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
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
Ultrasound ablation for liver cancer

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

- Focused ultrasound: \(>200\ \text{W/cm}^2\), ablate smaller volumes
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:

\[ R_{01}(y, z) = \int \int w(y - y', z - z') I_0(y', z')^* I_1(y', z') \, dy' \, dz' \]
\[ = \langle I_0(y, z)^* I_1(y, z) \rangle \]

• Echo decorrelation image:

\[ \Delta(y, z) = 1 - \frac{|R_{01}(y, z)|^2}{R_{00}(y, z) R_{11}(y, z)} \]
Relationship to tissue changes

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

$$E[\Delta(y, z)] \approx 1 - \rho(\delta r, y, z) \frac{\langle S_{\gamma01}(2k_0e_z, y, z) \rangle^2}{\langle S_{\gamma00}(2k_0e_z, y, z) \rangle \langle S_{\gamma11}(2k_0e_z, y, z) \rangle} \approx 1 - \frac{S_{\gamma01}(2k_0e_z, y, z)^2}{S_{\gamma00}(2k_0e_z, y, z)S_{\gamma11}(2k_0e_z, y, z)}$$

- With tissue motion, echo decorrelation also depends on autocorrelation $\rho$ 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:
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
  - 5.0 MHz, 64 elements in $24 \times 5 \text{ mm}^2$ aperture

Echo decorrelation imaging by image-ablate arrays: \textit{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 image](image1)

![Tissue section](image2)
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/cm² SPTA
- Echo-decorrelation-guided ultrasound ablation feasible *in vivo*
- Future experiments to employ 64-element, 5.0 MHz arrays, bulk and focused ultrasound ablation
Conclusions

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