Ionoacoustics for Proton Range Verification

SK Patch, Acoustic Range Estimates

Y Hao, Washington University in St Louis

$t = 10 \mu s$

$t = 46 \mu s$

$t = 57 \mu s$

$t = 24 \mu s$
Thermoacoustic Signal Chain

I. Energy deposited by particle beam
II. tissue heats & increases pressure
III. thermoacoustic pulses propagate away
IV. acoustic receivers somehow detect pressure changes
V. data processing, i.e. math: image reconstruction, Bragg peak localization . .
I. Energy deposited by particle beam

a) Units: \([E/V] = J/m^3 = N/m^2 = \text{Pascal}\)

b) Deposition rate

micro: 1 proton stops from \(O(10^8 \text{ m/s})\) within just a few ns

macro: many protons in pulse w/envelope \(I\) (hardware limited)

Various pulse envelopes, \(I(t)\), with FWHM from 250 ns to 4-5 \(\mu\text{s}\).

(generally) stress-confined...
Importance of Stress Confinement

Positive (compression) followed by weak negative (rarefaction)

49 MeV, 4 pC single-turn extraction

bipolar thermoacoustic signal
Importance of Stress Confinement

Destructive interference when stress confinement fails.

4 pC over 2 μs @ 10 MHz

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

• straggle of degraded clinical beam broadens Bragg curve

degraded 227 MeV in 6 μs
I. Energy deposited by EM photons or charged particles

a) Units: \([E/V] = J/m^3 = N/m^2 = \text{Pascal}\)

b) Deposition rate

OBEY STRESS CONFINEMENT – HIGH INSTANTANEOUS DOSE RATE BEST

c) Spatial variations – due to unknown tissue parameter, \(\Gamma\)

\[
p_o = \Gamma \frac{E}{V} \quad \text{where} \quad \Gamma \text{is conversion efficiency (E density to pressure)}
\]

\[
p_o = \Gamma \rho D \quad \text{where} \quad D = \text{dose in Gy}
\]

<table>
<thead>
<tr>
<th>Tissue</th>
<th>HU range</th>
<th>SOS (m/s)</th>
<th>(\Gamma)</th>
<th>(\rho) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>(-1000, -200)</td>
<td>343</td>
<td>0.376</td>
<td>1.2</td>
</tr>
<tr>
<td>fat</td>
<td>(-200, -50)</td>
<td>1480</td>
<td>0.877</td>
<td>920</td>
</tr>
<tr>
<td>muscle, organ</td>
<td>(-50, 100)</td>
<td>1540</td>
<td>0.208</td>
<td>1040</td>
</tr>
<tr>
<td>bone</td>
<td>(100, +1000)</td>
<td>3200</td>
<td>0.788</td>
<td>2000</td>
</tr>
</tbody>
</table>

Plateau in bone generates stronger signal that Bragg peak in prostate

Analysis: Thermoacoustic *Tomography*

Measurement aperture surrounds object.

Range Verification permits only limited measurement aperture.

2D sinogram

stacks of 2D reconstructions TUFFC 63(2), (2016)
Brief History of Thermoacoustic Range Verification

1979 - early work at National Labs (US & USSR)

1990s – fast extraction synchrotron studies in Japan
• Tada J, Hayakawa Y, Hosono K and Inada T 1991 Time resolved properties of acoustic pulses generated in water and in soft tissue by pulsed proton beam irradiation—a possibility of doses distribution monitoring in proton radiation therapy Med. Phys. 18 1100-4
Background on Thermoacoustic Range Verification

21st century - renewed interest


2015
- Assmann W et al. Ionoacoustic characterization of the proton Bragg peak with submillimeter accuracy Med. Phys. 42
- Alsanea F, Moskvin V and Stantz K M Feasibility of RACT for 3D dose measurement and range verification in a water phantom Med. Phys. 42
- Patch lab (LBNL 2016, WUSTL 2018, ANL 2019)

Recent experimental results generated by clinical synchrocyclotrons
- Patch, et al. Thermoacoustic range verification during pencil beam delivery of a clinical plan, Radiother & Oncology, 2021
- more and more...

hypofractionated 6 Gy clinical delivery to anthropomorphic hydrogel phantom

high dose in research mode delivery to water
- 12-layer, single field RT plan
- 6 Gy/fraction to liver
- hydrogel imaging phantom (CIRS 057a)
- IBA ProteusOne w/S2C2, paused between layers
- remote readout via digital scope (Siglent)
- 4 TA receivers + US array

Dose close to acoustic hardware,
Pinpoint Receiver Locations
by manual co-reg in 3D Slicer

Multiplanar reformat by tipping coronal to match ultrasound image.

Fiducials placed to mark
- center of ultrasound array (F3)
- centers of thermoacoustic receivers (F53, F56)
Thermoacoustic Simulations – combines Monte Carlo energy density maps w/acoustic software

Monte Carlo by MC2 package in OpenReggui
- inputs: planning CT, RT plan, CT and beam calibrations (M Cohilis)
- model energy density actually delivered by using system log files
- accounted for range shifter (K Souris)

k-Wave acoustic software (key features)
- custom script takes inputs: RT plan, beamlet energy maps, planning CT, HU ranges for tissue types, receiver locations, tissue properties (soundspeed, density, Grüneisen), planning MRI & US should be used also
- accounts for proton pulse envelope, measured by gamma detector
- segments tissue based upon CT and assigns soundspeed, Grüneisen, and density
- records thermoacoustic signals at receiver locations, can make movie
2nd layer results. 148.5 MeV – measured in thick, simulated thin

Path from Spot A to receivers:
- clear to Rx 1 & 2 (red & blue)
- obstructed to Rx 3 & 4 (cyan & magenta)

Notes for Ch 1-2 signals:
- simulated is zero until arrival of “N” from Bragg Pk
Table 2. Time shifts between measured and simulated data in abdominal phantom.

<table>
<thead>
<tr>
<th>layer</th>
<th>spot</th>
<th>#pul</th>
<th>LR (mm)</th>
<th>$p_0$ (Pa)</th>
<th>$\delta x$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>A</td>
<td>23.0</td>
<td>-74</td>
<td>5.0</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>23.0</td>
<td>-74</td>
<td>5.1</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>23.0</td>
<td>-74</td>
<td>5.0</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>20.0</td>
<td>-75</td>
<td>10.1</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>21.0</td>
<td>-75</td>
<td>8.5</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>23.0</td>
<td>-76</td>
<td>10.3</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

-0.2 ± 0.7 mm
$\sigma = 0.7 \text{ mm} < 1.19 \text{ mm}$

Radiother & Oncol 2021
simplified “2-step” method
Med Phys 2018
### High dose rate therapy may enable pulse-by-pulse verification

<table>
<thead>
<tr>
<th>ion</th>
<th>E (MeV)</th>
<th>PW (us)</th>
<th>q/pulse (pC)</th>
<th># pulses</th>
<th>target</th>
<th>accuracy (mm)</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>148-156</td>
<td>4-5</td>
<td>O(1)</td>
<td>20-23</td>
<td>CIRS gel</td>
<td>-0.2 +/- 0.7</td>
<td>Green J, 159, pp. 224-230, (2021). S2C2 synchrocyclotron delivered clinical plan; custom receivers to oscilloscopes</td>
</tr>
<tr>
<td></td>
<td>97-123</td>
<td>4-5</td>
<td>8</td>
<td>1-50</td>
<td>CIRS gel</td>
<td>WIP</td>
<td>synchrocyclotron @ WUSTL, custom ARE to oscilloscopes limited Monte Carlo capability to quantify accuracy</td>
</tr>
<tr>
<td></td>
<td>99-122</td>
<td></td>
<td>15-20</td>
<td>1</td>
<td>Lexan</td>
<td>WIP</td>
<td>wireless data acquisition, 500 ksps only</td>
</tr>
<tr>
<td></td>
<td>194.5</td>
<td></td>
<td>15-20</td>
<td>1</td>
<td>water</td>
<td>WIP</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- pristine beam averaged 50x
- High dose rate therapy may enable pulse-by-pulse verification
CONFORMAL & HIGH DOSE RATE (15-20 pC/pulse)

- a. sagittal plane p & ρ
  - service mode
  - large spot

- b. coronal plane, lateral transducer takes beam
  - lateral irradiated

C.
CONFORMAL & HIGH DOSE RATE (15-20 pC/pulse)

- Service mode
- Large spot
- Lateral irradiated

b. coronal plane, lateral transducer takes beam

c. TA @ lateral receiver (vertically oriented)

- Compact rad. detector
- PMT assembly
- TA @ distal receiver (horizontal)

d. Vert. receiver located distal (runs 82-89)

Color ~ measured
Black ~ simulations

Assume:
- Constant charge/pulse
- 2035 m/s soundspeed
CONCLUSIONS

1. Obey stress confinement – clinical synchrocyclotrons great

2. Quantifying dose difficult due to
   i. limited angle data (experimental constraint)
   ii. unknown tissue parameter, $\Gamma$ (fundamental constraint)

3. Can pinpoint the Bragg peak, which could perhaps
   - better inform adaptive planning
   - provide confidence for hypofractionation

4. Based upon current hardware,
   - averaging required for conventional dose rates
   - single shot may be sufficient for high dose rates
     safety interlock - should be possible to halt within 1 pulse

Funding: NIH-NCI SBIR Award #R44CA243764