THERMOACOUSTIC RANGE VERIFICATION DESPITE ACOUSTIC HETEROGENEITY AND SOUNDSPEED ERRORS

S. K. Patch†, UW-Milwaukee & A.R.E.  
B. Mustapha, Argonne National Laboratory  
D. Santiago-Gonzalez, Argonne National Laboratory
Particle therapy can minimize collateral damage

Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds
Particle therapy can maximize collateral damage

Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds
Particle therapy can maximize collateral damage

Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds
Patient Positioning is Critical

Patient Positioning Systems (PPS) use “room coordinates”
Patient Positioning is Critical

Patient Positioning Systems (PPS) use absolute coordinates.

Treatment Planning based upon x-ray CT ("CAT scan")
- images reconstructed in absolute coordinates
- acquired days/weeks prior to treatment, repeated infrequently

<table>
<thead>
<tr>
<th>Modality</th>
<th>Coordinates</th>
<th>Physical interpretation</th>
<th>cost / mass / scan time</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray CT</td>
<td>absolute</td>
<td>$\rho$, “density”</td>
<td>$$$, 1 ton, seconds</td>
</tr>
<tr>
<td>MRI</td>
<td>quasi-absolute</td>
<td>H density + relaxation times</td>
<td>$$$, 1 ton, minutes</td>
</tr>
<tr>
<td>PET</td>
<td>absolute (low res.)</td>
<td>511 keV emissions</td>
<td>$$$, 1 ton, many minutes</td>
</tr>
<tr>
<td>ultrasound</td>
<td>relative to soundspeed</td>
<td>$Z$, acoustic impedance</td>
<td>$, 3 lbs, seconds</td>
</tr>
<tr>
<td>thermoacoustic</td>
<td>relative to soundspeed</td>
<td>induced pressure = $\Gamma \rho$ dose</td>
<td>$, 4 lbs, seconds</td>
</tr>
</tbody>
</table>
Thermoacoustic Signal Generation

\[ p_o(x) = \Gamma \left( \frac{E}{V} \right) (x) \]  

instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC instantaneously
Thermoacoustic Signal Generation

\[ p_o(x) = \Gamma \left( \frac{E}{V} \right)(x) \] instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC in 2 \( \mu s \)

initial pressure > 0
Thermoacoustic Signal Generation

\[ p_o(x) = \Gamma \left( \frac{E}{V} \right)(x) \] instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC in 2 \( \mu s \)
Thermoacoustic Signal Generation

\[ p_o(x) = \Gamma \left( \frac{E}{V} \right)(x) \] instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC in 2 μs
Thermoacoustic Signal Generation

\[ p_0(x) = \Gamma \left( \frac{E}{V} \right)(x) \] instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC in 2 μs

\[ \text{pressure} > 0 \]

\[ \begin{align*}
\text{Pa} \\
\mu s
\end{align*} \]

\[ \begin{align*}
\text{Pa} \\
\mu s
\end{align*} \]
Thermoacoustic Signal Generation

\[ p_0(x) = \Gamma \left( \frac{E}{V} \right)(x) \] instantaneous deposition

\[ \Gamma \sim 0.1 \text{ in water, 0.2 in muscle and organ, 0.7 in fat} \]

49 MeV: 4 pC in 2 \( \mu \text{s} \)

DuHamel says

Obey stress confinement: Build up pressure faster than it runs away

2D-kwave sim
Thermoacoustics History

Emissions detected in fluids (in late 70’s): Sulak et al, Askariyan, et al

Emissions detected in patients (mid ‘90s): Hayakawa, et al

Recent resurgence (2013 – present): Parodi, Jones/Avery, SKP

However, until recently primary criticism was errors (absolute) induced by soundspeed inhomogeneity.

Synchrocyclotron pulse durations $\leq TOF \sim 2 \text{ HWHM} / v_s$
- $6\ \mu s$ Mevion@WUSTL;
- $4.5 - 5\ \mu s$ (IBA S2C2 @ Newport)
Thermoacoustics @ ATLAS

low E beams
- particle range < 2.5 mm
- minimal straggle, sharp Bragg curve
- fast delivery for stress confinement
- bandwidth in ultrasound regime, detect TA emissions with 1-4 MHz ultrasound array

TRANSDUCER

(b)
60-120 mm of phantom
HWHM < 150 μm

range in target (mm)

(kJ/m³ ~ Gy) \times 10^{-7}
Thermoacoustics @ ATLAS

low E beams
- particle range < 2.5 mm
- minimal straggle, sharp Bragg curve
- fast delivery for stress confinement
- bandwidth in ultrasound regime, detect TA emissions with 1-4 MHz ultrasound array
Thermoacoustics @ ATLAS

60 MeV 4He
- Ti foil vacuum exit window
- acrylic tape liquid entry window
- 165 pA average current, 100 Hz PRF
- FWHM: 3.9 mm horiz. / 6.9 mm vert.
- safflower oil target
- CIRS bone and in-house gelatin
Thermoacoustics @ ATLAS

60 MeV 4He
- Ti foil vacuum exit window
- acrylic tape liquid entry window
- 165 pA average current, 100 Hz PRF
- FWHM: 3.9 mm horiz. / 6.9 mm vert.
- safflower oil target
- CIRS bone and in-house gelatin
Spatial variations deform US; shift thermoacoustic

Benchtop Prep with “visible” acoustic source

channel data from H20M56

Rx beamform

B-mode=Tx/Rx beamform
Spatial variations deform US; shift thermoacoustic

Benchtop Prep with “visible” acoustic source + acoustic scatterers
Spatial variations deform US; shift thermoacoustic ATLAS without scatterers, $z_{peak} = (-11.6, 121.8)$ with scatterers, $z_{peak} = (-8.8, 118.1)$
Conclusions

- Thermoacoustic range verification is robust to acoustic heterogeneity \textit{relative to ultrasound image}
- CT-ultrasound co-registration is a solved problem, sold by most major vendors
- Preliminary measurements w/ IBA S2C2 encouraging, but lots of work still to do

W/ J. Lambert, Rutherford Cancer Center Newport