SonoKnife: Development, Testing and Treatment Planning

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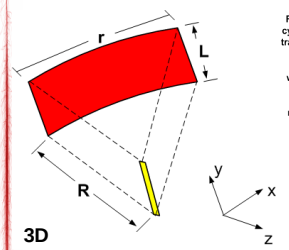
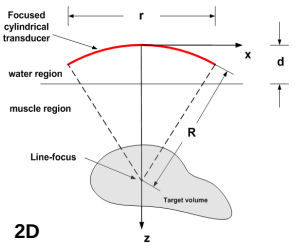
NO COI

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

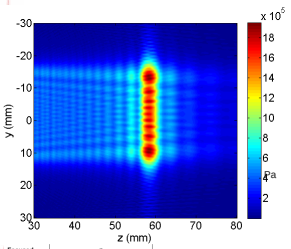


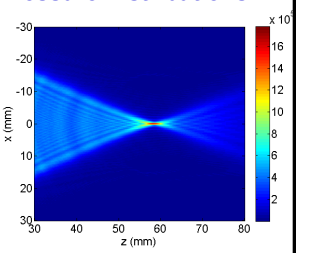


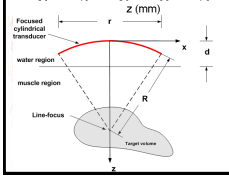
- R – radius of curvature
- r - the aperture size
- L - width of transducer
- d - position of water/muscle interface
- f - excitation frequency

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/cm^2

Homogeneous Models

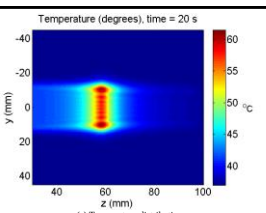
Focal Plane Temperature & Thermal Dose Distributions

for nominal parameter values

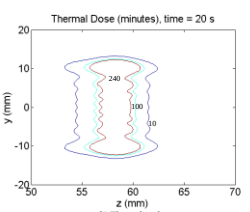
Max Temperature: ~ 62ºC

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/cm^2

Thermal conduct: 0.5 W/m/ºC
Heat capacity: 3720 J/kg/ºC
Blood perfusion: 5 kg/m^3/s
Density: 1138 kg/m^3
Speed of sound: 1569 m/s
Attenuation: 0.04 Np/cm/MHz



(a) Temperature distribution



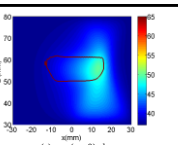
(b) Thermal isodoses

Step-Scanning Simulations

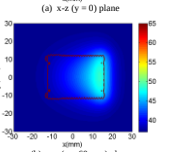
Homogeneous Models

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

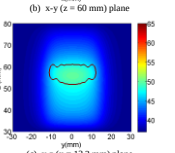
- Scanning step: 1.25 mm
- No. steps: 24
- For steps 1-3, 4-6 and 7-24, power was on for 5.8 s/step, 5.0 s/step and 4.15 s/step, respectively.
- Power-off period of 30 s in-between steps.
- Time to complete the entire scan was 797 s.
- Nominal parameter values were used except for: emittance = 6 W/cm^3, 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.



(a) x-z (y = 0) plane

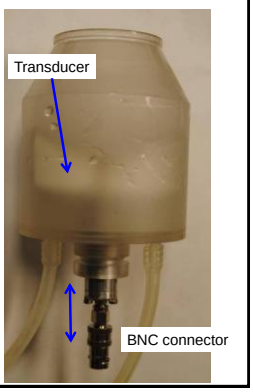


(b) x-y (z = 60 mm) plane

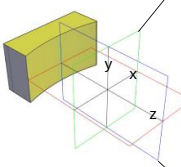


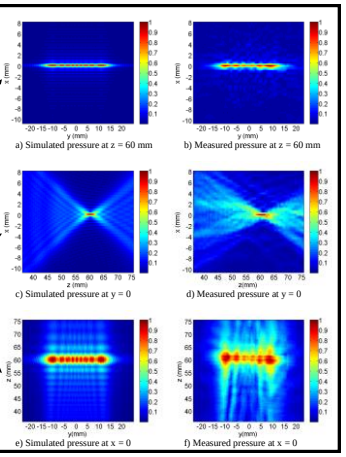
(c) y-z (x = 13.2 mm) plane

SonoKnife Prototype



Comparison of Measurements to Simulations

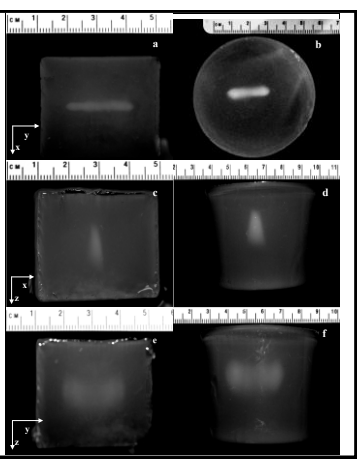




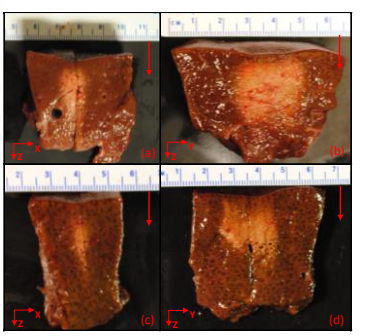
Frequency: 3.55 MHz
FWHM: 0.5×26×4 mm

SonoKnife "Lesions" in Gel Phantoms

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

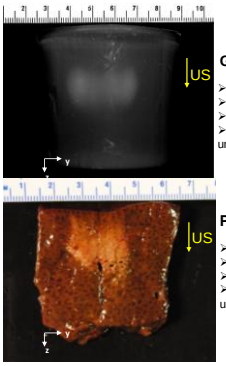


Ex Vivo SonoKnife Ablations (Porcine Liver)



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

Homogenous Simulations & Ex-Vivo Experiments

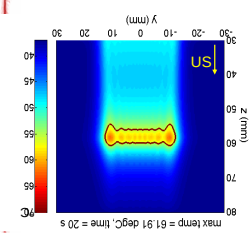


Gel Phantom

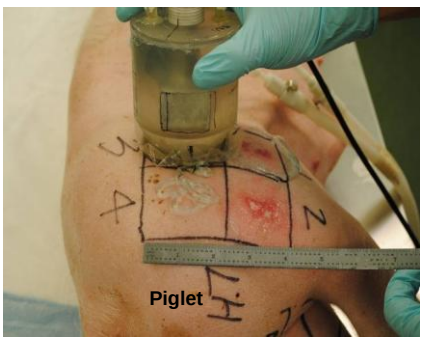
- 3.5 MHz Transducer
- 120 W e-power
- 20 s sonication time
- Focus at 15 mm under the surface

Pig's Liver

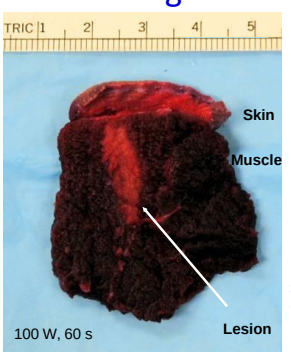
- 3.5 MHz Transducer
- 108 W e- power
- 20 s sonication time
- Focus at 20 mm under the surface



In vivo SonoKnife Ablations (Piglet)



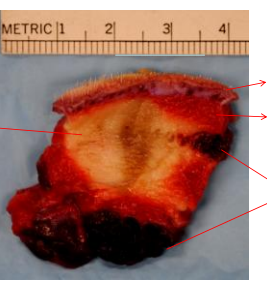
In vivo SonoKnife Ablation (Piglet)
Thigh



3.5 MHz
6 mm wide
18.5 mm long

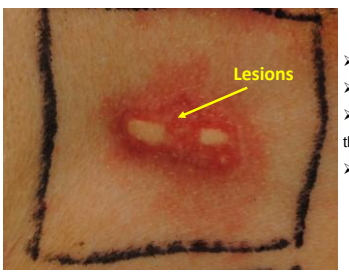
In vivo SonoKnife Ablation (Piglet)
Neck

21 mm wide
16 mm long



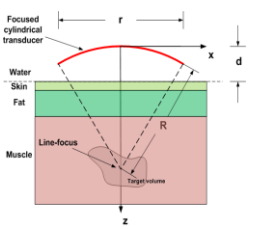
3.5 MHz, 100 W, 40 s

Skin Burns Were Observed in Vivo Experiments at 3.5 MHz



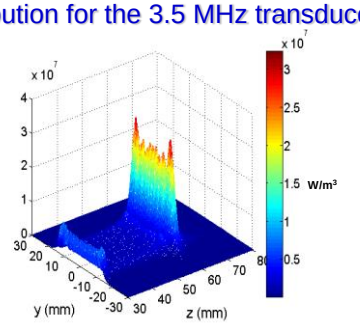
- 30 Kg Pig's Neck
- 100 Watts Electric Power
- Focus at 22 mm under the skin
- Sonication time: 40 s

Layered-Medium Model and Simulation Parameters



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

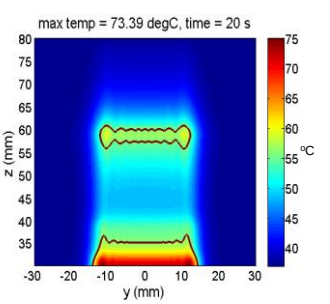
Multi-layer Simulated Power Deposition Distribution for the 3.5 MHz transducer



X = 0 plane
3.5 MHz transducer

Without Attenuation

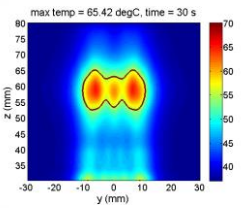
Multi-layer Simulated Temperature Distribution for the 3.5 MHz transducer



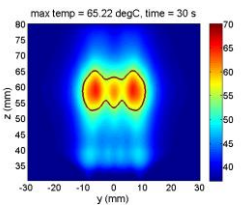
X = 0 plane
3.5 MHz transducer

Multi-layer Modeling Shows Two Possible Ways to Reduce Skin Burns

Results at 1 MHz

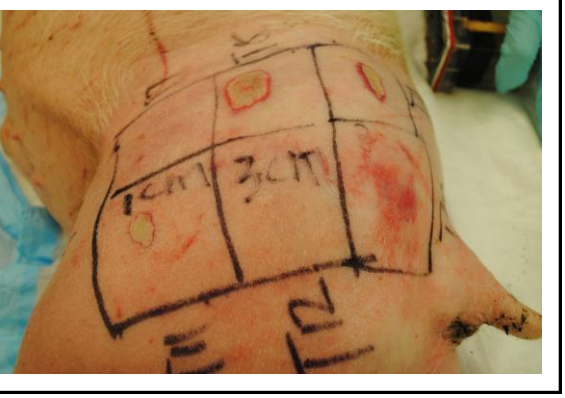


X = 0 plane
1.0 MHz transducer **without** pre-cooling of the skin

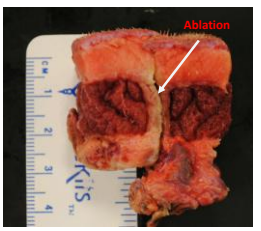


X = 0 plane
1.0 MHz transducer **with** pre-cooling of the skin to about 8ºC

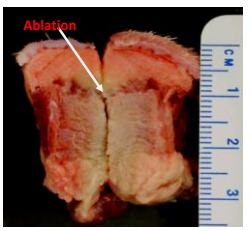
In Vivo Ablations: Skin Burns



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

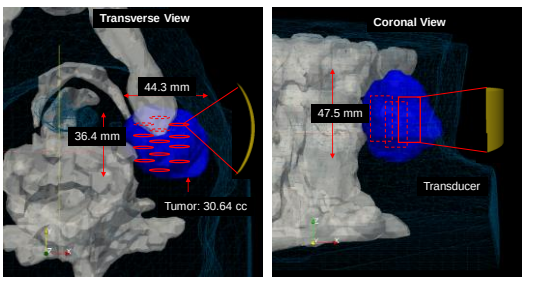


Y = 0
Transducer Frequency: 1 MHz;
Focal depth: 3 cm below the surface;
Electrical Power: 92 W;



X = 0
Sonication Time: 3 minutes;
Ice cooling time: 7 min

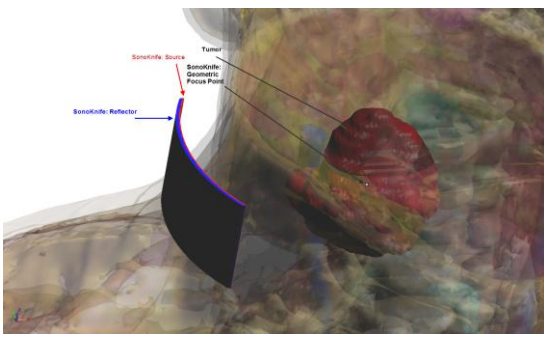
Imaged-Based Treatment Planning



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

Treatment Planning

Courtesy of Collaborators from http://www.itis.ethz.ch/



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/cm^2):
  - 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

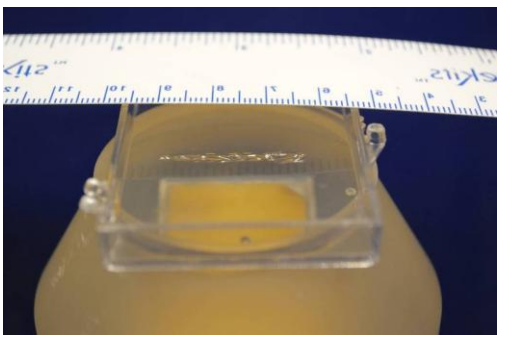
Spherical Transducer

f (MHz)	R (mm)	r (mm)		Max press. (MPa)	Max inten. (W/cm 2)	Avg. inten. (W/cm 2)	Acou. edge-x (mm)	Acou. edge-y (mm)	Acou. edge-z (mm)
3.0	60	47.95		9	2210	1204	0.88	0.88	6.75

Cylindrical Transducer

f (MHz)	R (mm)	r (mm)	L (mm)	Max press. (MPa)	Max inten. (W/cm 2)	Avg. inten. (W/cm 2)	Acou. edge-x (mm)	Acou. edge-y (mm)	Acou. edge-z (mm)
3.0	60	60	30	2	106	57	0.63	30.9	4.63

Line-Focus = Acoustic Edge



Tissue Properties and Boundary Conditions for Thermal Simulations

	Thermal conductivity (W/m/°C)	Blood Perfusion (Kg/m³/s)	Specific heat capacity (J/Kg/°C)	Density (kg/m³)	Speed of Sound (m/s)	Attenuation (dB/cm/MHz)
Water	0.615	0	4180	1000	1500	0.0022
Skin	0.266	5	3430	1200	1498	2.0
Fat	0.223	5	2325	921	1445	0.61
Muscle	0.50	5	3720	1138	1569	0.68

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