Noninvasive Temperature Estimation Based on the Energy of Backscattered Ultrasound

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Objective

To develop a method to produce 3D temperature maps in soft tissue

- noninvasively, conveniently & at low cost
- with 0.5 ^{o}C accuracy & 1 cm^3 resolution

Thermometry with Ultrasound

• Ultrasound is a nonionizing, convenient, and inexpensive modality with relatively simple signal processing requirements

• These attributes make it an attractive method to use for temperature estimation if a temperature-dependent parameter can be found, measured and calibrated

Temperature-dependent Parameters

Attenuation	$\alpha(T)$
Speed of sound	$c(T)$
Backscatter coefficient	$\eta(T)$

Approach

- Use a single backscatter view
- Find a simple measure from that view
- Employ standard equipment

Backscattered Power

Power received from tissue volume $S\tau$, where S is beam area and τ is signal duration, assuming a lossless medium is [Sigelmann and Reid, 1973]

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

H and δ are the amplitude and duration of the insonifying burst
R is the distance from the transducer to the scattering volume

and

$\alpha(T)$, $c(T)$ and $\eta(T)$ apply to the scattering volume

Backscattered Energy Normalized to 37°C

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

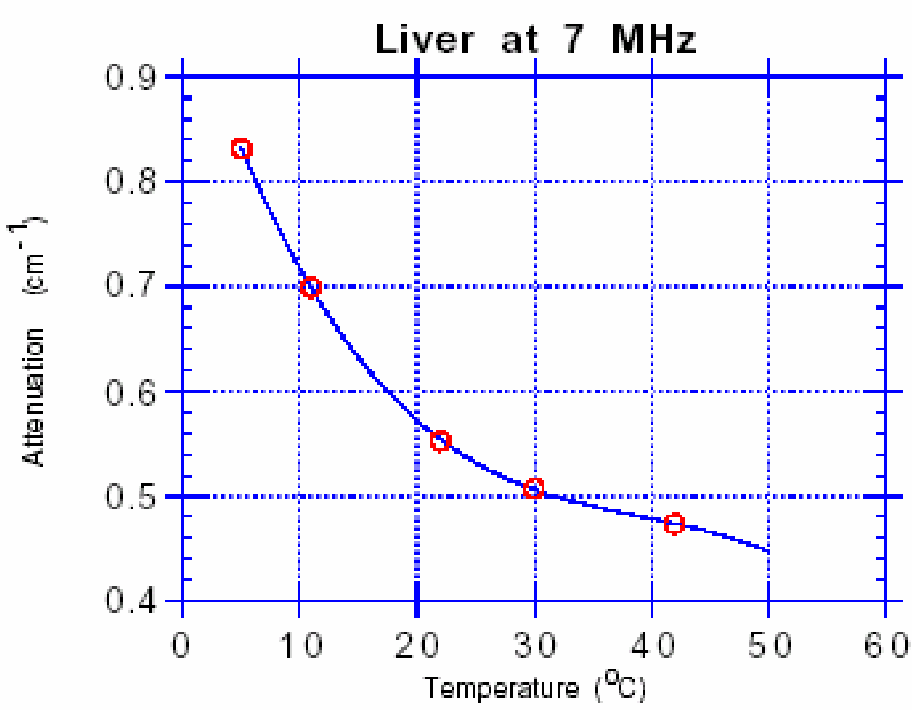
$$\eta(T)/\eta(37) = \frac{\left(\dfrac{\rho_m c(T)_m^2 - \rho_s c(T)_s^2}{\rho_s c(T)_s^2}\right)^2 + \dfrac{1}{3}\left(\dfrac{3\rho_s - 3\rho_m}{2\rho_s + \rho_m}\right)^2}{\left(\dfrac{\rho_m c(37)_m^2 - \rho_s c(37)_s^2}{\rho_s c(37)_s^2}\right)^2 + \dfrac{1}{3}\left(\dfrac{3\rho_s - 3\rho_m}{2\rho_s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

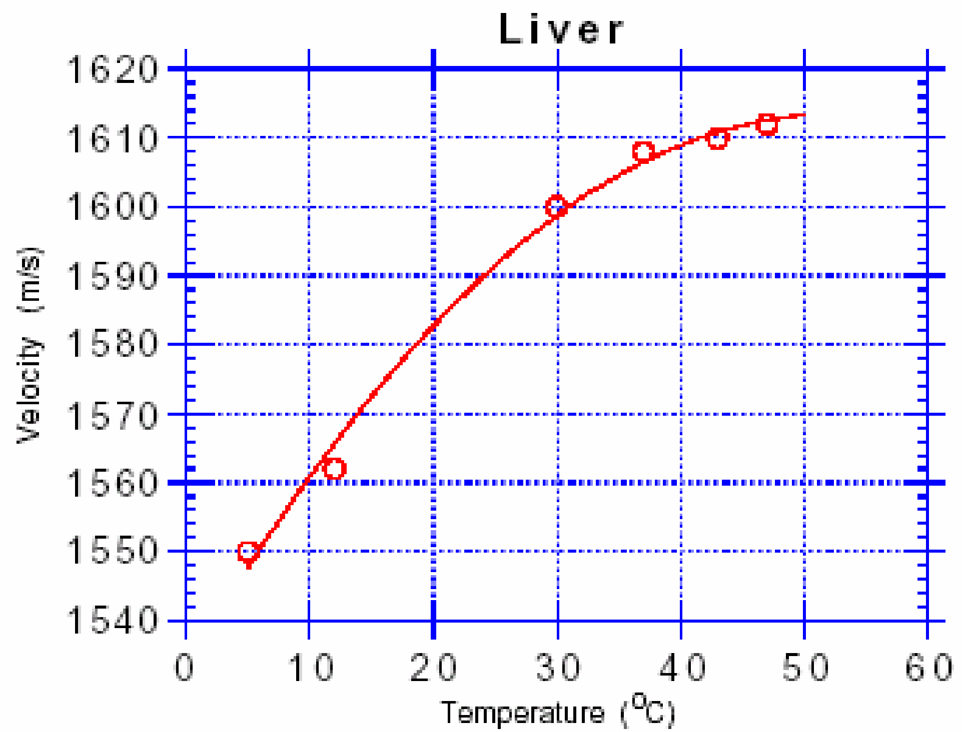
where ρ is the density of the medium (m) or scatterer (s).

The backscatter coefficient is given by the scattering cross section of a subwavelength scatterer (Morse and Ingard, 1968)

Normalized Backscattered Energy

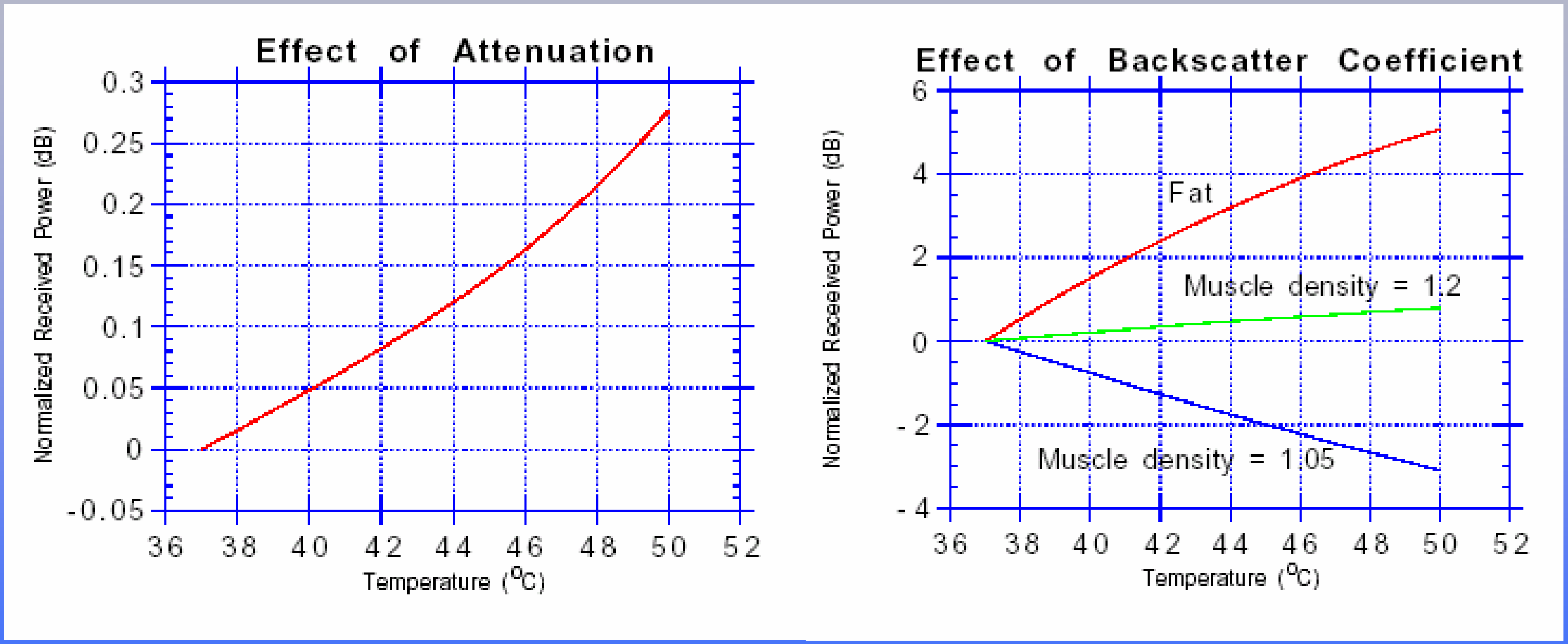
Attenuation and speed of sound in liver from Bamber and Hill (1979) as extracted by Haney and O'Brien (1986) were used to predict changes in backscattered energy.



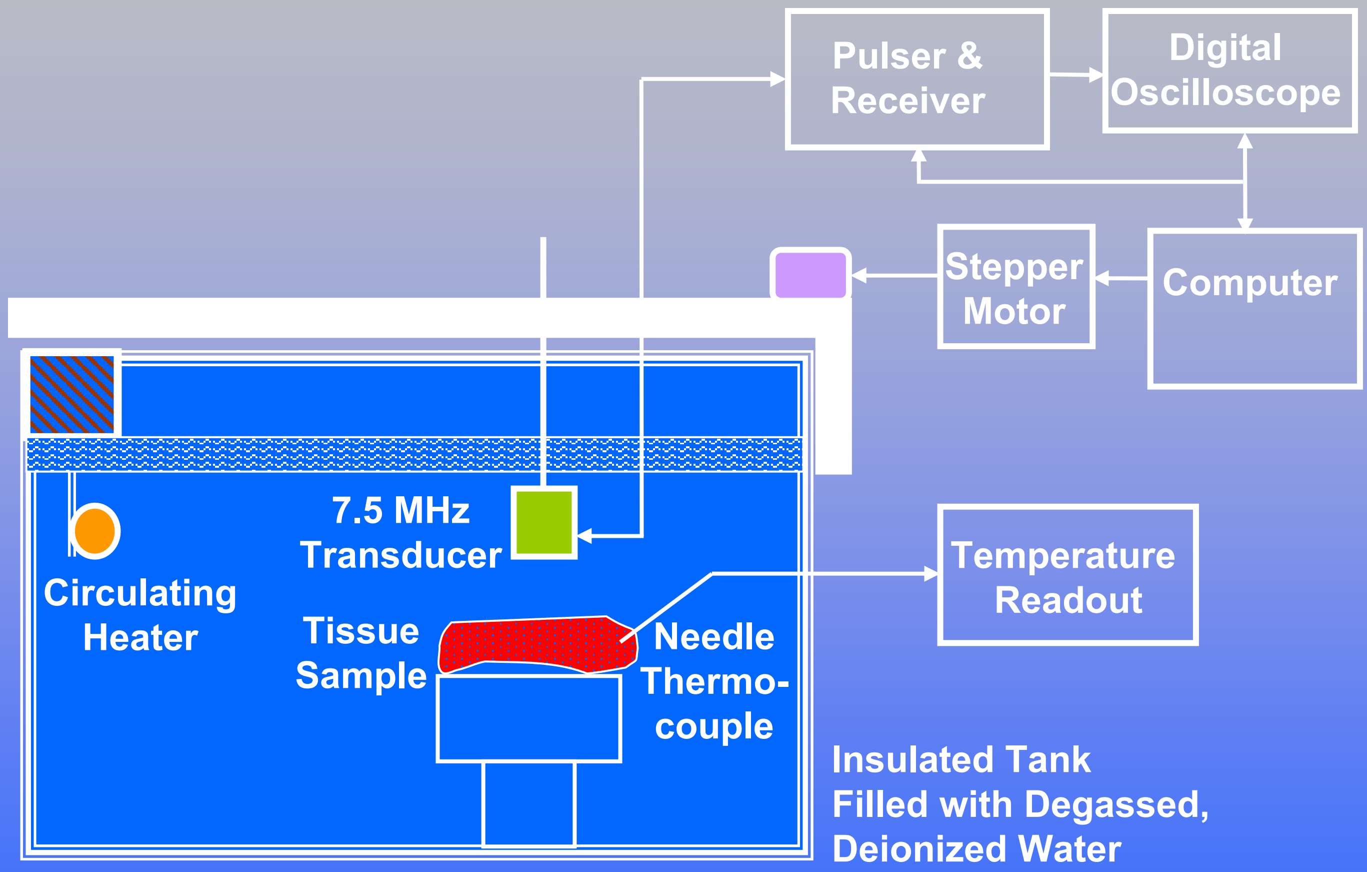


Polynomial fits (lines) of these and other data (circles) were used to predict the effect of attenuation and backscatter coefficient on the backscattered power level.

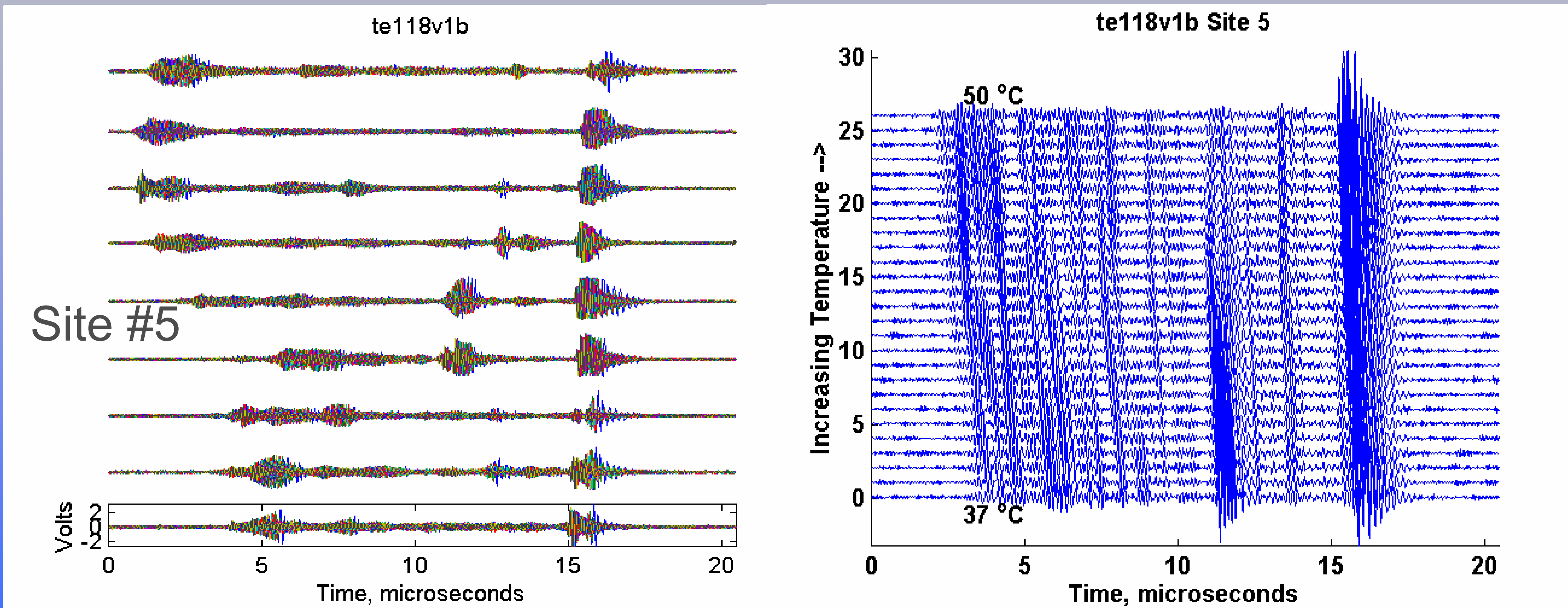
Predicted Changes in Backscattered Energy



Measurement of Backscattered Ultrasound



A-Mode Echo Signals



Alternatives for Following Changes in Backscattered Energy

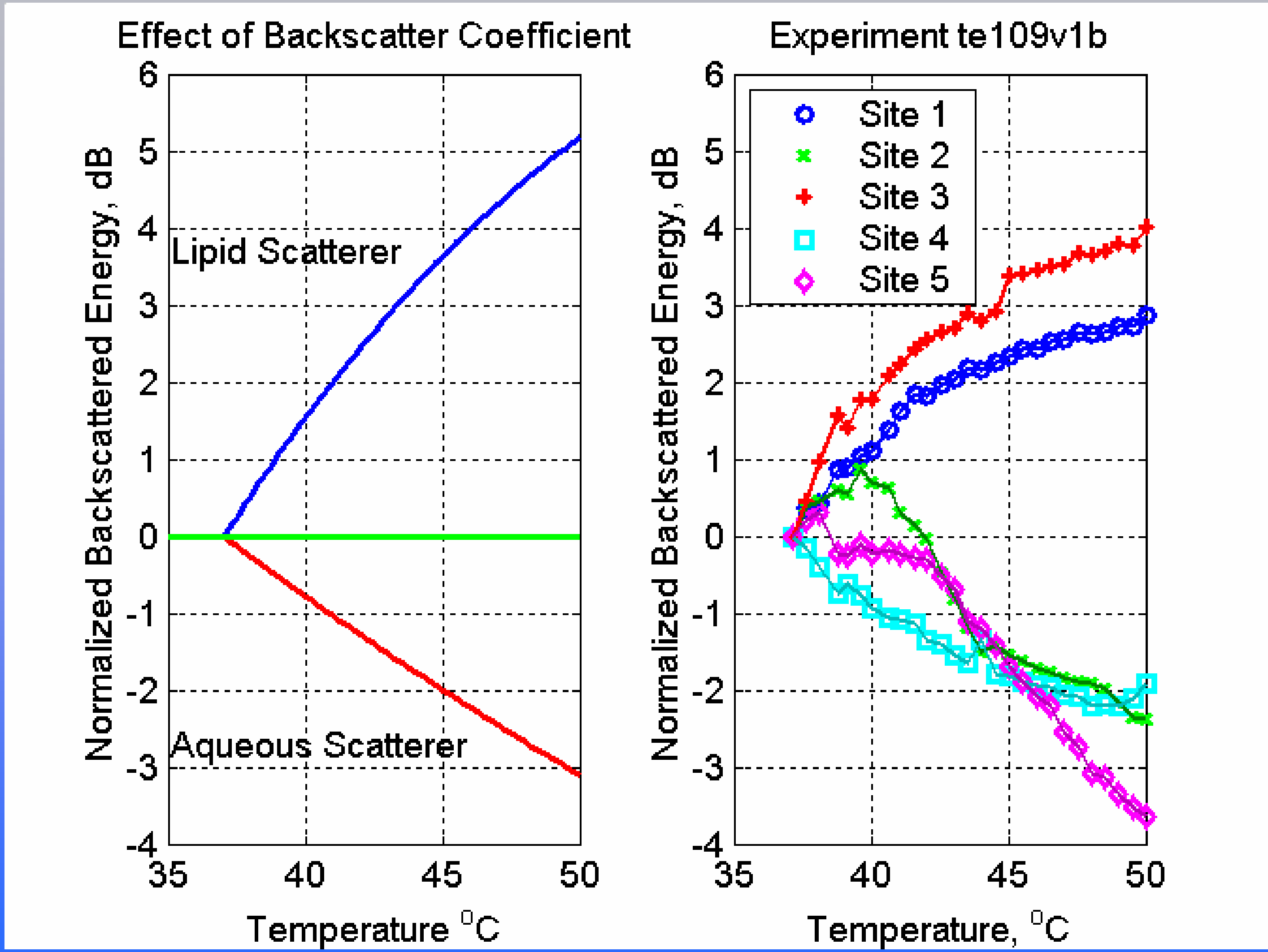
Follow changes in echo energy from:

1) Tissue regions with multiple scatterers

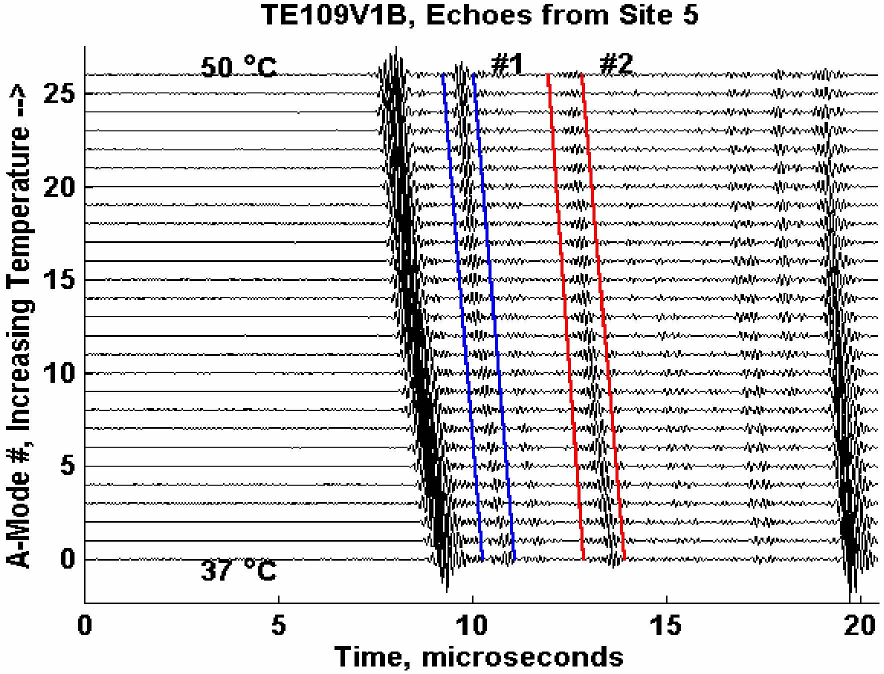
2) Selected individual scatterers

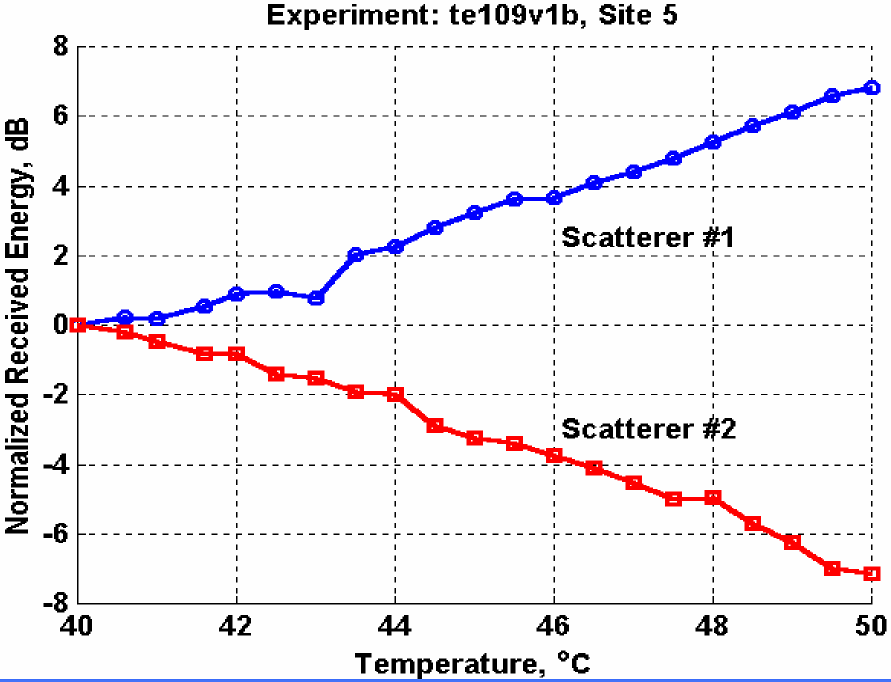
3) Collections of individual scatterers

Predicted Change in Backscattered Energy and Measured CBE over 1 cm of Bovine Liver

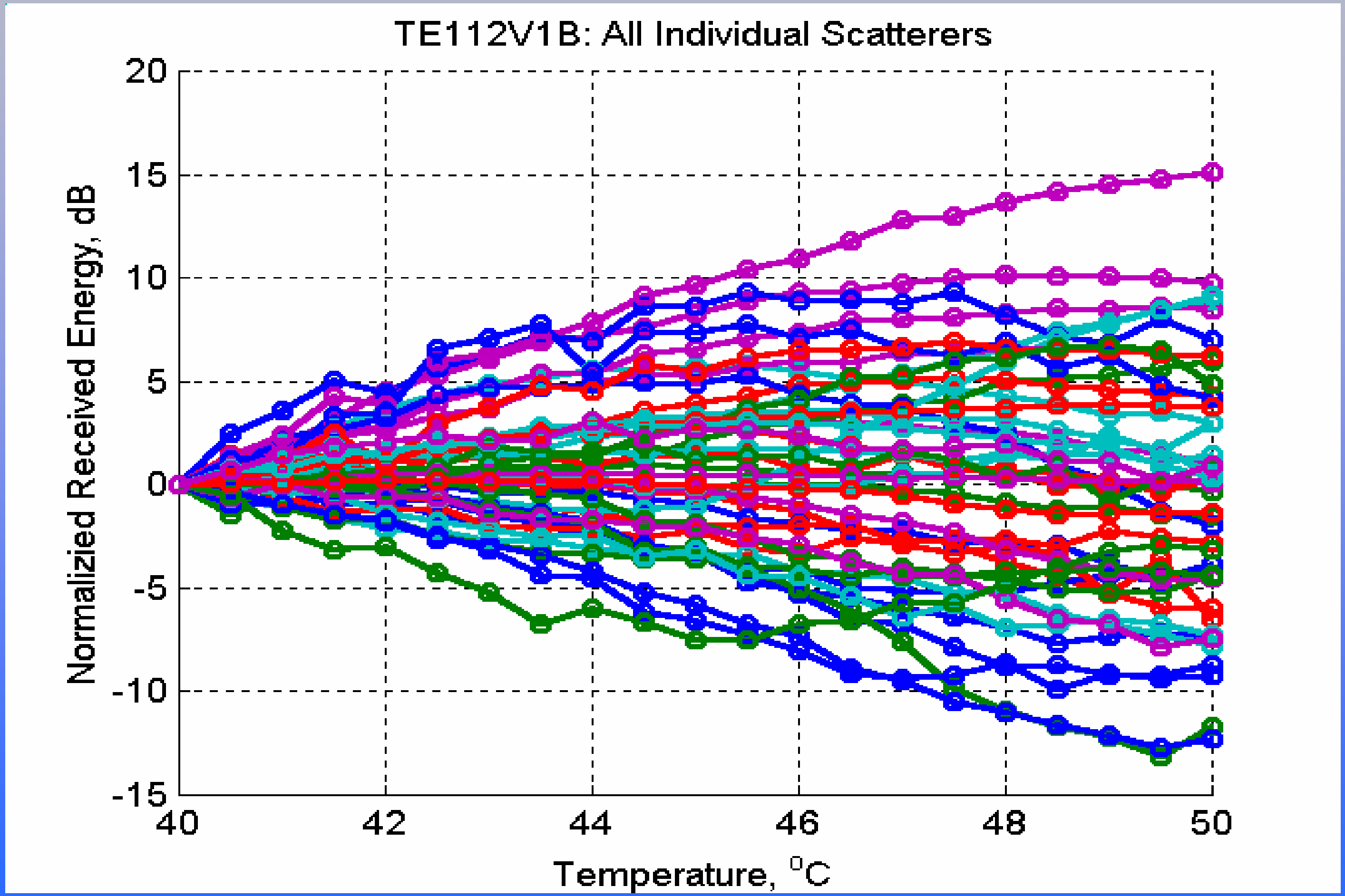


Change in Backscattered Energy from Individual Scatterers in Bovine Liver



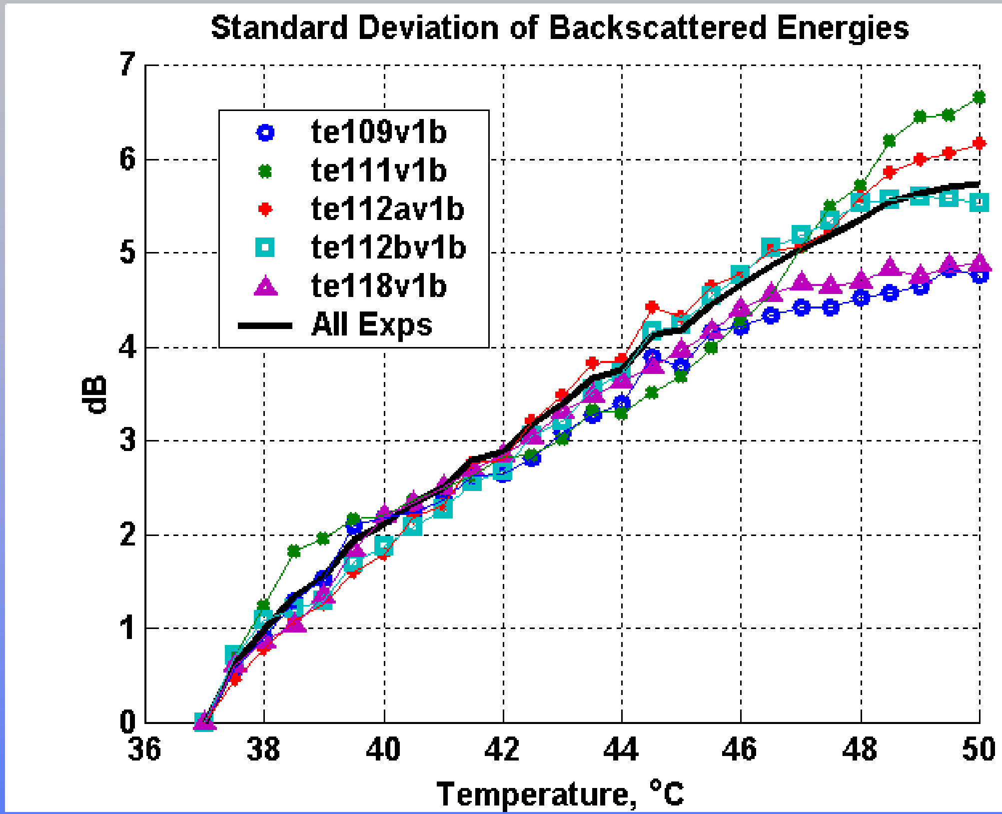


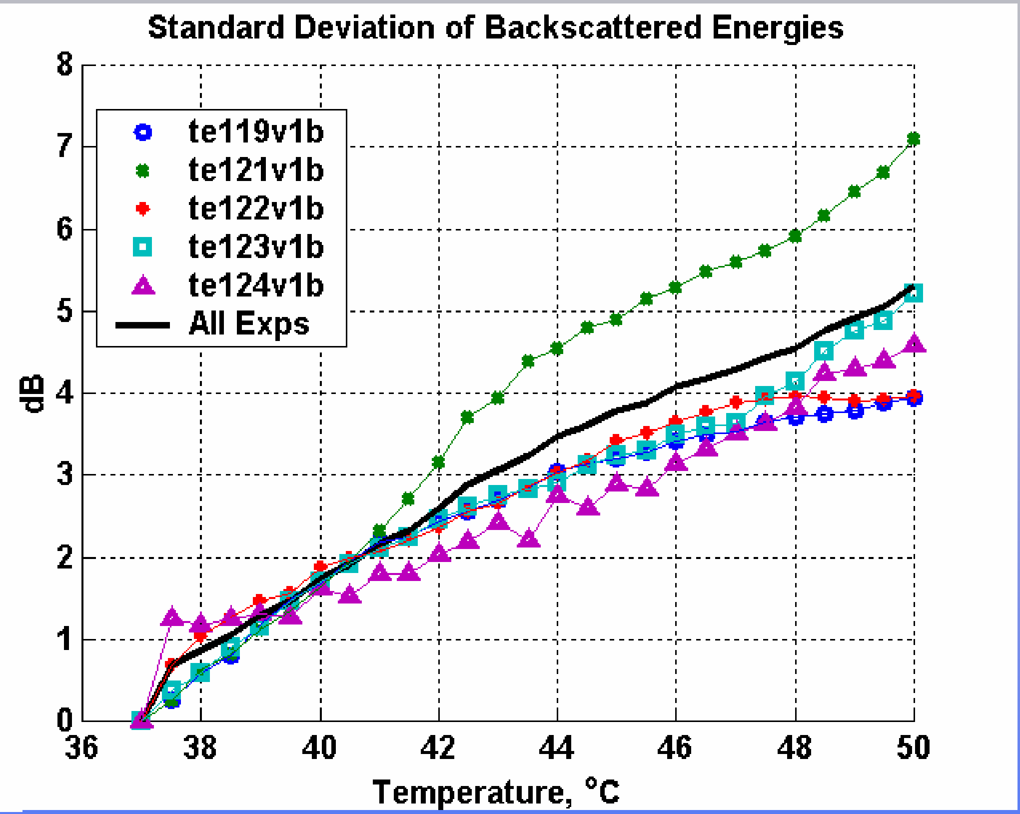
Distribution of the Change in Backscattered Energy from Individual Scatterers in Bovine Liver



Bovine Liver

Turkey Breast





Polynomial fit of Changes in Backscattered Energy with Temperature
$CBE(T) = a_o + a_2T + a_2T^2$ m/s

	a_o	a_1	a_2	Corr. Coeff.
Bovine Liver	-42.0916	1.6798	-0.0144	0.9982
Turkey Breast	-35.7138	1.4121	-0.0119	0.9983

Summary & Conclusions

- Measured changes in backscattered energy (CBE) from 37 to 50 ^{o}C were consistent with our model of the energy reflected from sub-wavelength scatterers
- The standard deviation of the CBE of 120 scatterers from both bovine-liver and turkey-breast samples increased nearly monotonically with temperature
- For both liver and turkey samples the scatterers were contained in an insonified volume of less than 1 cm^3, suggesting clinically useful resolution may be possible
- Because this approach exploits inhomogeneities present in tissue, if it is successful *in vitro*, it holds promise for *in vivo* application

Future Work

- **Automate segmentation of individual scatterers**

  (Initial Results given in Mini-Presentation MP01-4)

- **Develop calibration curves for key tissue types**
- **Track scatterers *in vivo* in 3D**