Change in Ultrasonic Backscattered Energy for Temperature Imaging: Factors Affecting Temperature Accuracy and Spatial Resolution in 3D

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Supported by NIH Grants R21 CA90531, R01 CA107558 and the Wilkinson Trust at Washington University

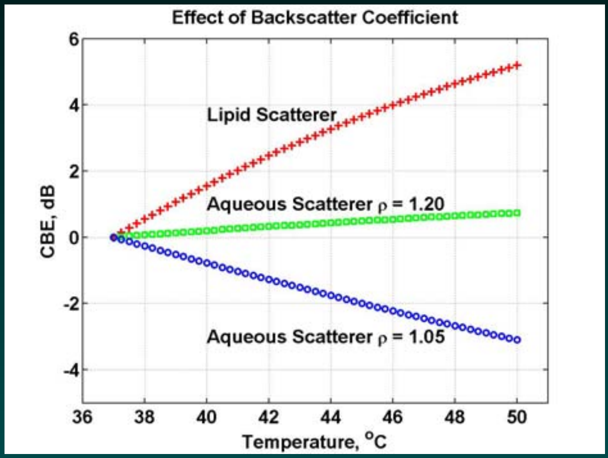
Objective of Ultrasonic Thermometry

To develop a method to produce 3D temperature maps in soft tissue during hyperthermia cancer treatment

- with at least 0.5°C accuracy & 1 cm^3 resolution
- non-invasively, conveniently at low cost with a single view from standard equipment

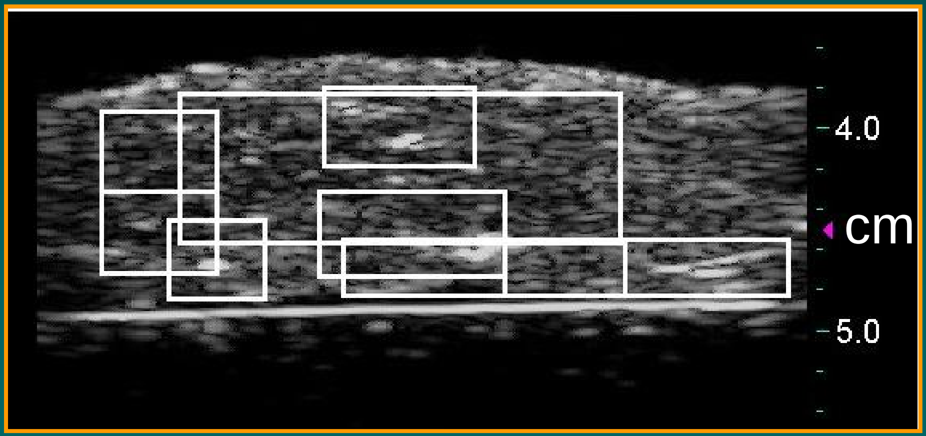
Change in backscattered energy (CBE) as a monotonic temperature-dependent parameter

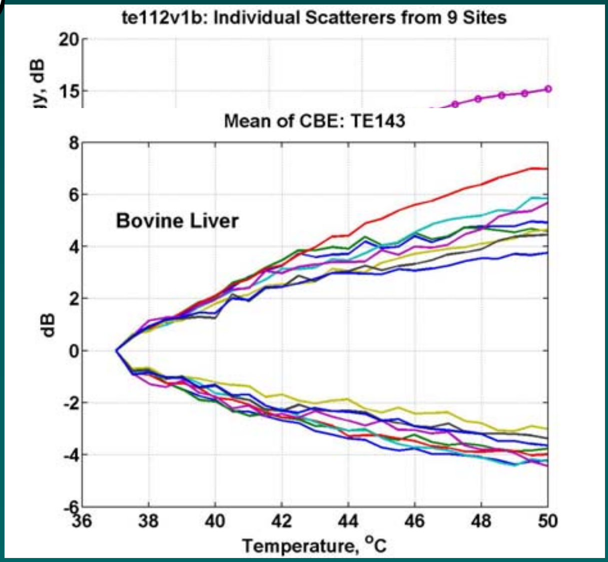
- CBE single-scatterer prediction
  U Med & Bio, 20:915-922, 1994



- CBE from isolated echoes in 1D
  Medical Physics, 30:1021-1029, 2003
- CBE over selected regions in 2D
  IEEE UFFC, 52:1644-1652, 2005

Bovine Liver





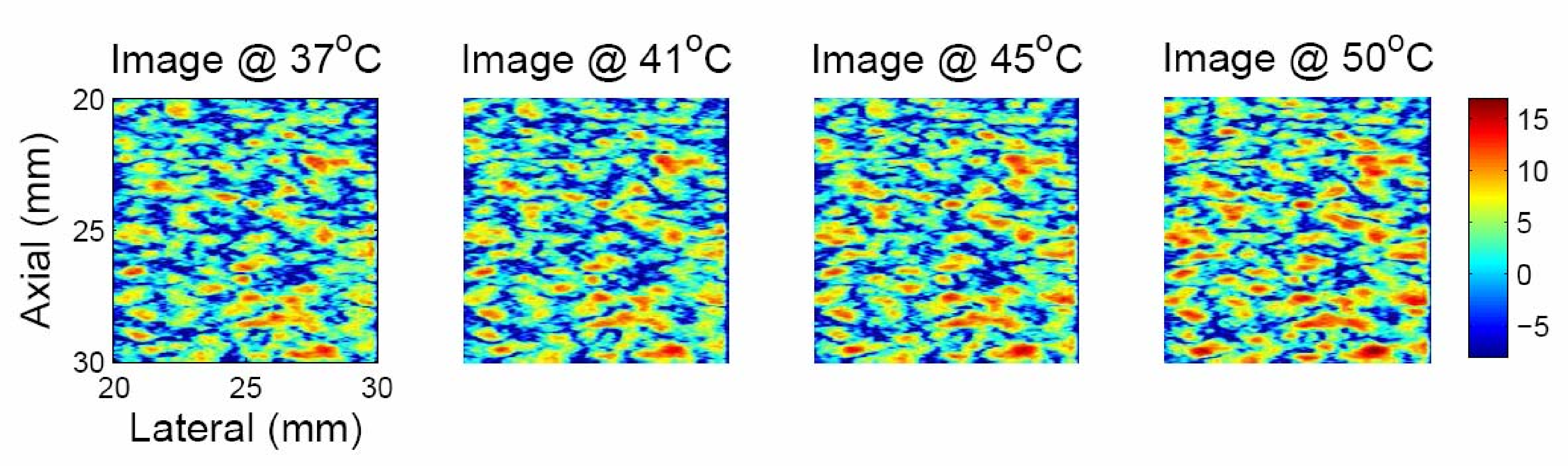
I. Simulation of Scatterer Collections

- To provide a theoretical representation for images of multiple scatterers to extend our single-scatterer model
- To determine limits on spatial resolution and temperature accuracy by studying effects of
  - Scatterer Population
  - Signal-to-Noise Ratio
  - Region Size

Simulation Methods

Discrete-Scatterer Model

- Superposition of point-spread-functions
- Temperature dependence of individual scatterers from single-scatterer model

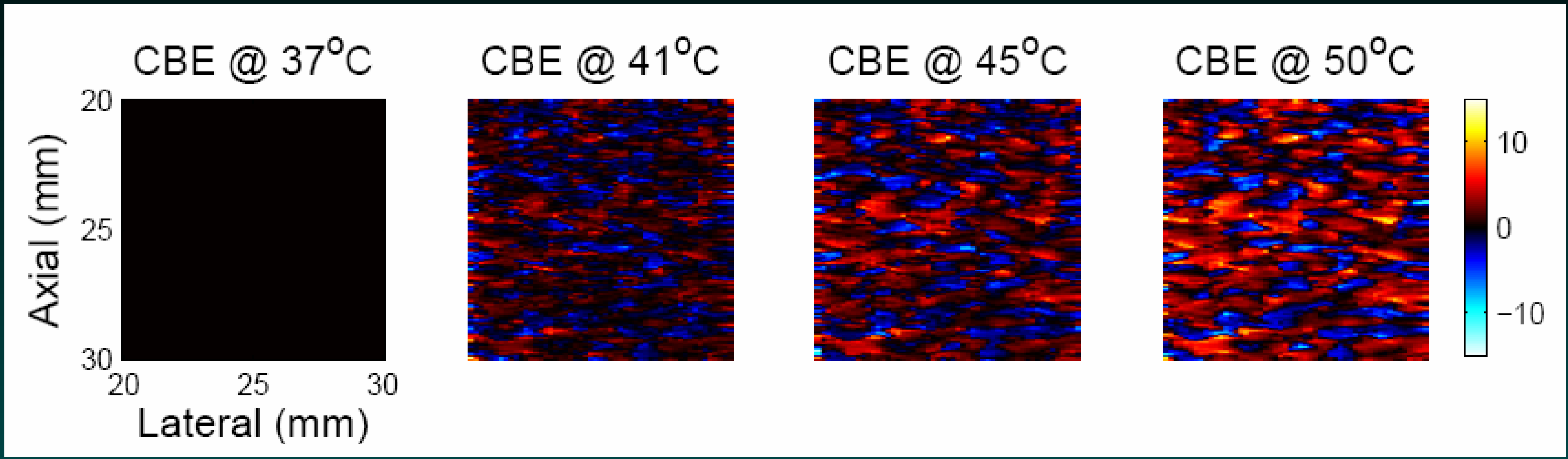


Simulated images for heating of lipid and aqueous scatterers randomly placed in a liver-like medium

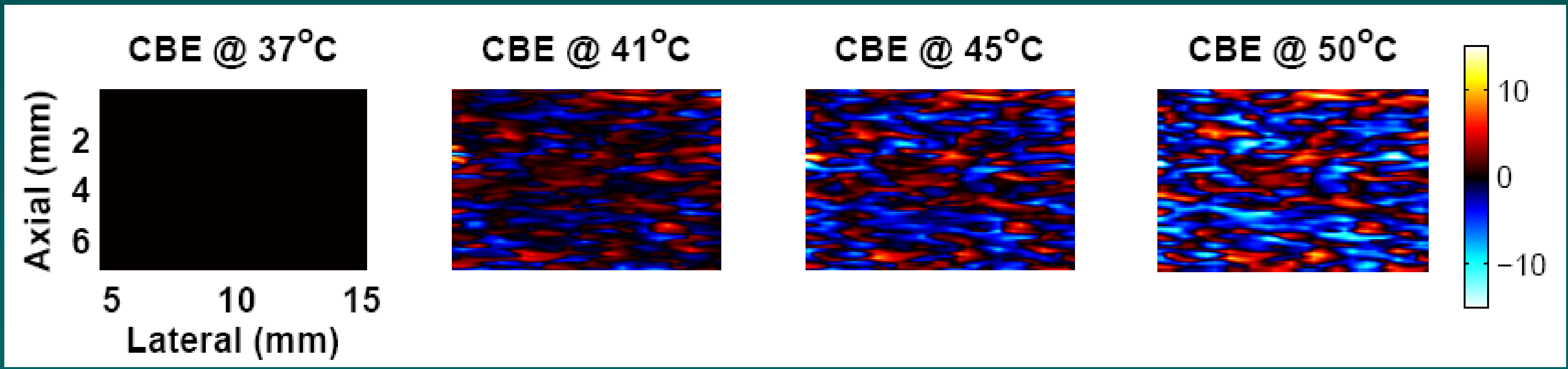
Trobaugh & Arthur, *IEEE Trans. UFFC*, 48:1594-1605, 2001

Trobaugh et al., *Ultrasound in Med. & Biol.*, in review

Simulated and Measured CBE

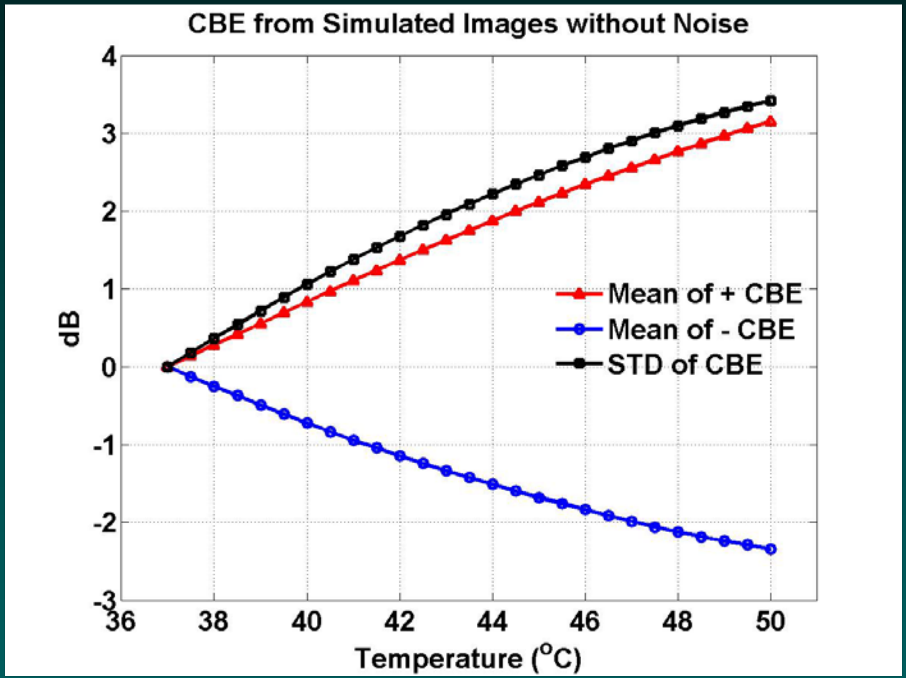


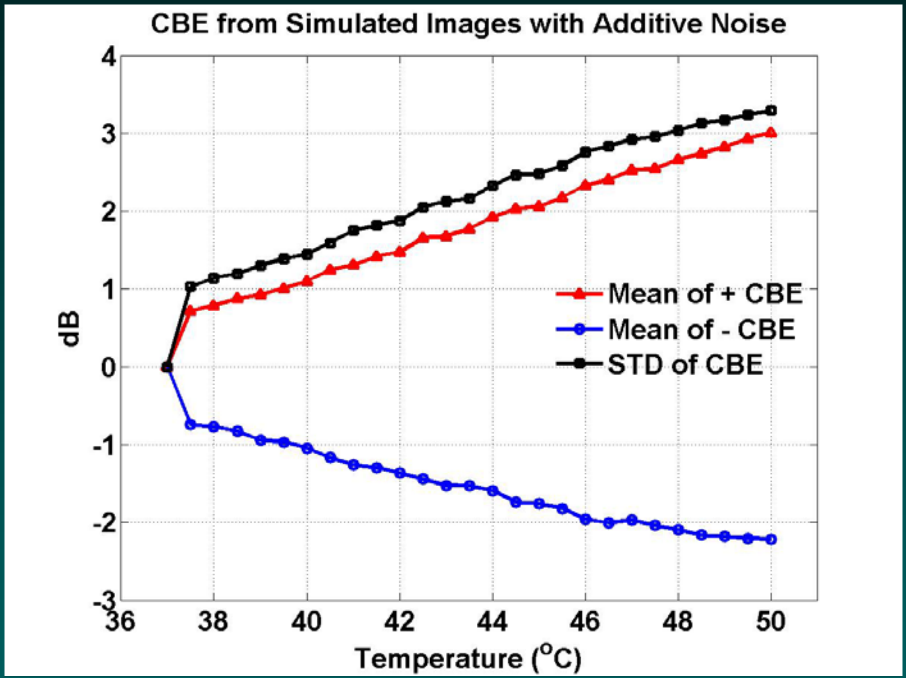
CBE from simulated images computed in the same manner used for measured images
Increase in BE (red) Decrease in BE (blue)



CBE measured in bovine liver

Change in Backscattered Energy from Simulated Images

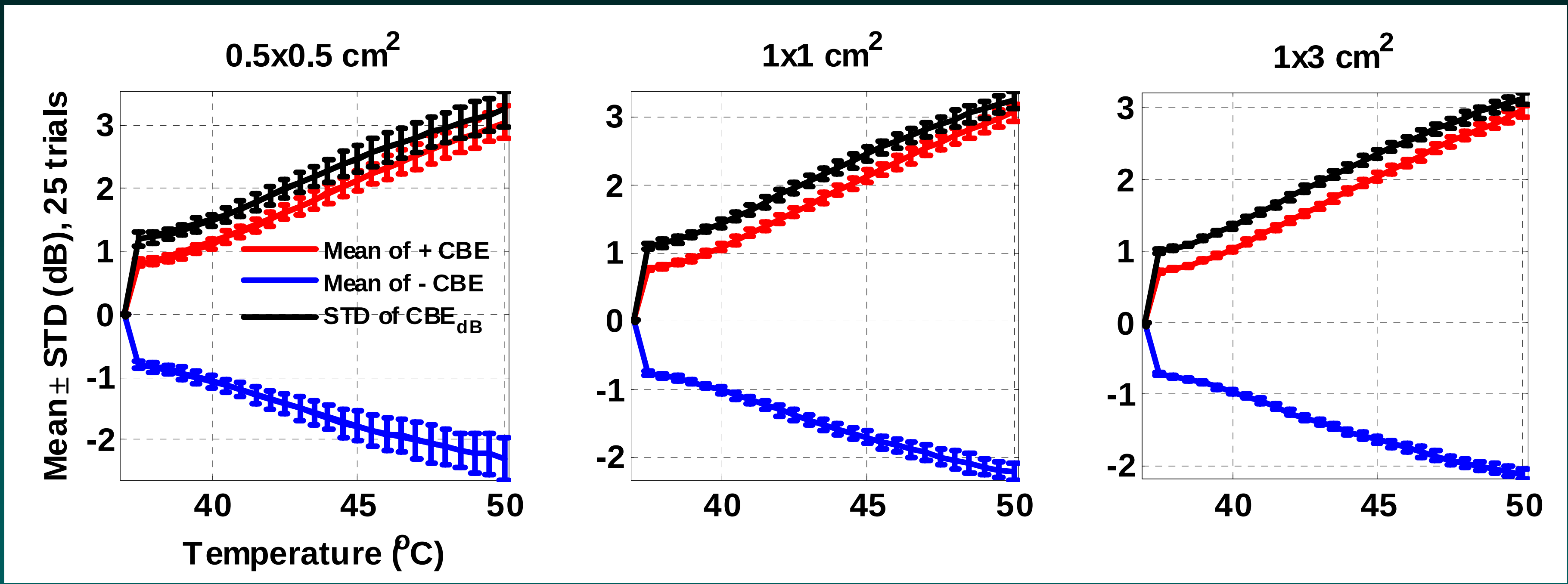




No Noise **With Noise (SNR=19dB)**

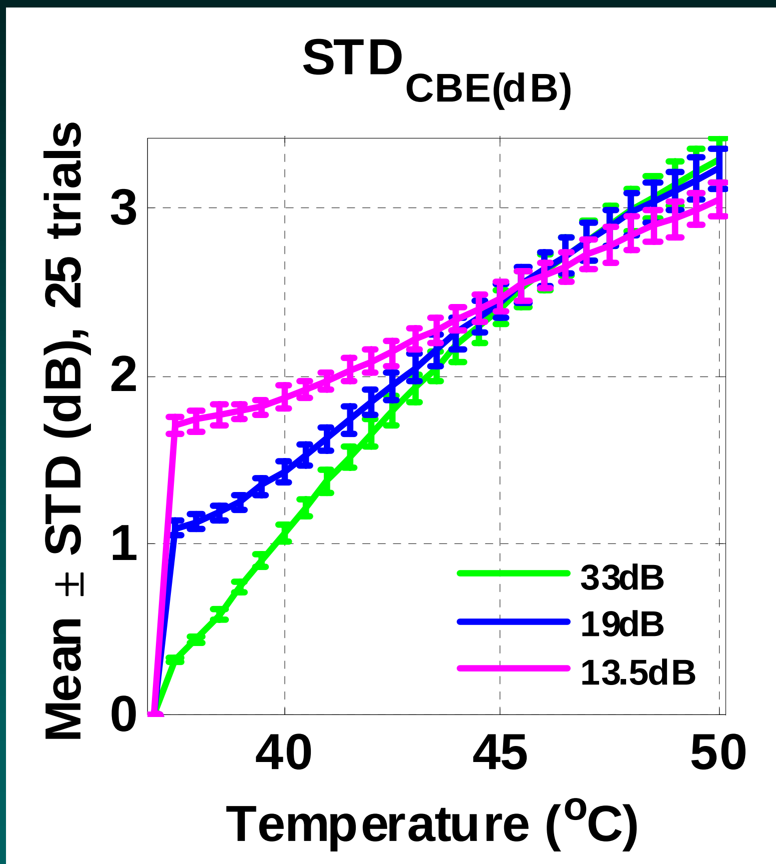
Multiple sub-wavelength scatterers (2:1 ratio of lipid to aqueous scatterers)

Change in Backscattered Energy from Simulated Images

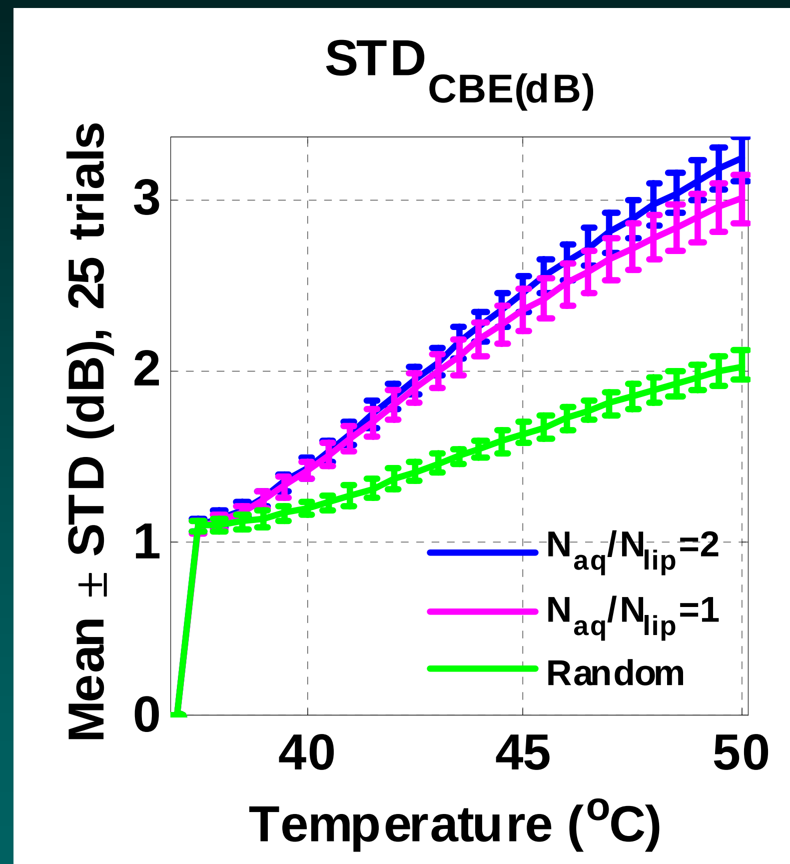


Region Size

Change in Backscattered Energy from Simulated Images

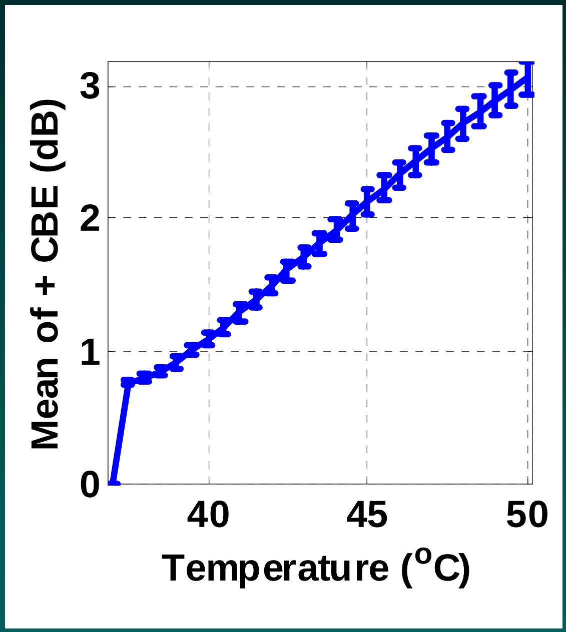


Signal-to-Noise

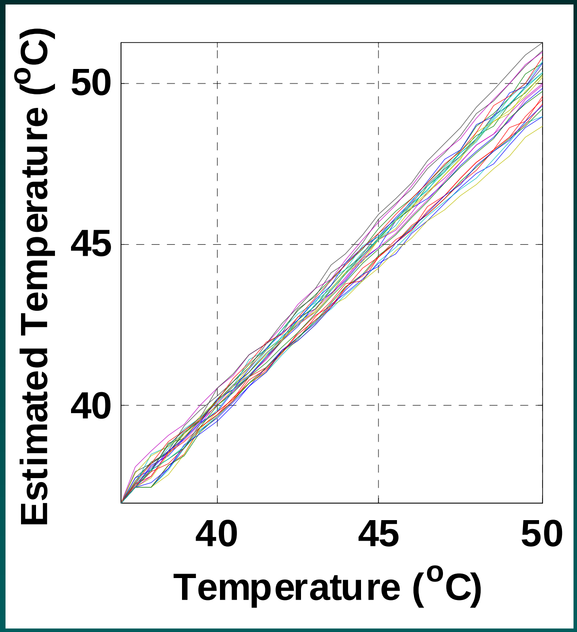


Scatterer Population

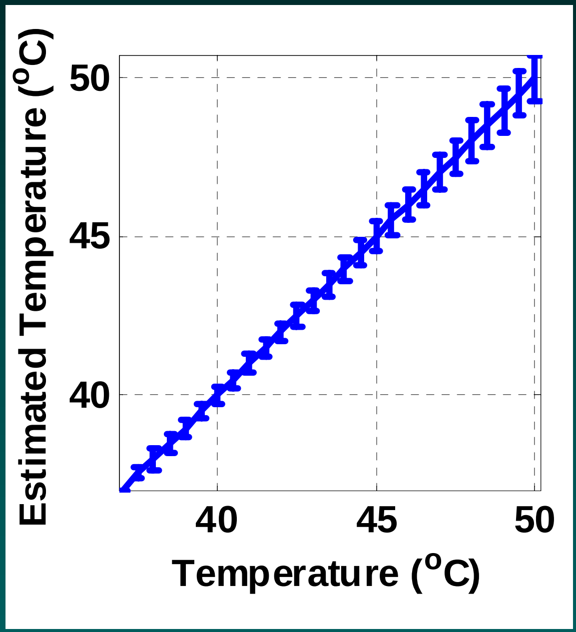
Temperature Estimation from CBE in Simulated Images



Calibration



Estimates



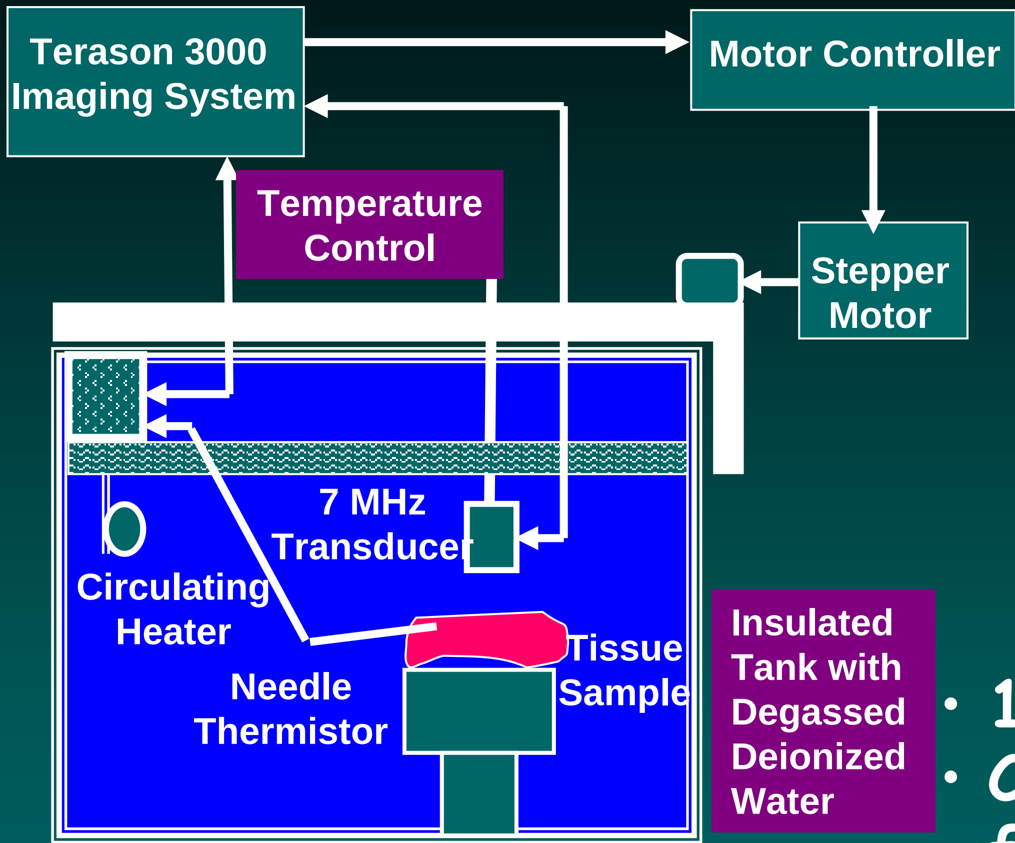
Errors

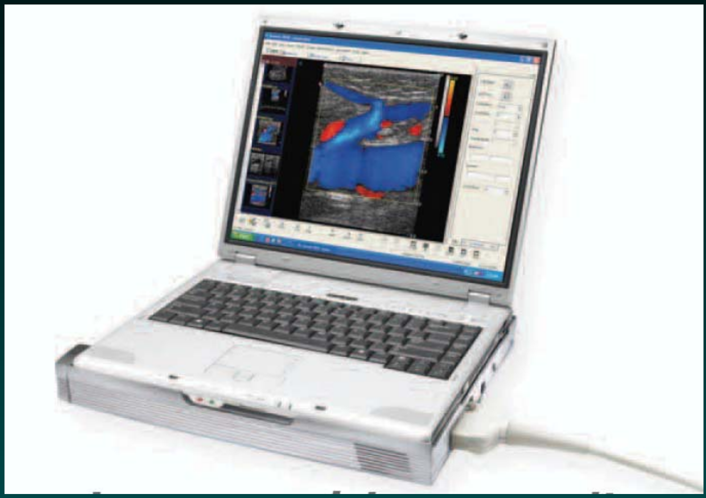
Temperature Estimation from CBE in Simulated Images

	Mean + CBE	Mean - CBE	STD CBE
Scatterer Population	Accuracy ($\pm^o$C)	Accuracy ($\pm^o$C)	Accuracy ($\pm^o$C)
$N_{aq}/N_{lip} = 2$ (baseline)	0.716	1.385	0.971
$N_{aq}/N_{lip} = 1$	0.897	1.649	1.116
Random f(T)	0.612	2.222	1.227
Signal-to-Noise Ratio			
13.5dB	0.917	1.839	1.175
19dB (baseline)	0.716	1.385	0.971
33dB	0.907	1.144	0.768
Region Size (cm^2)			
.5x.5	1.485	2.291	1.817
1x1 (baseline)	0.716	1.385	0.971
1x3	$\boxed{0.488}$	0.768	0.583

Accuracy (95%) in ^{o}C for estimating temperature at 44^{o}C

II. Temperature Estimation *in vitro*





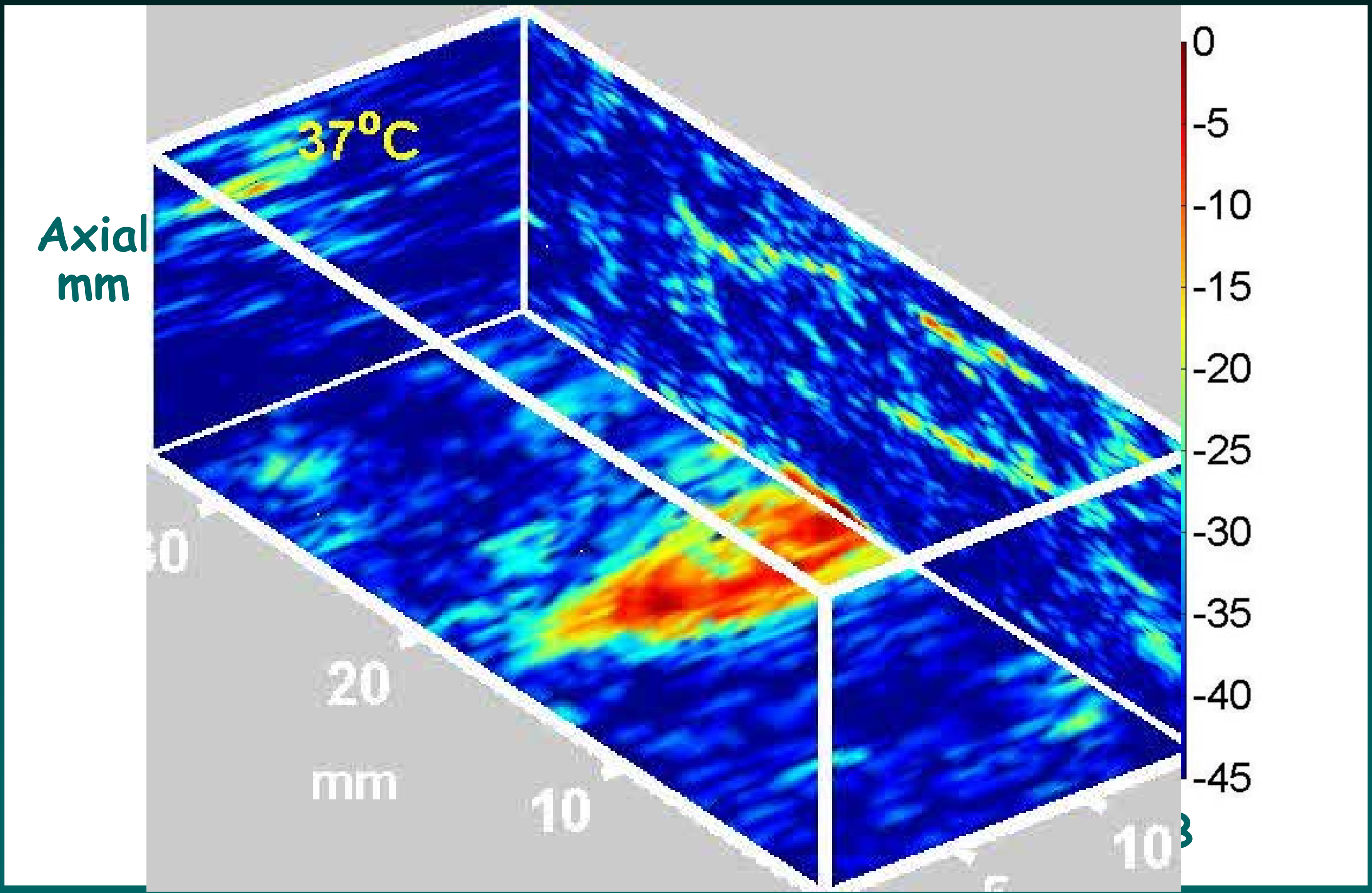
Terason 3000 (Teratech, Corp., Burlington, MA)

- 128 Element 7 MHz Array
- Control of temperature from 37 to 50°C and image acquisition with AutoIt®
- Access to RF signals

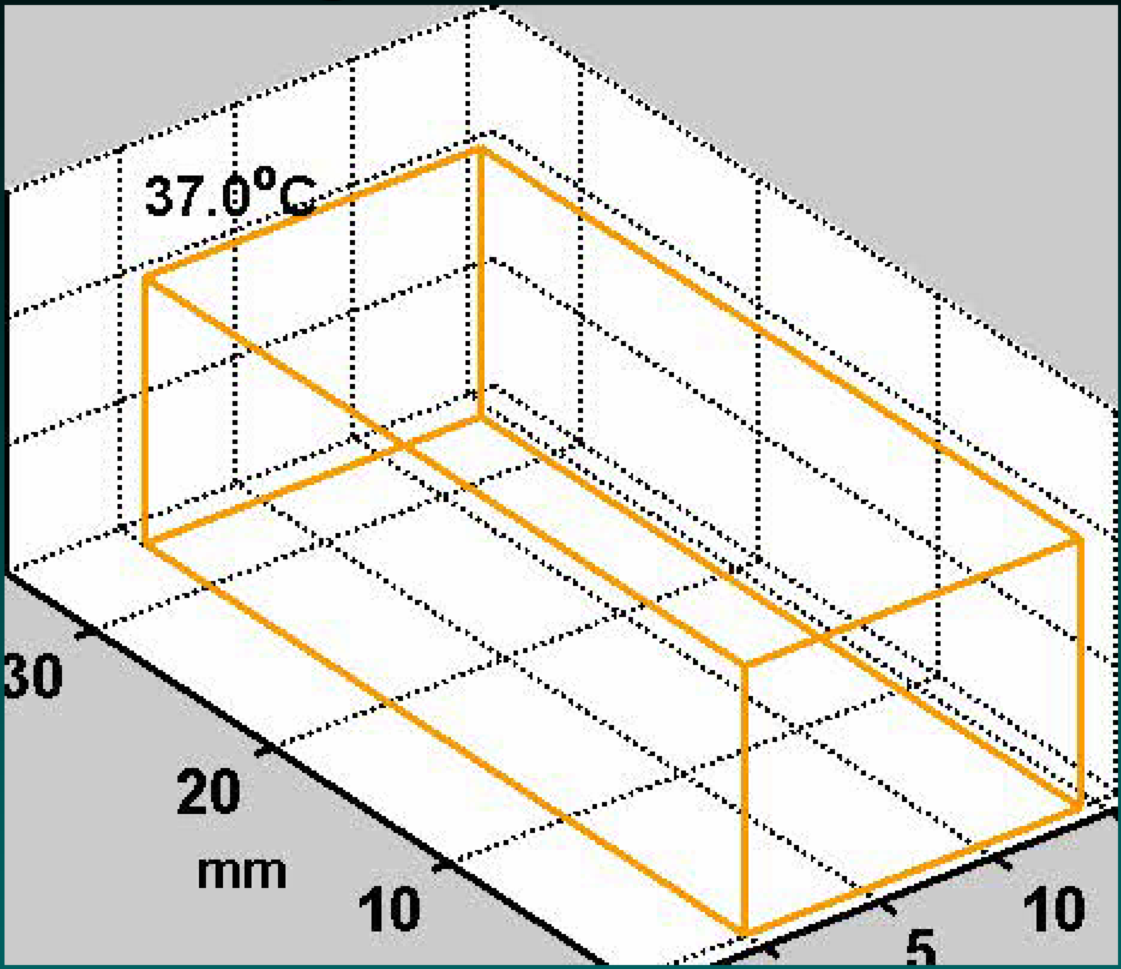
3D Dataset

Images were taken at 0.6 mm intervals in elevation at each temperature

Measured Backscattered Images in 3D from 37 to 50°C

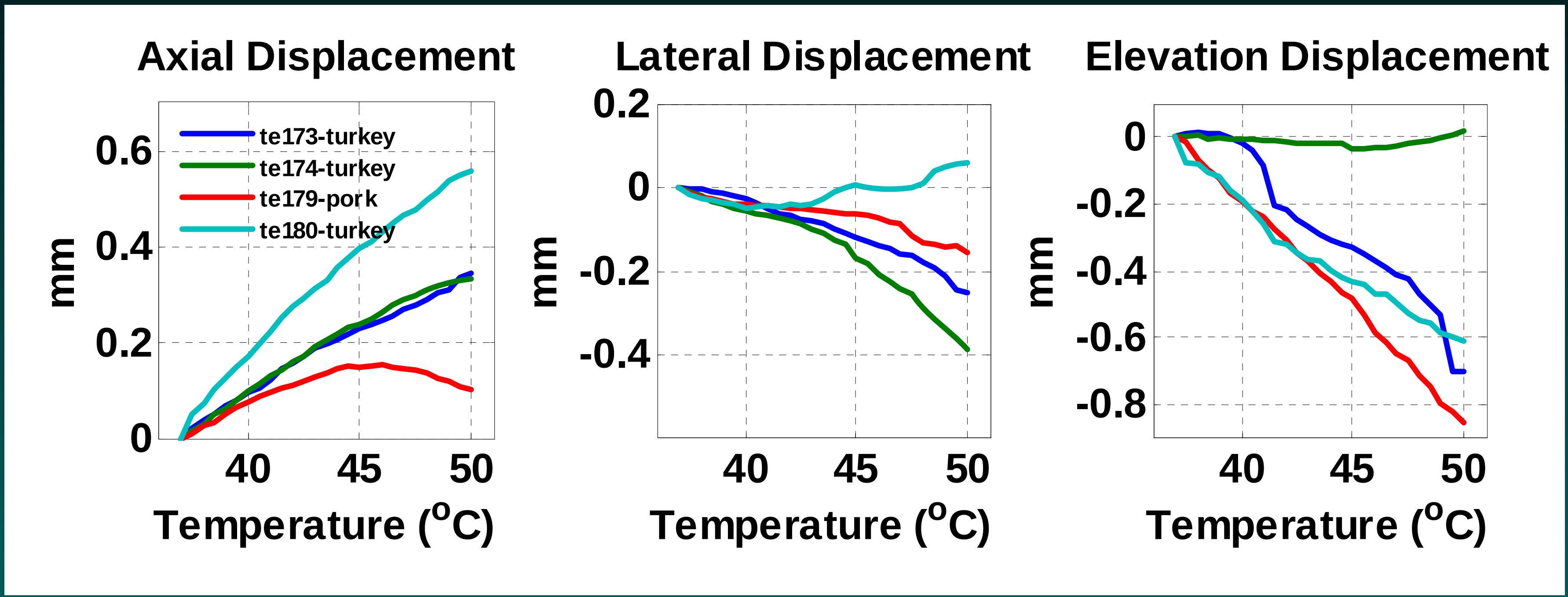


Non-Rigid Motion in 3D



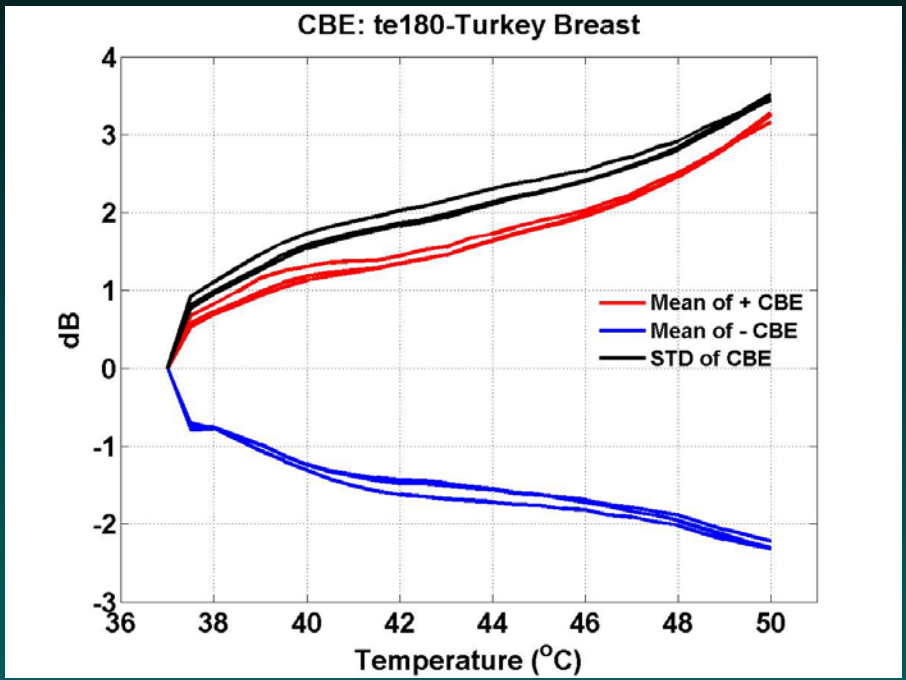
- Arrow lengths are 5X actual motion field
- Estimated using conventional optimization
- Comparable to motion seen previously in 2D

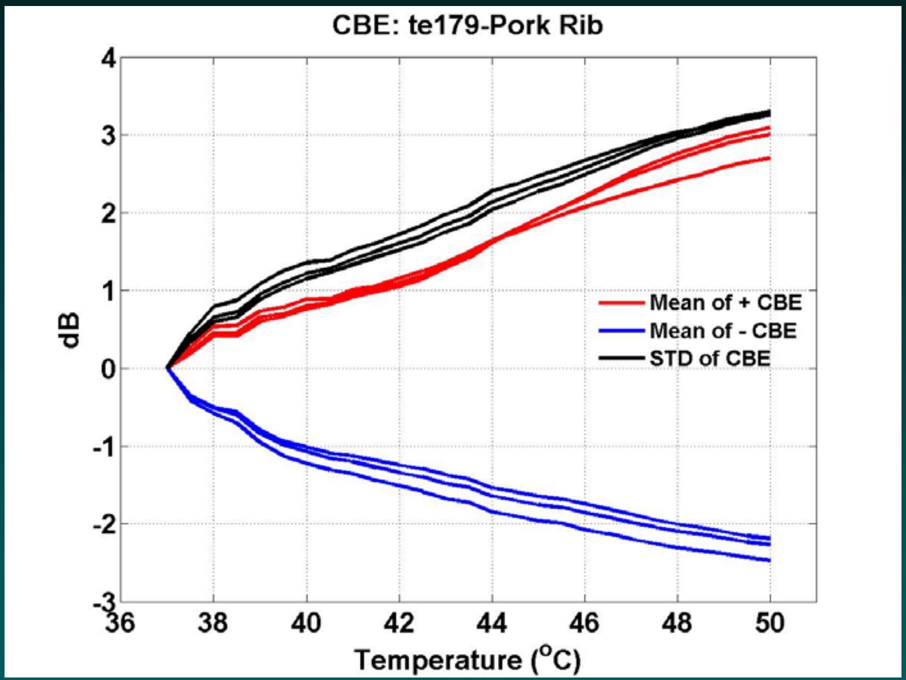
3D Motion with Temperature



Average Displacements in a 3 cm^3 Volume
for each Tissue Specimen

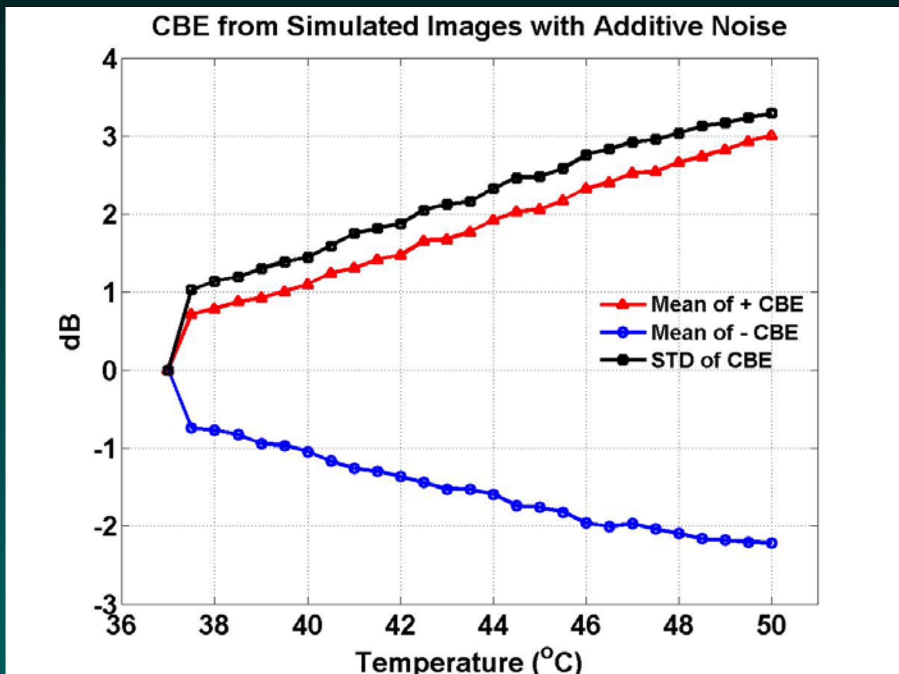
Change in Backscattered Energy



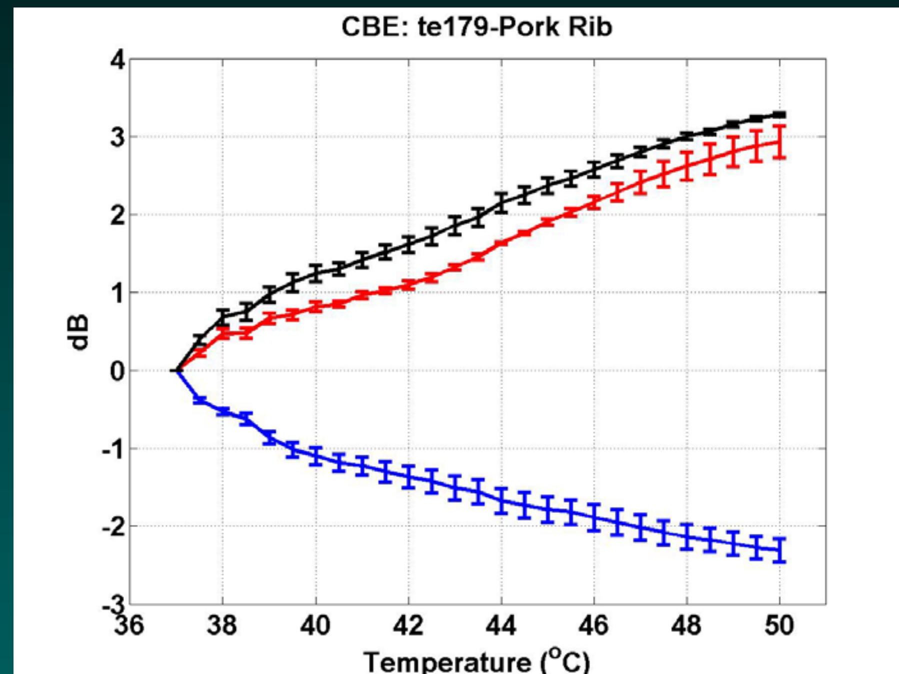


CBE Measures in Separate 1 cm^3 Volumes

Change in Backscattered Energy



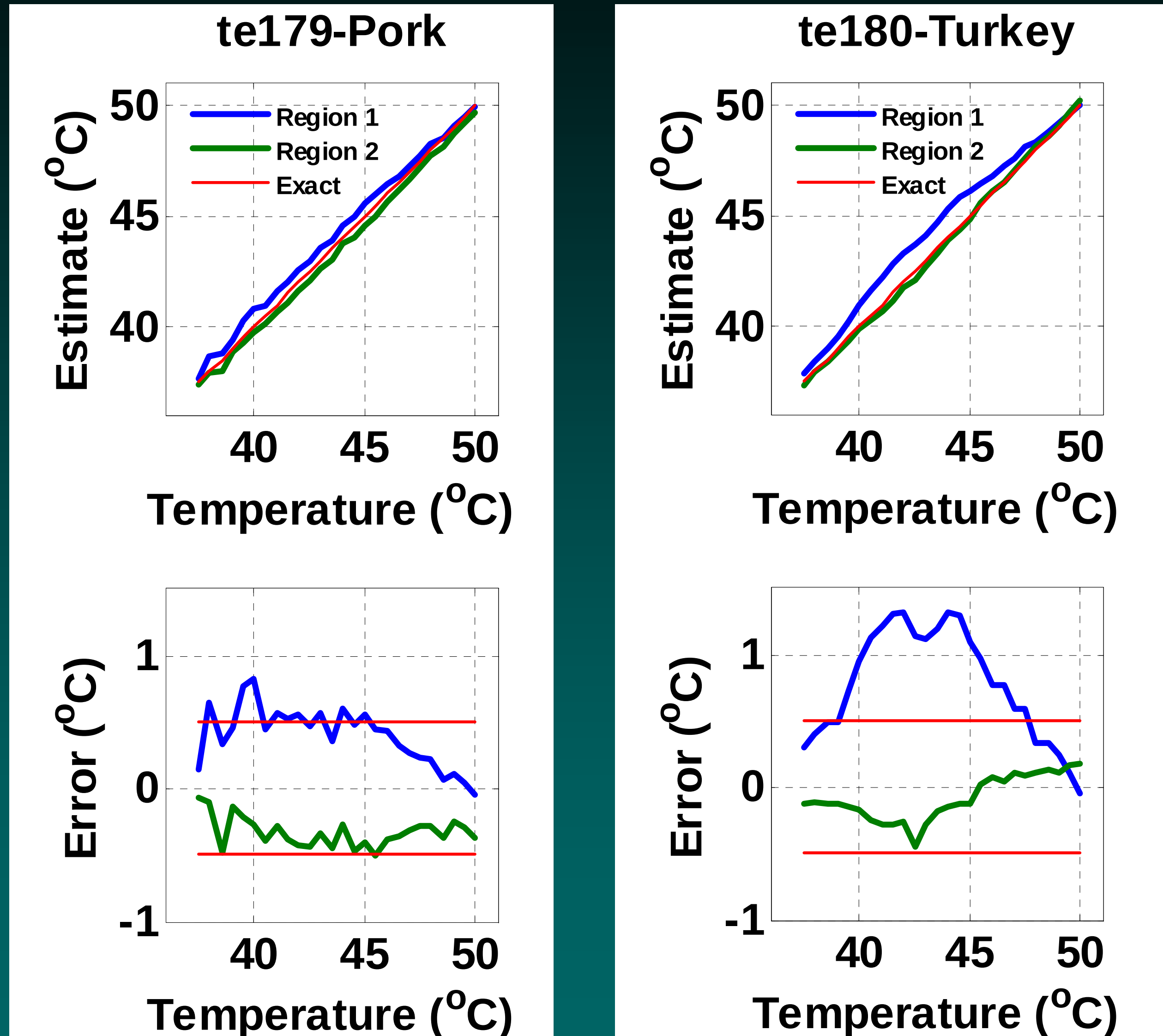
Simulated with Noise
(SNR=19dB)



Measured in 3D

Temperature Estimation in 3D

Estimation in two regions of 1 cm^3 each, based on calibration from a third cm^3 in the same tissue specimen



Summary & Conclusions

- Change in backscattered energy (CBE) was nearly monotonic & consistent in magnitude in
  - Predictions
    - Single-scatterer model
    - Multiple-scatterer simulations
  - Measured values
    - 1D isolated sites *in vitro* in liver, turkey & pork
    - 2D motion-compensated images in *in vitro* beef liver, turkey breast & pork muscle specimens
    - 2D compensated images *in vivo* in mice
    - 3D compensated images *in vitro* in turkey and pork
- We expect CBE to enable noninvasive temperature imaging for hyperthermia

Future Directions for Thermometry Based on Ultrasonic CBE

- Refinement of the CBE model
  - Histological study of scatterer distribution
  - Evaluation of images & CBE using simulation
- Development of clinically relevant heating and measurement systems
  - Small Animal Heating with Ultrasound
  - CBE imaging with Sonotherm heating system in humans