Introduction & Motivation

• Rationale: Advanced (persistent / recurrent) head and neck tumors remain a challenge.

• Advantages of non-invasive thermal ablation:
  – Reduce the need for or circumvent surgery
  – Enhancement of ionizing radiation therapy and/or chemotherapy
  – Provide treatment options to a patient population currently at high risk and poor prognosis

• SonoKnife’s main features:
  – Non-invasive
  – Line-focused (an acoustic “knife”)
  – Scanned (either manually by a physician or by machine)

• Line-focusing **might** afford advantages over point-focusing:
  – Lower peak acoustic intensities (avoiding NPL and cavitation)
  – Faster coverage of treatment volumes by “carving out”
**SonoKnife Radiator**

- R – radius of curvature
- r - the aperture size
- L - width of transducer
- d - position of water/muscle interface
- f - excitation frequency

**Nominal values:**
- R = 60 mm
- r = 30 mm
- L = 30 mm
- d = 30 mm
- f = 3 MHz

**Simulated Focal Plane Pressure Distributions**

Radius of curvature R = 60 mm
Aperture size r = 60 mm
Depth of the array L = 30 mm
Depth of water d = 30 mm
Frequency f = 3 MHz
Transducer surface intensity: 3 W/cm²

**Homogeneous Models**

**Focal Plane Temperature & Thermal Dose Distributions**

for nominal parameter values

- Max Temperature: ~ 62°C
- Frequency f = 3 MHz
- Radius of curvature R = 60 mm
- Aperture size r = 60 mm
- Depth of the array L = 30 mm
- Depth of water d = 30 mm
- Emittance: 3 W/cm²
- Thermal conduct: 0.5 W/m°C
- Heat capacity: 3720 J/kg°C
- Blood perfusion: 5 kg/m²s
- Density: 1138 kg/m³
- Speed of sound: 1569 m/s
- Attenuation: 0.04 Np/cm/MHz

**Step-Scanning Simulations**

**Homogeneous Models**

Temperature and thermal dose distributions on central planes after step-scanning the acoustic edge in the x direction from -15 mm to 15 mm.

- Scanning step: 1.25 mm
- No. steps: 24
- For steps 1-3, 4-6 and 7-24, power was on for 5.8 s/step, 5.0 s/step and 4.15 s/step, respectively.
- Power-off period of 30 s in-between steps.
- Time to complete the entire scan was 797 s.
- Nominal parameter values were used except for: emittance = 6 W/cm², W_b was set to zero at points that reached 240 EM43, and the skin temperature was held at 22°C to simulate forced cooling.
- The contours shown in each figure in dark red represent the cumulative 240 EM43 thermal isodoses after the scan was completed.
SonoKnife Prototype

Transducer

BNC connector

Comparison of Measurements to Simulations

Frequency: 3.55 MHz
FWHM: 0.5×26×4 mm

Ex Vivo SonoKnife Ablations (Porcine Liver)

Frequency = 3.5 MHz,
Acoustic power = 108 W
Depth of Focus = 1.5 cm
Exposure times:
Top panel: 30 s.
Low panel: 20 s.
Red arrows:
Direction of acoustic radiation

SonoKnife "Lesions" in Gel Phantoms

Exposure: 120 W for 30 s.
Propagation along z-direction.

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Homogenous Simulations & Ex Vivo Experiments

**Gel Phantom**
- 3.5 MHz Transducer
- 100 W e-power
- 20 s sonication time
- Focus at 20 mm under the surface

**Pig's Liver**
- 3.5 MHz Transducer
- 120 W e-power
- 20 s sonication time
- Focus at 15 mm under the surface

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**In vivo SonoKnife Ablations (Piglet)**

**Thigh**
- 3.5 MHz
- 100 W, 60 s
- 6 mm wide
- 18.5 mm long

**Neck**
- 3.5 MHz
- 100 W, 40 s
- 21 mm wide
- 16 mm long
Skin Burns Were Observed in Vivo Experiments at 3.5 MHz

- 30 Kg Pig's Neck
- 100 Watts Electric Power
- Focus at 22 mm under the skin
- Sonication time: 40 s

Layered-Medium Model and Simulation Parameters

- Transducer surface intensity is 3 W/cm²
- A 3D volume pressure is calculated
- The thickness of each tissue:
  - Skin – 2 mm
  - Fat – 8 mm
  - Muscle – 40 mm

Multi-layer Simulated Power Deposition Distribution for the 3.5 MHz transducer

Multi-layer Simulated Temperature Distribution for the 3.5 MHz transducer
Multi-layer Modeling Shows Two Possible Ways to Reduce Skin Burns Results at 1 MHz

\[ X = 0 \text{ plane} \]

\[ 1.0 \text{ MHz transducer without pre-cooling of the skin} \]

\[ X = 0 \text{ plane} \]

\[ 1.0 \text{ MHz transducer with pre-cooling of the skin to about } 8^\circ \text{C} \]

In Vivo Ablations: Skin Burns

In Vivo Results on a Pig’s Neck for a 1 MHz Transducer with Pre-cooling of the Skin

In Vivo Results on a Pig’s Neck for a 1 MHz Transducer with Pre-cooling of the Skin

\[ Y = 0 \]

Transducer Frequency: 1 MHz;
Focal depth: 3 cm below the surface;
Electrical Power: 92 W;
Sonication Time: 3 minutes;
Ice cooling time: 7 min

Imaged-Based Treatment Planning

Segmentation of anatomical structures (ITK-Snap)
Placement of acoustic focus for Step-n-Shoot strategy
Start with the deepest zones
Conclusions

• Feasible but .... much works remains
• Well-defined acoustic edge in simulations and in measurements in aqua, in gel, ex vivo and in vivo.
• Step-scanning only demonstrated in simulations thus far.
• Skin burns in live piglet: acoustic powers ~100 W (emittance ~1.2 W/cm²):
  • the thicker the fat layer
  • frequencies > 1 MHz
  • focal depth < 1 cm
  • sonications > 60 s
  • skin pre-cooling helps
• Other potential applications: sonication along (thrombolysis) and/or across vessels (hemorrhage control), subcutaneous sonolipolysis, transcostal therapy, thermal therapy of long bones.....

THANK YOU
Comparison of a Cylindrical Section and a Spherically Focused Transducers with Equivalent Radiating Areas

### Spherical Transducer

<table>
<thead>
<tr>
<th>f (MHz)</th>
<th>R (mm)</th>
<th>r (mm)</th>
<th>Max press. (MPa)</th>
<th>Max inten. (W/cm²)</th>
<th>Avg. inten. (W/cm²)</th>
<th>Acou. edge-x (mm)</th>
<th>Acou. edge-y (mm)</th>
<th>Acou. edge-z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>60</td>
<td>47.95</td>
<td>9</td>
<td>2210</td>
<td>1204</td>
<td>0.88</td>
<td>0.88</td>
<td>6.75</td>
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### Cylindrical Transducer

<table>
<thead>
<tr>
<th>f (MHz)</th>
<th>R (mm)</th>
<th>r (mm)</th>
<th>L (mm)</th>
<th>Max press. (MPa)</th>
<th>Max inten. (W/cm²)</th>
<th>Avg. inten. (W/cm²)</th>
<th>Acou. edge-x (mm)</th>
<th>Acou. edge-y (mm)</th>
<th>Acou. edge-z (mm)</th>
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</thead>
<tbody>
<tr>
<td>3.0</td>
<td>60</td>
<td>60</td>
<td>30</td>
<td>2</td>
<td>106</td>
<td>57</td>
<td>0.63</td>
<td>30.9</td>
<td>4.63</td>
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</tbody>
</table>

**Line-Focus = Acoustic Edge**

Tissue Properties and Boundary Conditions for Thermal Simulations

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Thermal Conductivity (W/m·°C)</th>
<th>Blood Perfusion (L·m⁻³·s⁻¹)</th>
<th>Specific Heat Capacity (J/kg·°C)</th>
<th>Density (kg/m³)</th>
<th>Speed of Sound (m/s)</th>
<th>Attenuation (dB/cm·MHz)</th>
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</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.615</td>
<td>0</td>
<td>4180</td>
<td>1000</td>
<td>1500</td>
<td>0.0022</td>
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<tr>
<td>Skin</td>
<td>0.266</td>
<td>5</td>
<td>3430</td>
<td>1200</td>
<td>1498</td>
<td>2.0</td>
</tr>
<tr>
<td>Fat</td>
<td>0.223</td>
<td>5</td>
<td>2325</td>
<td>921</td>
<td>1445</td>
<td>0.61</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.50</td>
<td>5</td>
<td>3720</td>
<td>1138</td>
<td>1569</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Convective boundary condition at the water/skin boundary is used. For other boundaries, constant temperature 37°C is assumed.