THEORETICAL ESTIMATION AND EXPERIMENTAL TECHNIQUES FOR THE DETERMINATION OF THE TEMPERATURE DEPENDENCE OF BACKSCATTERED ULTRASONIC POWER

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ABSTRACT

The backscattered signal received from an insonified volume of tissue was modeled to determine the response of the backscattered signal to a change in temperature. The temperature dependent parameters of the model were velocity, attenuation and backscatter coefficient. Analysis of the model for a lipid scatterer and an aqueous scatterer in a water-based medium showed that the temperature dependence of backscattered power was dominated by the effect of temperature on the backscatter coefficient. The temperature dependence of attenuation had a small effect on backscattered power and the backscattered power was independent of effects of temperature on velocity. The temperature dependence of the backscatter coefficient was inferred assuming that the backscatter coefficient was proportional to the scattering cross-section of a small scatterer. Backscattered power increased nearly logarithmically with temperature over the range from 37 to 50 ºC. Our model predicted a change of +5 dB for the lipid scatterer and -3 dB for the aqueous-based scatterer over that temperature range. The primary deterrent to *in vitro* experimental verification has been outgassing at hyperthermic temperatures. Subjecting both tissue and water bath to a vacuum of 26 inches of mercury for 120 and 20 minutes respectively allowed the measurement of backscattered ultrasonic power at temperatures as high as 50 ºC without noticeable outgassing in either the tissue or the surrounding water. Preliminary experimental results in bovine liver suggest that backscattered power change was similar to that predicted; it changed from +4 to -3 dB over the range from 37 to 45 ºC.

Model for the Temperature Dependence of Backscattered Ultrasound

We previously derived an expression for normalized backscattered power [1]. It was based on the model of Sigelmann and Reid for the expected backscatter power for a single ultrasonic burst from a tissue volume defined by the beam area S and gate length τ assuming a lossless medium between the transducer and the scattering volume [2]:

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

H/R	The amplitude of the insonifying sinusoidal burst
δ	The duration of the insonifying sinusoidal burst,
R	The distacnce from the transducer to the scattering volume of tissue
α(T)	The temperature dependent attenuation within the tissue volume
c(T)	The temperature dependent speed of sound in the tissue volume
η(T)	The temperature dependent backscatter coefficient of the tissue volume

The term in brackets in eqn (1) is nearly unity for the cases of interest and will be neglected in this analysis.

Model for the Temperature Dependence of Backscattered Ultrasound

The backscatter coefficient was inferred from the scattering cross-section of a small scatterer [3].

$$\sigma_S = \frac{4\pi k^4 a^6}{9}\left[\left(\frac{\kappa_S-\kappa_m}{\kappa_m}\right)^2+\frac{1}{3}\left(\frac{3\rho_S-3\rho_m}{2\rho_S+\rho_m}\right)^2\right] \quad (2)$$

k	wave number
a	radius of the scatterer
κ	compressibility of the medium *m* and the scatterer *S*.

Assuming the backscatter coefficient is proportional to the scattering cross section and normalizing equation (1) to a reference condition at 37 ° C results in

$$P_n(T) = \alpha(37)/\alpha(T)\times\eta(T)/\eta(37)\times\frac{[1-e^{-2\alpha(T)c\tau}]}{[1-e^{-2\alpha(37)c\tau}]} \quad (3)$$

Where

$$\eta(T)/\eta(37) = \frac{\left(\frac{\rho_m c(T)_m^2-\rho_S c(T)_S^2}{\rho_S c(T)_S^2}\right)^2+\frac{1}{3}\left(\frac{3\rho_S-3\rho_m}{2\rho_S+\rho_m}\right)^2}{\left(\frac{\rho_m c(37)_m^2-\rho_S c(37)_S^2}{\rho_S c(37)_S^2}\right)^2+\frac{1}{3}\left(\frac{3\rho_S-3\rho_m}{2\rho_S+\rho_m}\right)^2} \quad (4)$$

And $1/\rho c(T)^2$ has been substituted for the compressibility κ.

MATERIALS AND METHODS (THEORETICAL)

- A tissue model was chosen to represent the range of possibilities which might be encountered in tumors: A lipid scatterer in a water based medium and an aqueous scatterer in a water based medium.
- The water based medium was chosen to be liver. The lipid based scatterer is represented by peritoneal fat, and the aqueous scatterer is represented by breast muscle.
- Temperature dependent attenuation and velocity data for these tissues were extracted from the literature and fit with polynomials. These polynomials were then used to evaluate equation (3) for the relative backscattered ultrasonic power shown below.
- In our model it was assumed that there was no intervening tissue between the transducer and the volume of interest.

SPEED OF SOUND IN A WATER-BASED MEDIUM

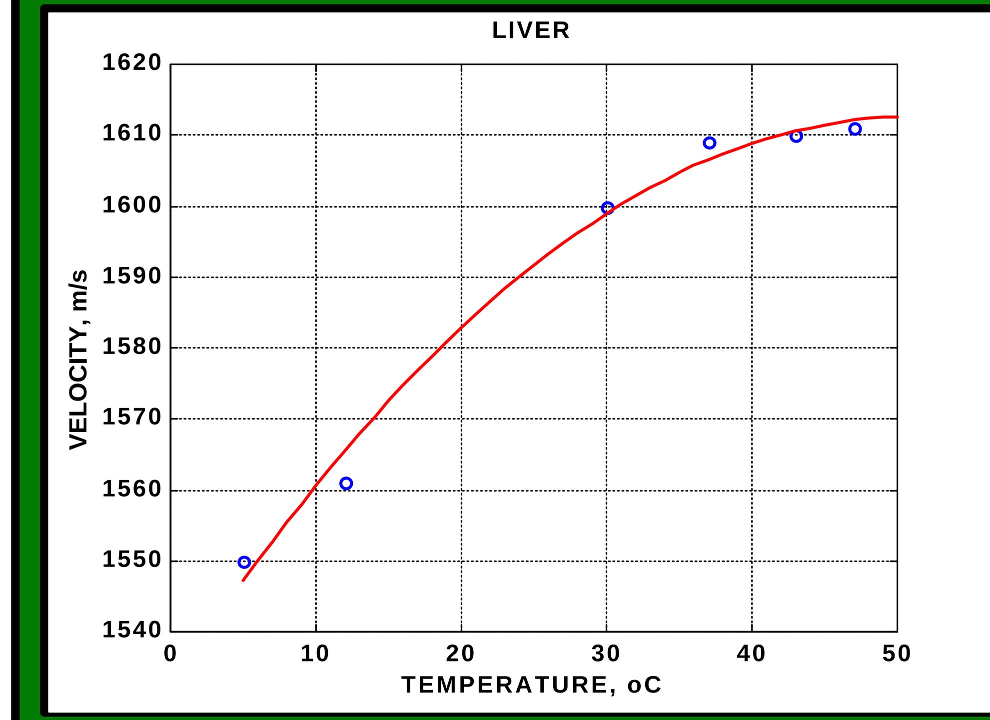


Fig. 1. Speed of sound in liver versus temperature. The curve is a second-degree polynomial fit (r>0.99) of the data points (circles). Data were taken from [4] as extracted in [5].

Polynomial Coefficients for Velocity as a Function of Temperature

$v(T) = a_o + a_2T + a_2T^2$ m/s

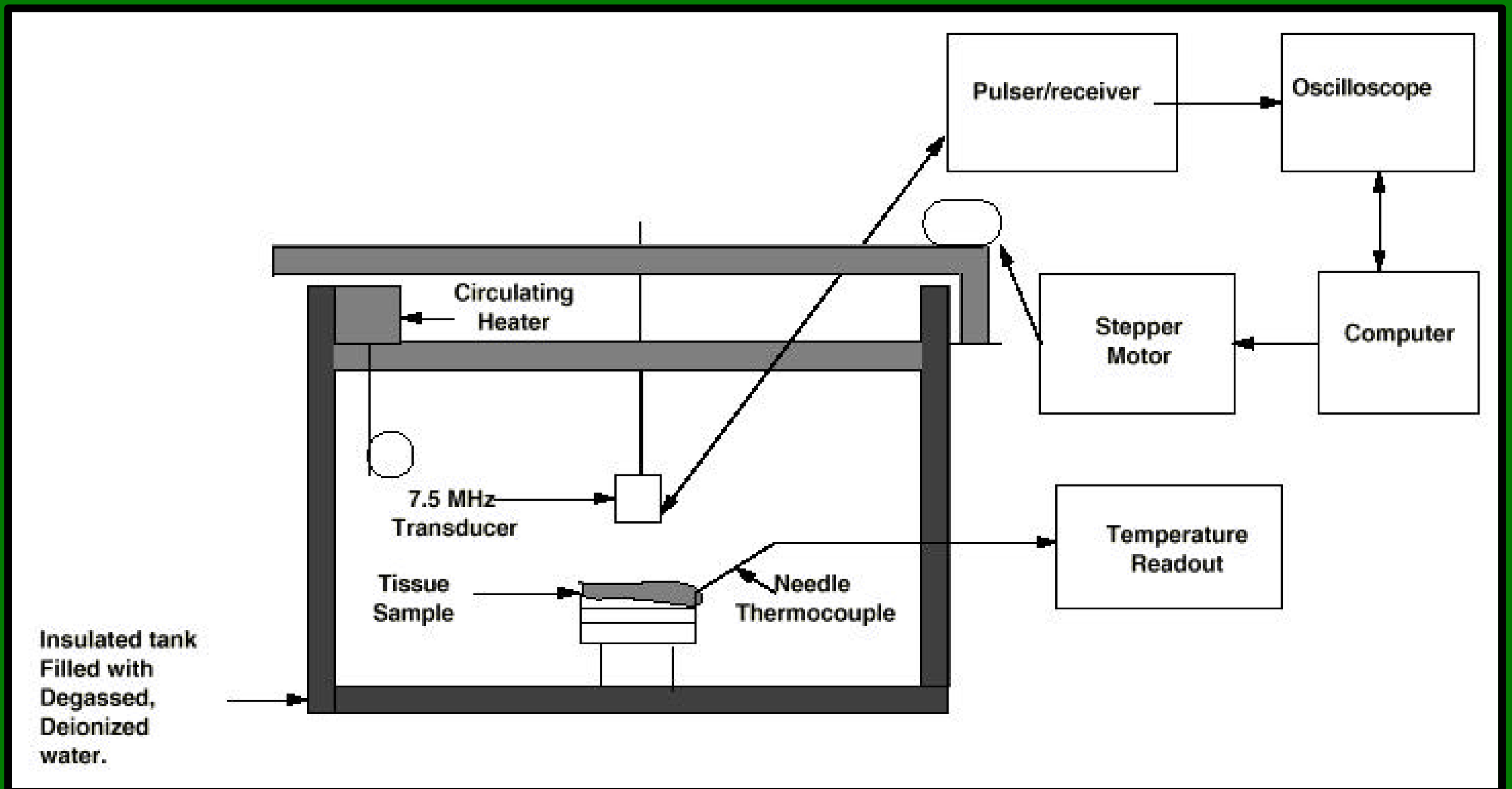
	MEDIUM Liver	AQUEOUS SCATTERER Breast Muscle	LIPID SCATTERER Peritoneal Fat
a_o	1533.1	1471.4	1810.7
a_1	3.0625	3.9979	-13.892
a_2	-0.029208	-0.03513	0.10160
ρ	0.99678	0.99117	0.99953

ρ is the correlation coefficient

MATERIALS AND METHODS (EXPERIMENTAL)

- Backscattered ultrasound was obtained at five positions in a 1 cm slice of fresh Bovine liver.
- A 7.5 MHz circular piston, peizo-electric transducer was excited by a MetroTek pulser/receiver. The backscattered signal was sampled at a 50 MHz rate by a Tektronix 100 MHz oscilloscope.
- The temperature of a tank of degassed, deionized water containing the liver sample was varied from 20 to 50 ºC. Data were acquired at each of the five positions at 33 temperatures between 20 and 50 ºC. From 37 to 50 ºC data were taken every 0.5 ºC.
- Each A-line vector, which contained the complete echo signal from the slice of liver, was analyzed to determine the received power at each temperature at each transducer position.
- Received power was normalized to the power at 37 ºC.

Fig. 3. Measurement of backscattered ultrasound from a sample of fresh bovine liver. The transducer was scanned over five different measurement points each separated by 2 mm. Water in the tank was heated to control the liver temperature, which was monitored with an invasive thermocouple probe.



SPEED OF SOUND IN SCATTERERS

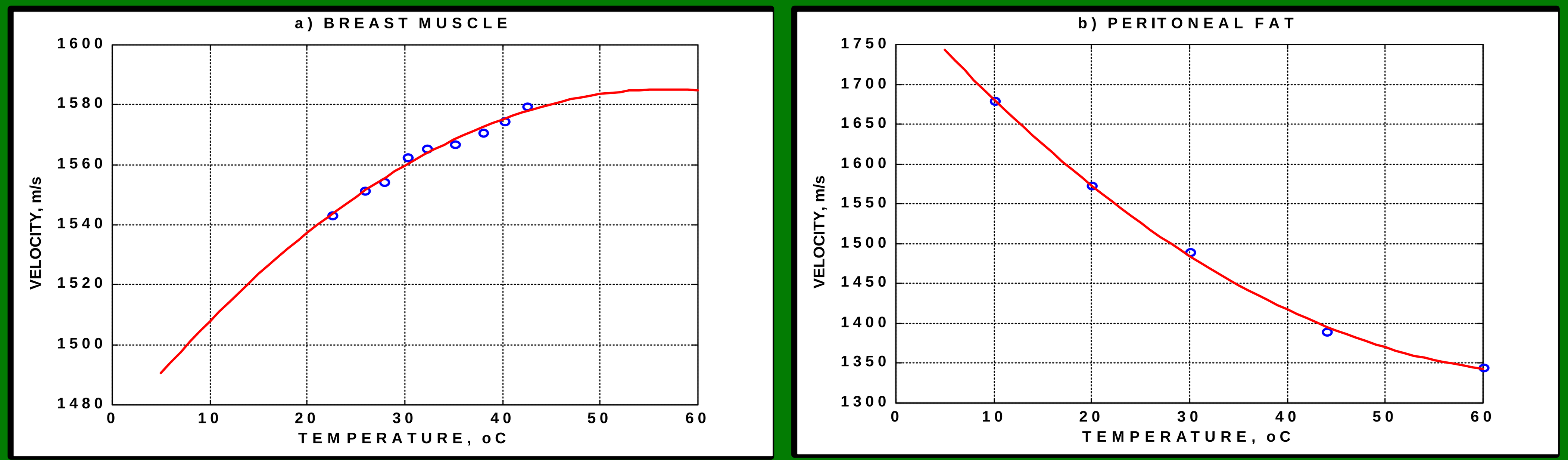


Fig. 2. Speed of sound in (a) breast muscle and (b) peritoneal fat versus temperature. The curves are second-degree polynomial fits (r>0.99) of the data points (circles). The polynomial in (a) was subsequently used to represent the velocity of an aqueous scatterer in calculations of (b) the velocity of a lipid-based scatterer in calculations of the backscatter coefficient. Data from [6].

PREDICTED BACKSCATTERED POWER

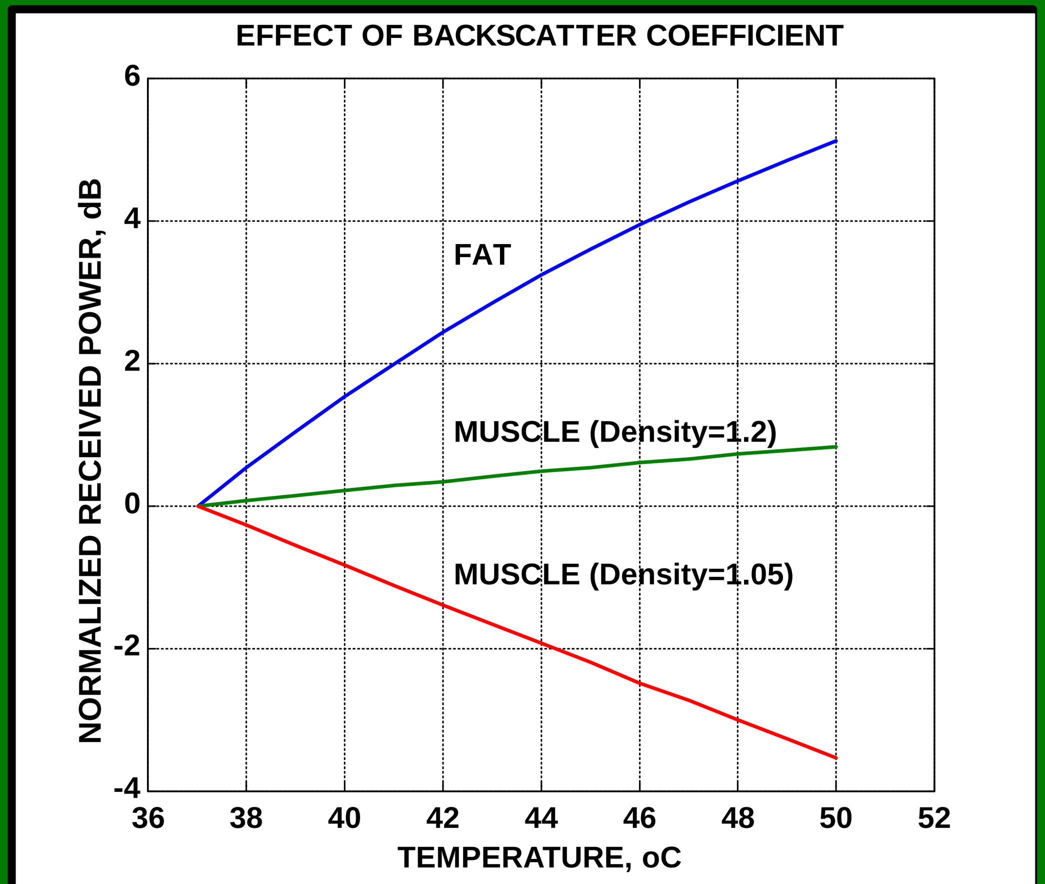


Fig. 4. Normalized received power predicted by eqn(4) using the polynomials in Figs. 1 and 2 for the temperature dependence of velocity. Predictions assumed a water-based medium (Fig. 1). Scatterer for fat was taken from Fig 2a; for muscle from Fig 2b.

MEASURED BACKSCATTERED POWER

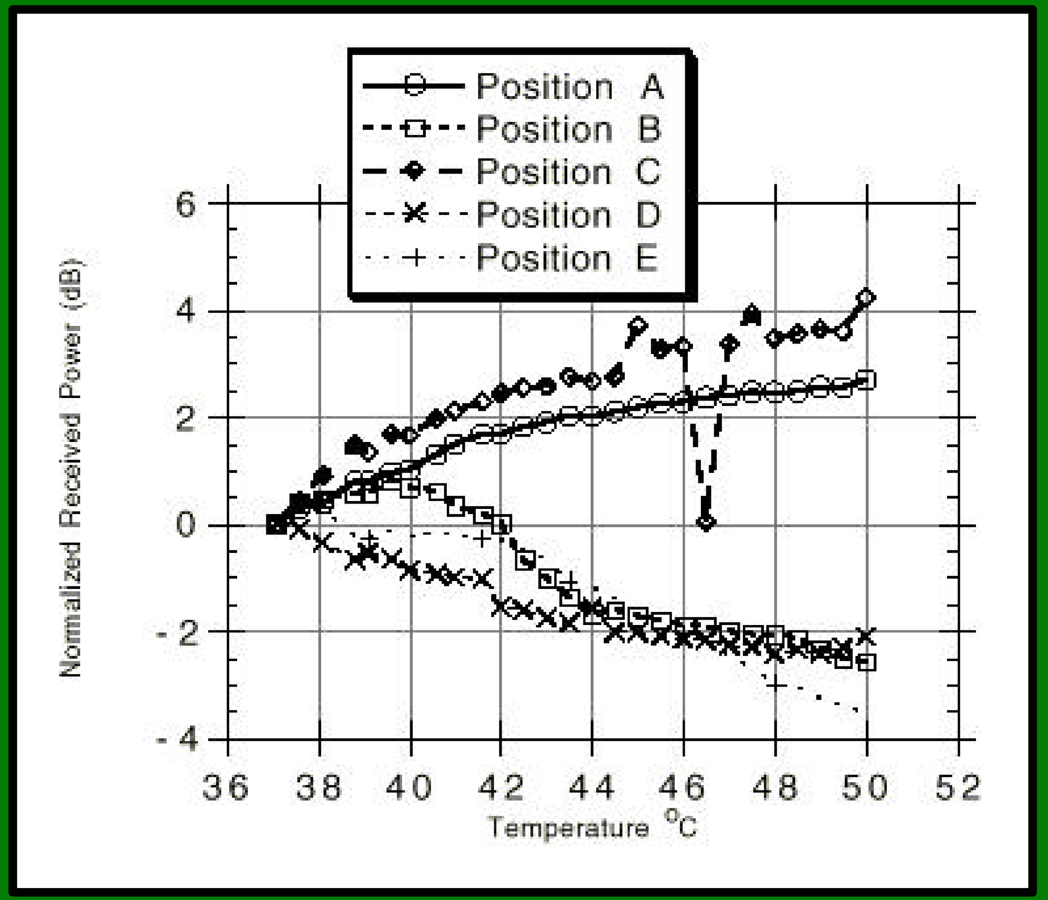


Fig. 5. Normalized received power of backscatter data from fresh Bovine liver. Five A-lines separated by 2 mm were analyzed at each temperature. Power was normalized to that at 37 ºC.

DISCUSSION AND CONCLUSIONS

- Our previously reported theoretical analysis of the temperature dependence of backscattered power was dominated by the temperature dependence of the backscatter coefficient.
- The calculated change in received power received based on equation (3) showed a 5 dB increase in the backscattered power from 37 to 50 ºC for a lipid scatterer and a 3 dB decrease over the same temperature range for an aqueous scatterer with a density of 1.05.
- The trends in the measurements reported here were either an increase of about 3 dB or a decrease of about 3 dB in backscattered power with temperature beyond 37 ºC. These trends are comparable in shape and magnitude to the values derived from our model.
- It remains to be determined, however, whether or not the changes in backscattered power with temperature that we measured are due to the mechanisms assumed in our model.

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