynomial. Thus far we have segmented the individual scatterers by hand. We are also working on utilizing automatic techniques such as matched filters and arbitrary segment intervals. Supported in part by R21 CA90531.

Goals

ï Measure the effect of temperature change on ultrasound tissue characteristics using the simplest measurement possible: backscatter

ïEvaluate the prospects of using this measurement as a method for noninvasive thermometry during hyperthermia

Theory

In order to explore the potential of using pulse-echo measurements from a single transducer for thermometry, we parametrically analyzed a theoretical model for the backscattered energy received from a small tissue volume in response to an insonifying burst. Backscattered energy was determined relative to the energy received from the same volume at a reference temperature (37 °C). Temperature dependence of attenuation and velocity was taken from the literature. Although we found no data on the temperature dependence of the backscatter coefficient, we assumed that it was proportional to the scattering cross section of a small scatterer, which depends on the square of the scattering potential (Arthur and Broadstone 1989; Shung et al. 1992). Using reported attenuation and speed-of-sound (SOS) data, along with inferred backscatter coefficients, we predicted what changes in backscattered energy could be expected with temperature from certain medium and scatterer combinations.

$$P_r(T) = \frac{2H^2\delta}{8R^4\alpha(T)}\eta(T)S(1-e^{-2\alpha(T)c(T)\tau})\left(\frac{e^{\alpha(T)c(T)\delta}-e^{-\alpha(T)c(T)\delta}}{2\alpha(T)c(T)\delta}\right)$$

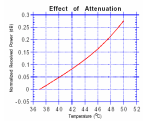
To eliminate parameters, which are not temperature dependent, we normalized the expression developed by Sigelmann and Reid (1973) for the average backscattered energy from a small scattering volume containing a random distribution of scatterers in response to insonification by a sinusoidal burst. The equation for normalized energy received at temperature T then becomes:

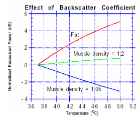
$$E_n(T) = [\alpha(37)/\alpha(T)][\eta(T)/\eta(37)]\frac{\left[1-e^{-2\alpha(T)x}\right]}{\left[1-e^{-2\alpha(37)x}\right]}$$

where α(T) is the attenuation within the tissue volume as a function of temperature, η(T) is the backscatter coefficient of the tissue volume as a function of temperature, and x is the length in the tissue volume. The backscatter coefficient is defined as the backscattering cross section per unit volume of scatterers (Shung et al., 1992). We inferred the temperature dependence of the backscatter coefficient from the scattering cross section of a small (subwavelength) scatterer. Assuming that the backscatter coefficient for a distribution of scatterers is proportional to the scattering cross section for a single scatterer, the temperature dependence for the ratio $\eta(T) / \eta(37)$ can be approximated as

$$\eta(T)/\eta(37) = \frac{\left(\frac{\rho_m c(T)_m^2 - \rho_s c(T)_s^2}{\rho_s c(T)_s^2}\right)^2 + \frac{1}{3}\left(\frac{3\rho_s - 3\rho_m}{2\rho_s + \rho_m}\right)^2}{\left(\frac{\rho_m c(37)_m^2 - \rho_s c(37)_s^2}{\rho_s c(37)_s^2}\right)^2 + \frac{1}{3}\left(\frac{3\rho_s - 3\rho_m}{2\rho_s + \rho_m}\right)^2}$$

Results: Theoretical

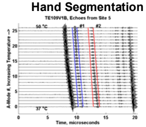




Predicted changes in normalized backscattered energy at 7.5 MHz due to a temperature increase. Predictions were made assuming the medium had the characteristics of liver. According to the theoretical analysis the temperature dependence of the backscattered energy should be dominated by the temperature dependence of the back scatter coefficient. According to the prediction we should expect a range of responses to increase in temperature depending on the type of scatterer.

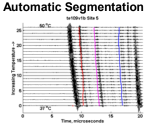
Results: Experimental

Hand Segmentation



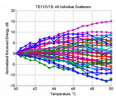
Echoes measured from a single site in a 1 cm thick sample of bovine liver at temperatures from 37 to 50 °C. The two delineated echoes that appear to track with temperature have energies that changed with temperature in opposite directions.

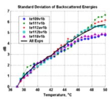
Automatic Segmentation



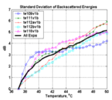
A simple matched filter technique that uses the hand segmented scatterers (hand segmentation) and correlates that signal in the subsequent higher temperatures.

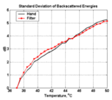
Backscattered energy change for 22 individual scatterers in a sample of bovine liver over the 40 to 50 °C temperature.





Standard deviation of backscattered energies at 0.5 °C intervals over the 37 to 50 °C temperature range of 120 scatterers. Five scatterers from each of 5 sites in 4 experiments and from 4 sites in 1 experiment were used.



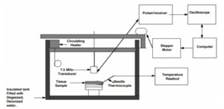


Comparison of the matched-filter technique with the handsegmentation method for all experiments on bovine liver.

Procedures

Experimental Setup

Measurements were made with the experimental configuration depicted in Figure 1. Tissue samples were heated in an insulated tank that was filled with deionized water, which had been degassed by vacuum pumping in an appropriate vessel. Tissue was placed in the focal zone (2 mm in diameter) of a focused, circular piston transducer. Center frequency of the transducer was 7.5 MHz. Temperature in the tank was set by a heater that circulated the water in the tank. The temperature in the tissue was monitored by a thermometer, which used an indwelling needle thermocouple. After temperature in the tank reached equilibrium, the transducer was pulsed with a MetroTek pulser and echoes recorded. The transducer was moved to the next site of interest and a new echo signal recorded. After all sites of interest had been insonified, the transducer was returned to its original position, so that the process could be repeated at the next temperature. The temperature range covered was 37 to 50 °C in 0.5 °C increments.



Configuration for the measurement of backscattered ultrasound from tissue samples. Deionized and degassed water in the tank was heated to equilibrium, as monitored by an invasive thermocouple probe in the tissue. The transducer was scanned over different sites and the backscattered signal recorded for subsequent analysis.

Data Analysis

Data were analyzed by identifying what appeared to be individual scatterers in the echo signal. These ìscatterersî were then tracked as there position shifted with temperature. We have segmented the scatterers by hand and with a simple matched filter technique.

The matched-filter method used the hand segmented scatterers at the baseline temperature (37 °C) then automatically identified these scatterers at subsequent temperatures

Summary and Conclusions:

- Measured changes in backscattered energy were consistent with our model of the energy reflected from sub-wavelength scatterers.
- Statistical analysis of the distribution of change in scatterer energy over the temperature range of 37 ñ 50°C was monotonic.
- Signal processing algorithms should provide the capability of identifying and following scatterers at different temperatures.

Future Directions:

The matched-filter technique used here is preliminary and can be improved by redefining the filter at each temperature step. Defining a stylized filter to eliminate noise may also contribute to better tracking of the signals.

Eventually in order to accurately track these signals it will be necessary to image the tissue samples in three dimensions.