Echo decorrelation imaging for guidance of ultrasound ablation

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Overview

- Thermal ablation of liver cancer
- Echo decorrelation imaging
- Monitoring radiofrequency ablation *ex vivo* and *in vivo*
- Echo decorrelation imaging by image-ablate arrays: bulk and focused ultrasound ablation

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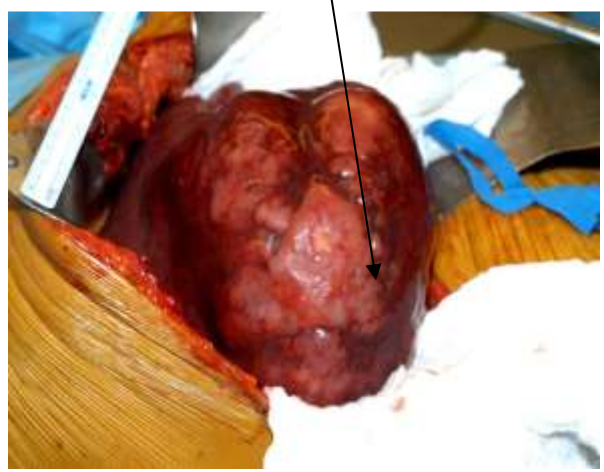
Target application: liver cancer

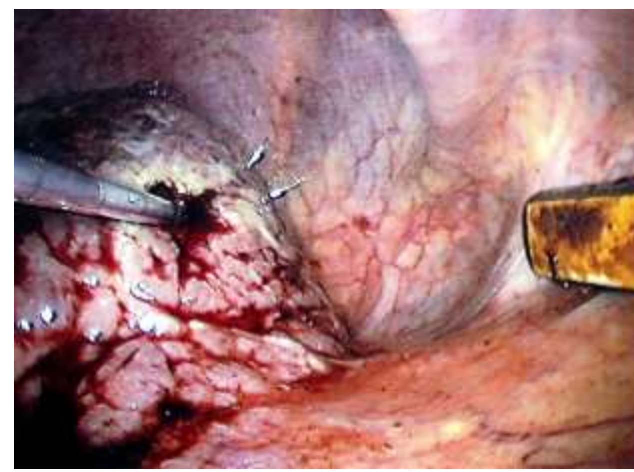
- Primary (hepatocellular carcinoma) or colorectal metastases
- Only ~15% of HCC cases are resectable
- Current standard for nonresectable tumors: minimally invasive, ultrasound-guided radiofrequency ablation (RFA)
- Desirable improvements: selectivity, reduced invasiveness, monitoring/control

HCC tumor

Palpable mass



Radiofrequency ablation



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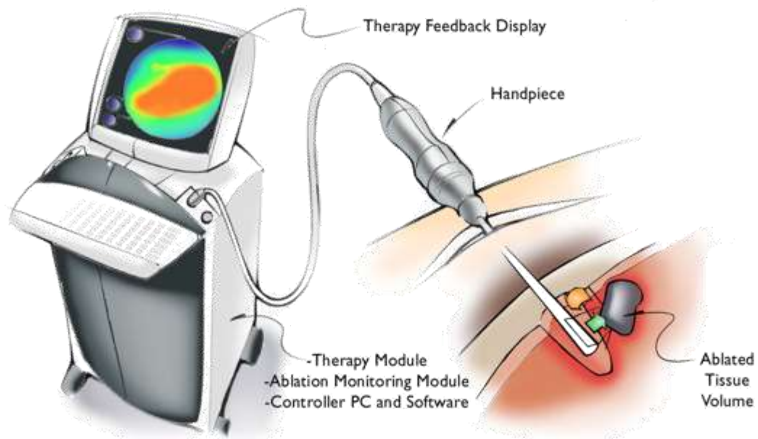
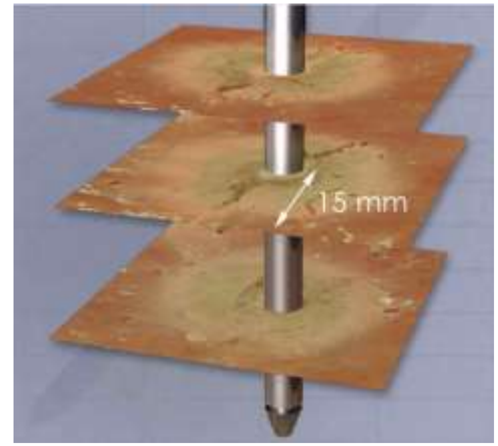
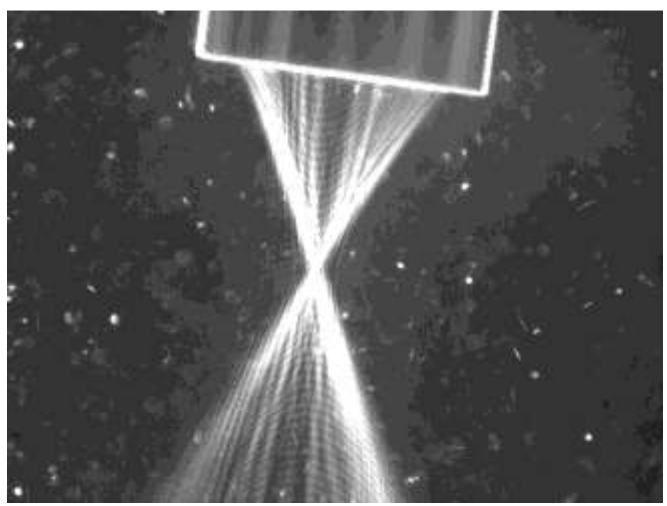
Ultrasound ablation for liver cancer

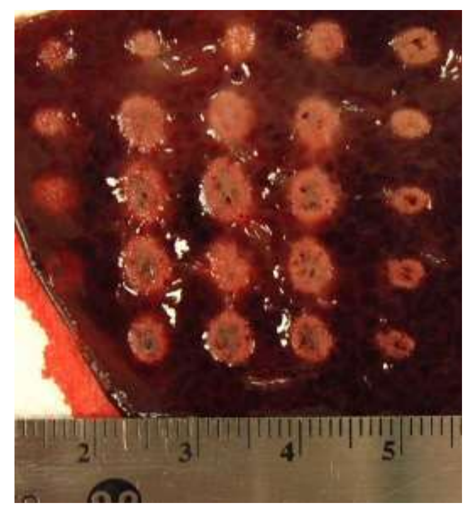
- Bulk ultrasound ablation: ~10-50 W/cm^2, unfocused/weakly focused for faster bulk tissue ablation
- Minimally invasive (interstitial/laparoscopic) like RFA





- Focused ultrasound: >200 W/cm^2, ablate smaller volumes





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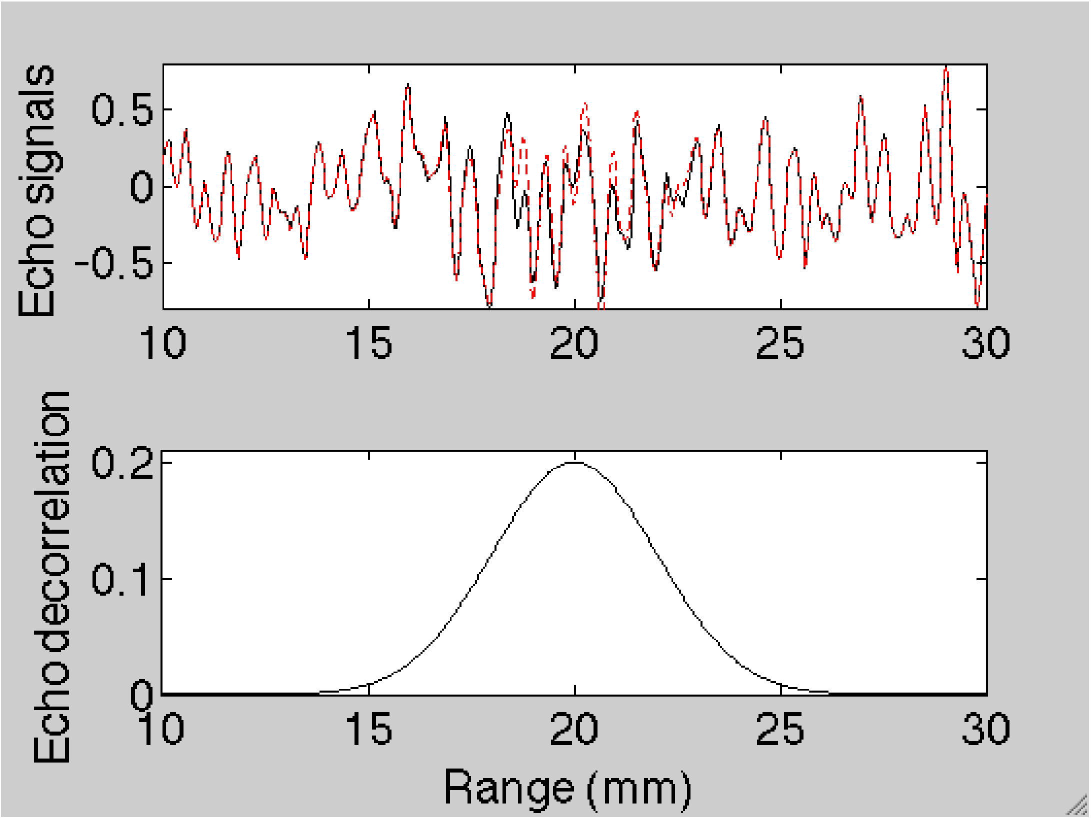
Echo decorrelation

- Ultrasound pulse-echo signals during ablation correlate imperfectly due to tissue state changes, gas activity, motion
- Challenge for correlation-based monitoring (US thermometry, elastography, etc.) during ablation
- Example: decorrelation of two echoes (real part of demodulated IQ signals)



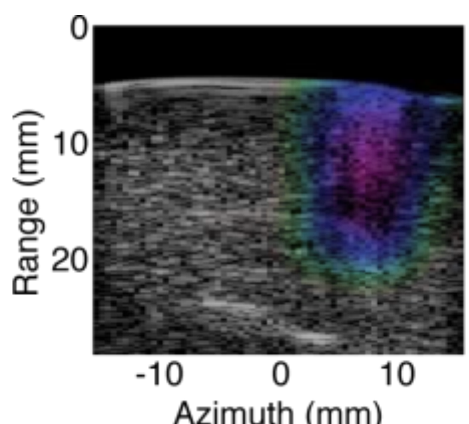
Echo decorrelation imaging

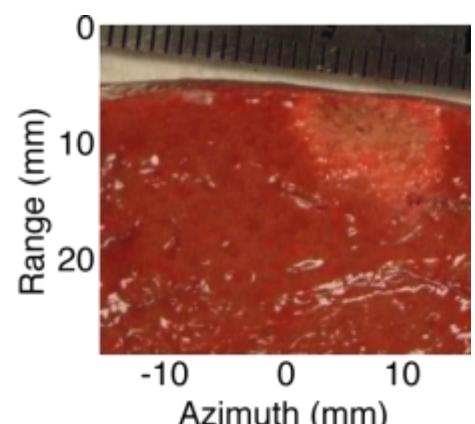
- Overall hypothesis: local echo decorrelation is caused by tissue changes associated with thermal ablation
- Map local echo decorrelation between adjacent image frames (~10-50 ms interframe time) in real time
- Position-dependent cross-correlation of complex pulse-echo image frames:

$$
\begin{aligned}
R_{01}(y,z) &= \iint w(y-y',z-z')\, I_0(y',z')^*\, I_1(y',z')\, dy'\, dz' \\
&= \langle I_0(y,z)^* I_1(y,z) \rangle
\end{aligned}
$$

- Echo decorrelation image:

$$\Delta(y,z) = 1 - \frac{|R_{01}(y,z)|^2}{R_{00}(y,z)\, R_{11}(y,z)}$$





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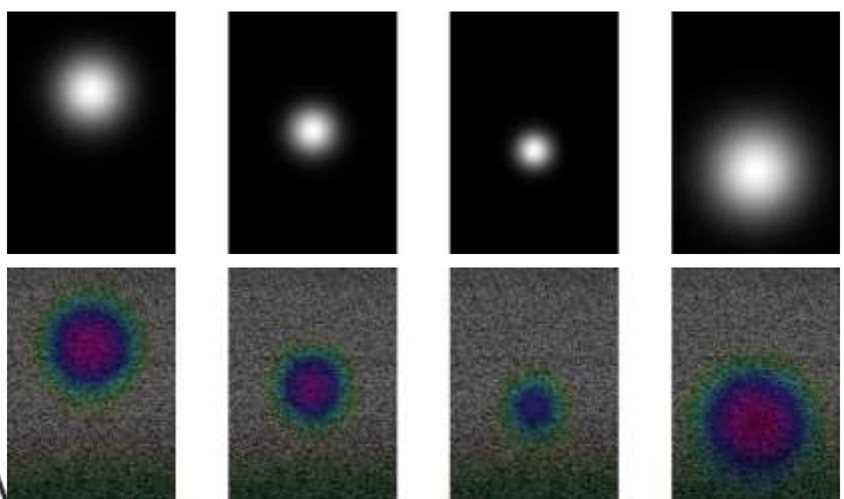
Relationship to tissue changes

- Theoretical model: backscatter $\propto$ spatial-frequency *power spectrum* of reflectivity γ
- Echo decorrelation $\propto$ spatial-frequency *decoherence spectrum* of tissue reflectivity:

$$E[\Delta(y,z)] \approx 1 - \rho(\delta\mathbf{r},y,z)\,\frac{\langle S_{\gamma_{01}}(2k_0\mathbf{e}_z,y,z)\rangle^2}{\langle S_{\gamma_{00}}(2k_0\mathbf{e}_z,y,z)\rangle\,\langle S_{\gamma_{11}}(2k_0\mathbf{e}_z,y,z)\rangle}$$

$$\approx 1 - \frac{S_{\gamma_{01}}(2k_0\mathbf{e}_z,y,z)^2}{S_{\gamma_{00}}(2k_0\mathbf{e}_z,y,z)S_{\gamma_{11}}(2k_0\mathbf{e}_z,y,z)}$$

- With tissue motion, echo decorrelation also depends on autocorrelation ρ of pulse-echo beam functions

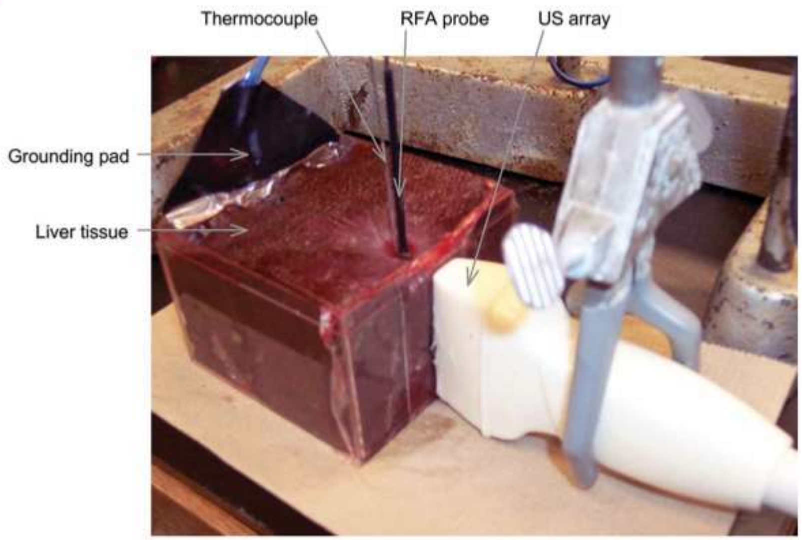


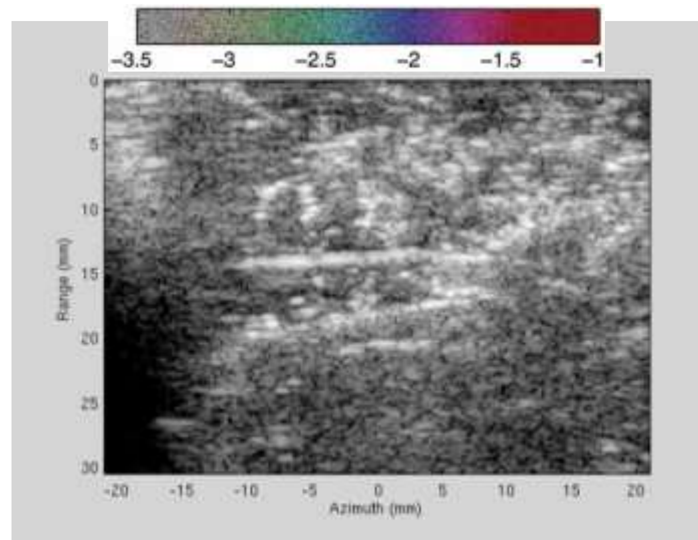
Reflectivity decoherence

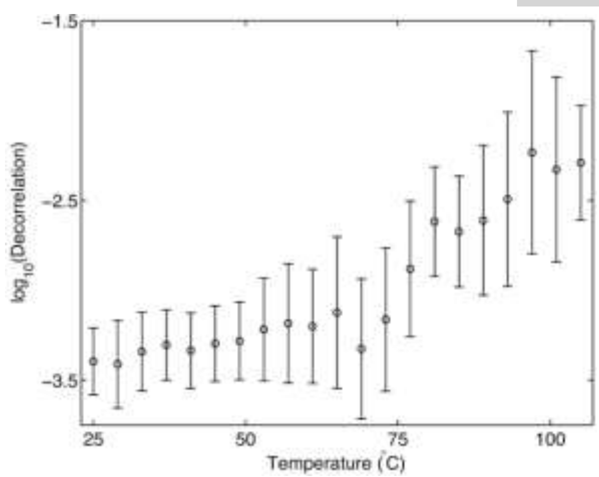
Simulated echo decorrelation

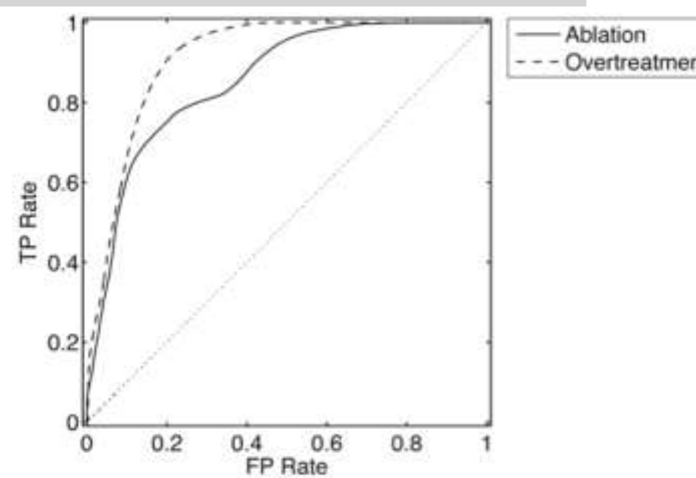
Ex vivo echo decorrelation imaging of RFA

- Clinical RFA needle in *ex vivo* bovine liver tissue, *N*=9
- Ultrasound imaging: 7 MHz linear array, 192 elements
- Hybrid images: B-scan, cumulative echo decorrelation





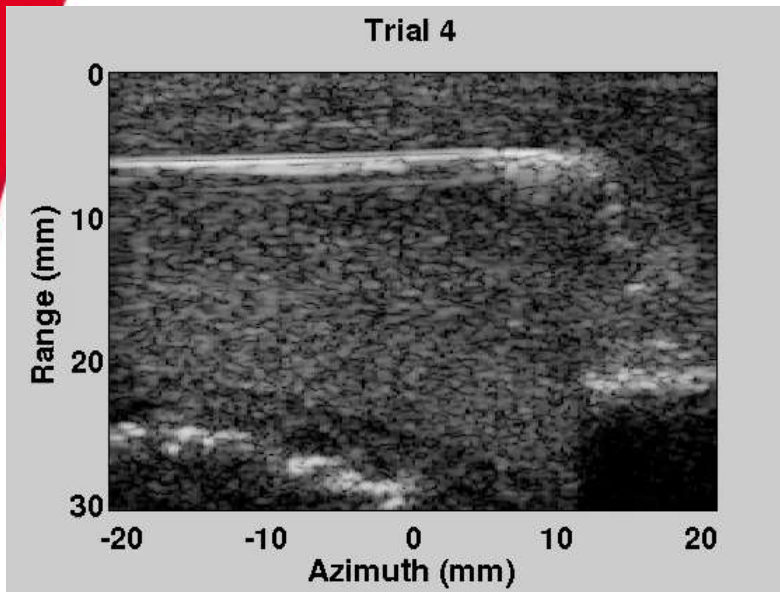


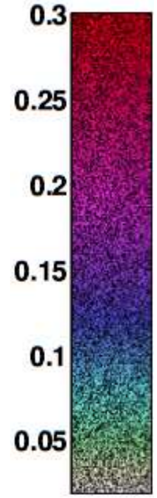


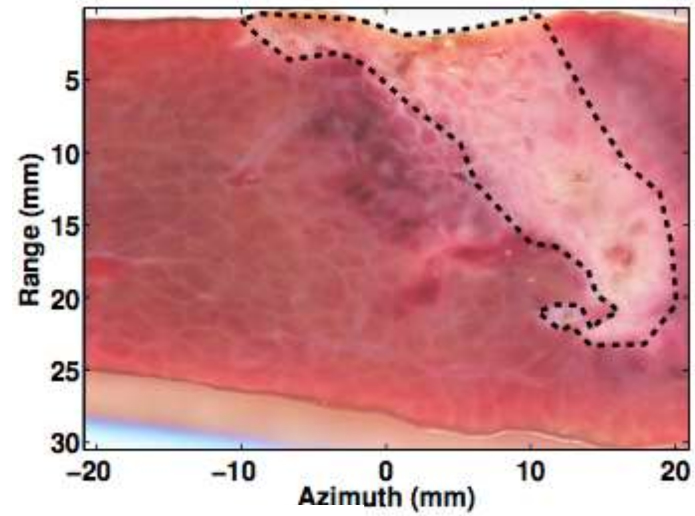
[Mast et al., J. Ultras. Med. 2008]

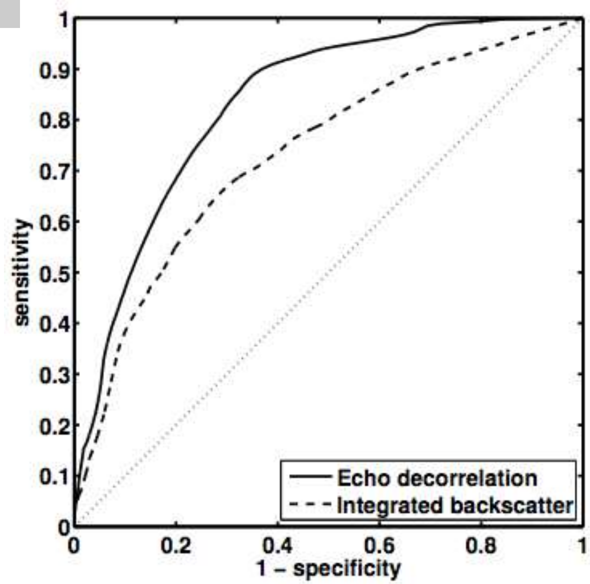
In vivo echo decorrelation imaging of RFA

- Ablation of swine liver, 20-60 W, 3-6 min, *N*=5
- Successful prediction of ablated tissue histology



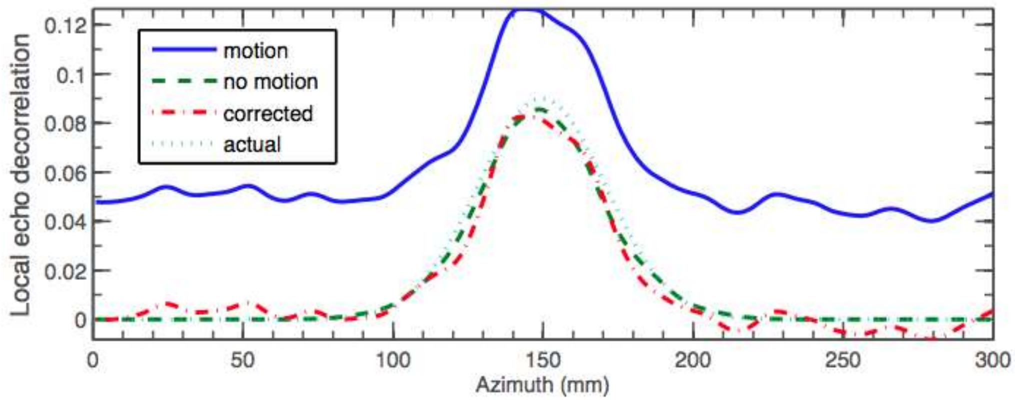






Motion correction of echo decorrelation

- Motion induced decorrelation depends on spatial autocorrelation of pulse-echo beam function
- Simulated correction using computed beams:



- *In vivo* correction from measured motion-induced decorrelation:

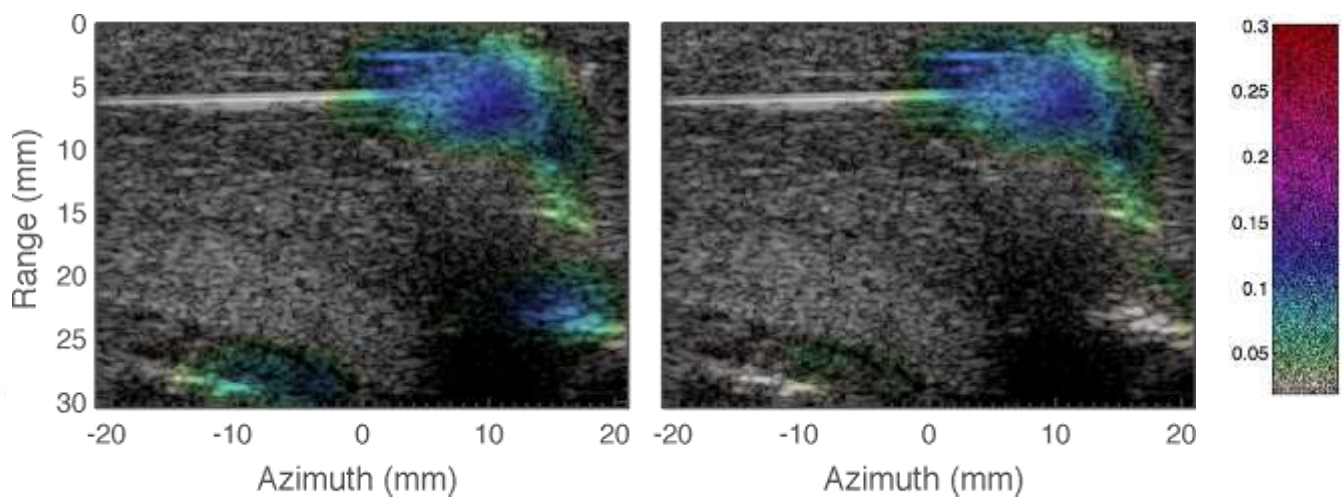


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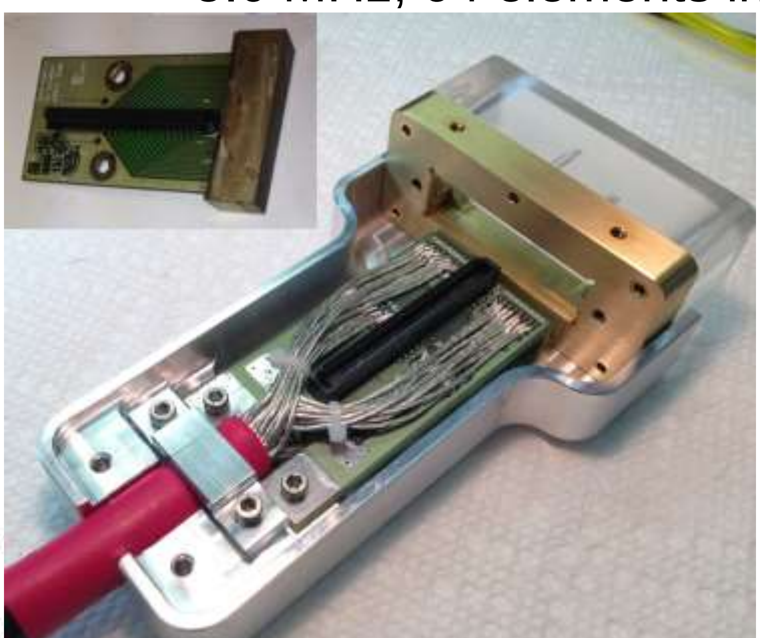
Image-ablate linear arrays

- Pulse-echo imaging and thermal ablation using same elements, ensuring monitoring/treatment of same volume
- 3.1-4.8 MHz, 32 elements in 3 mm needle

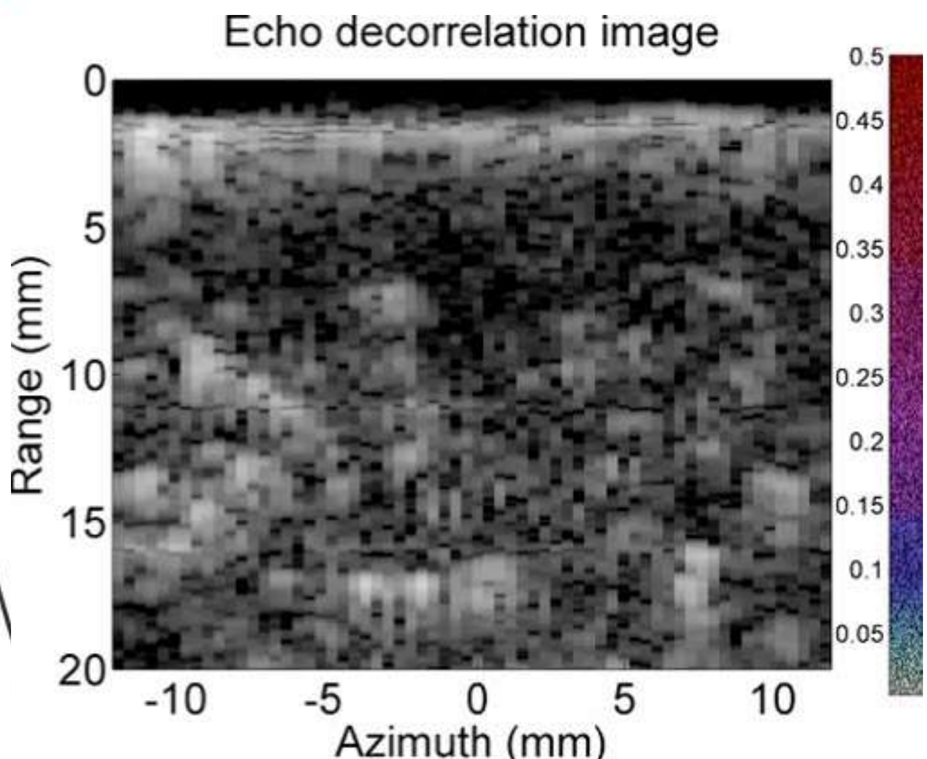
[Makin et al., J. Ultras. Med. 2005]

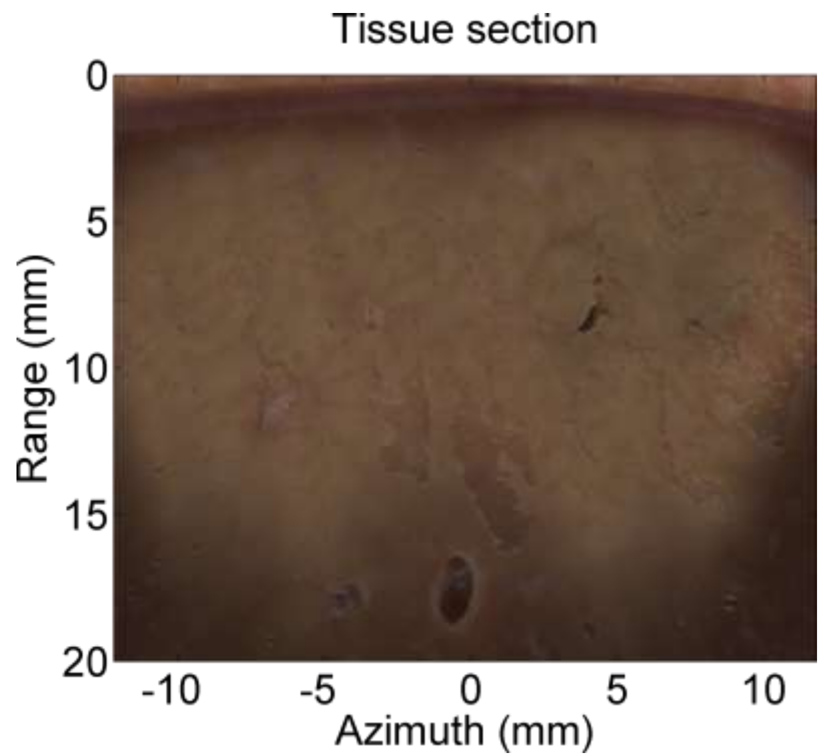
- 5.0 MHz, 64 elements in 24×5 mm^2 aperture



Echo decorrelation imaging by image-ablate arrays: *ex vivo* bulk ultrasound ablation

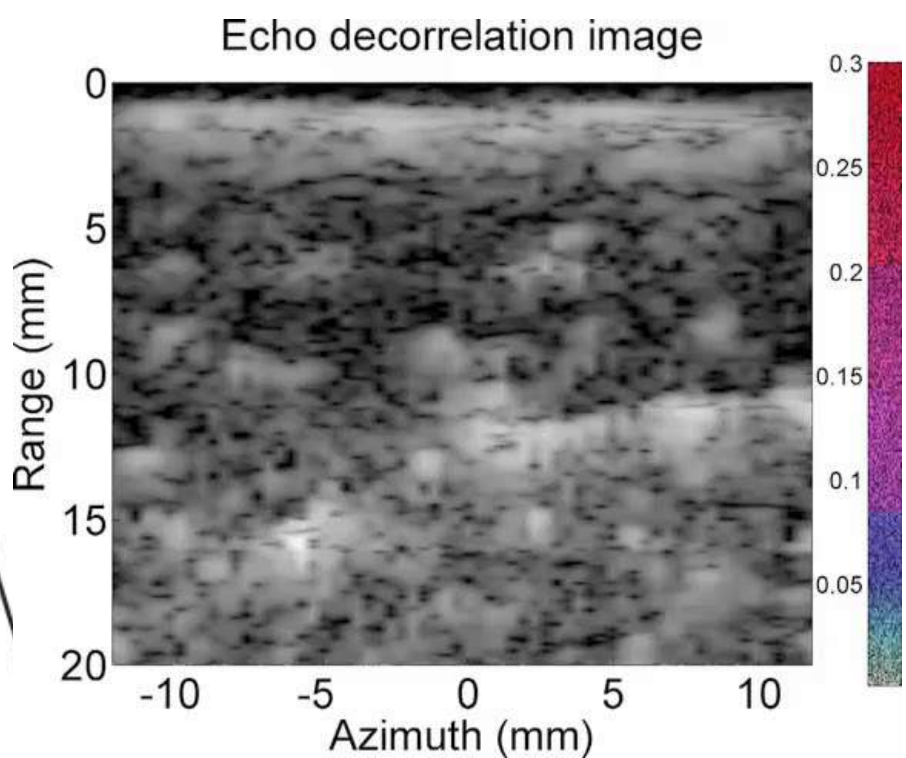
- 5.0 MHz, 24 mm aperture, unfocused
- 21 ablation pulses: 34 W/cm^2 SPTP, 5 s, imaging 4.3 fps
- Rest periods: 5 s, imaging 116 fps
- Widespread overall echo decorrelation, with late localized severe decorrelation (possible tissue boiling)

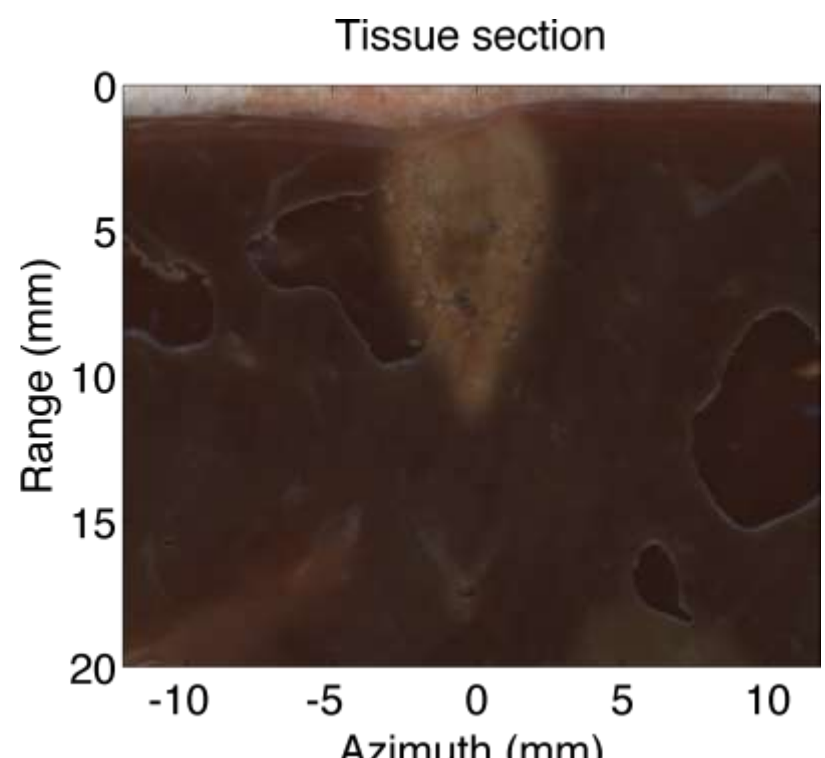




Echo decorrelation imaging by image-ablate arrays: *ex vivo* focused ultrasound ablation

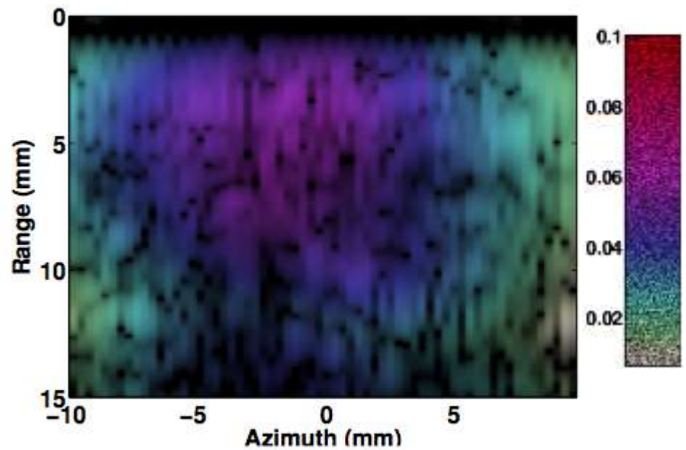
- 64-element arrays: image quality suitable for ablation targeting
- 5.0 MHz, 24 mm aperture, focused 10 mm past standoff (33 mm)
- 4 ablation pulses: 381 W/cm^2 SPTP, 5 s, imaging 4.3 fps
- Rest periods: 5 s, imaging 116 fps
- Echo decorrelation image consistent with expected lesion growth

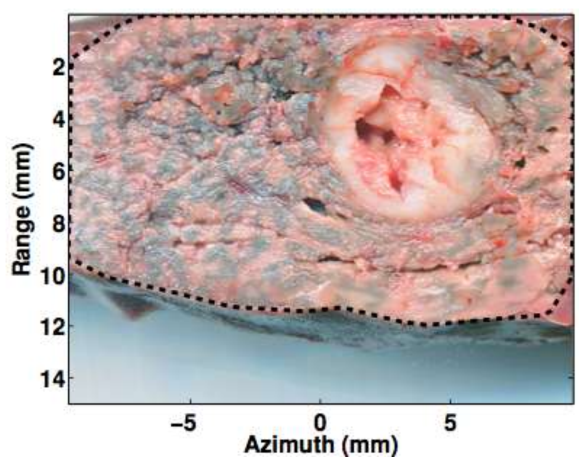


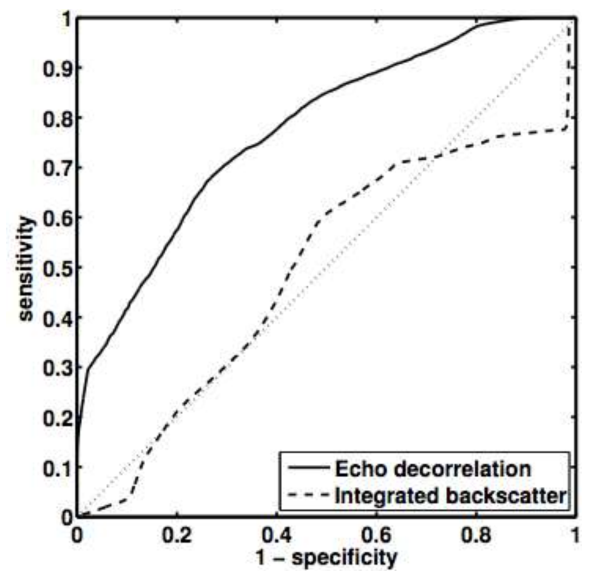


In vivo VX2 ablation by image-ablate arrays

- 3 mm, 32-element, 4.8 MHz arrays
- Unfocused 20 mm aperture, 95/120 s, 38.5 W/cm^2 SPTA
- Echo-decorrelation-guided ultrasound ablation feasible *in vivo*
- Future experiments to employ 64-element, 5.0 MHz arrays, bulk and focused ultrasound ablation







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Conclusions

- Echo decorrelation imaging predicts tissue ablation *ex vivo* and *in vivo*
- Echo decorrelation measures spatial-frequency decoherence of tissue reflectivity
- Motion effects *in vivo* can be effectively compensated
- Targeting, tissue ablation, and echo decorrelation imaging are feasible using image-ablate linear ultrasound arrays
- Ongoing work: test *in vivo* prediction of ablation-induced cell death, real-time control of thermal ablation for cancer treatment

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