Possible acoustic paths for communication and energy transfer with deeply implanted sensors using ultrasound

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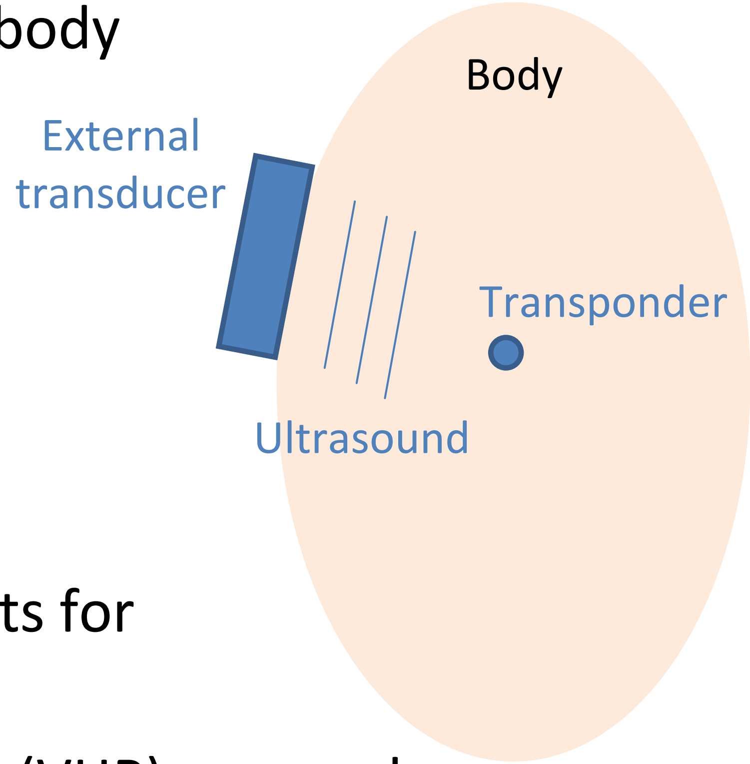
Motivation

- Communication and energy transfer between an external ultrasound transducer and a sensor (transponder) deeply-implanted in the body



- Suitable acoustic paths must be found
  - Efficient energy transfer
  - Minimization of adverse bio-effects

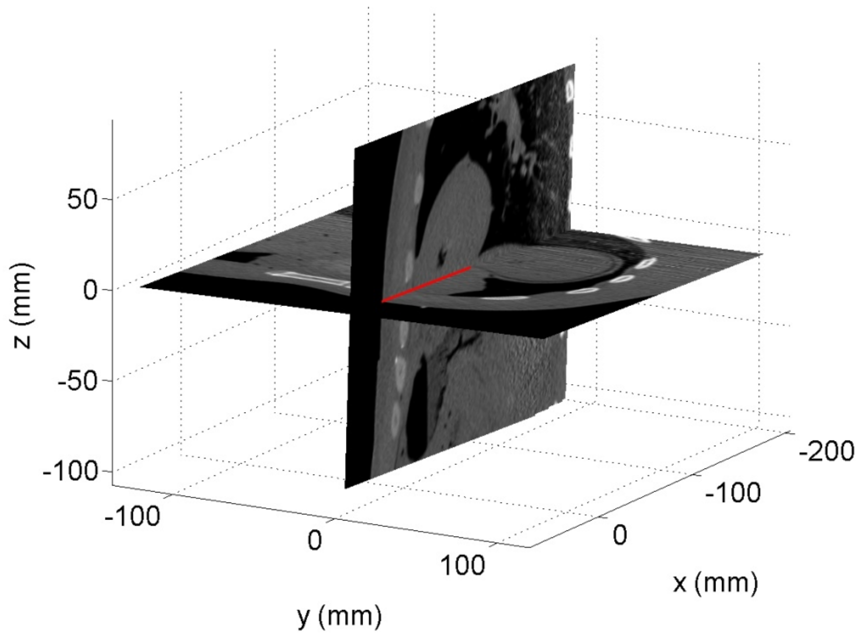
- **Goal of this work:**
  Develop an acoustic model that accounts for the geometry of the organs in the body
  => data from the Visible Human Project (VHP) are used

Outline

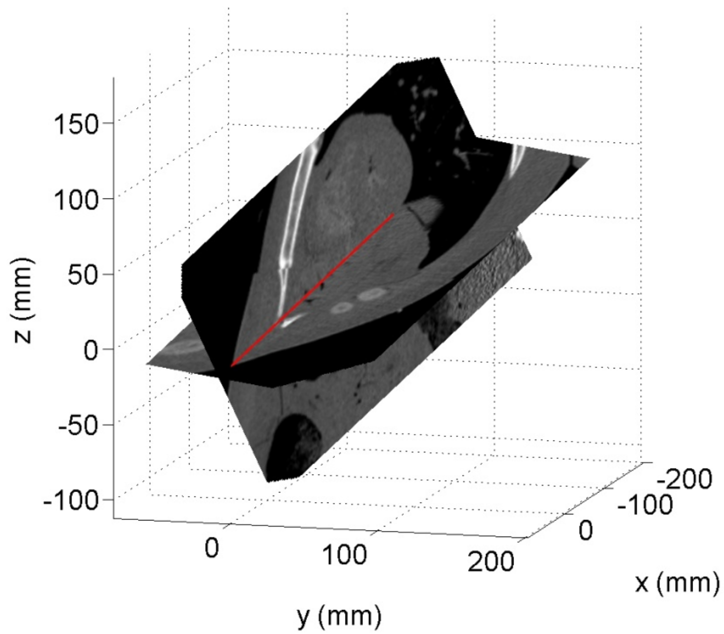
1. Ultrasound propagation model using the VHP data
2. Experimental validation of the model
3. Minimization of adverse bioeffects
4. Model results in realistic configurations
5. Conclusion

Selection of acoustic paths using the Visible Human Project data

- Use of the segmented data of the Visible Human Project (VHP) performed by VOXEL-MAN
- For a transponder on the epicard of the heart:



Path between the ribs

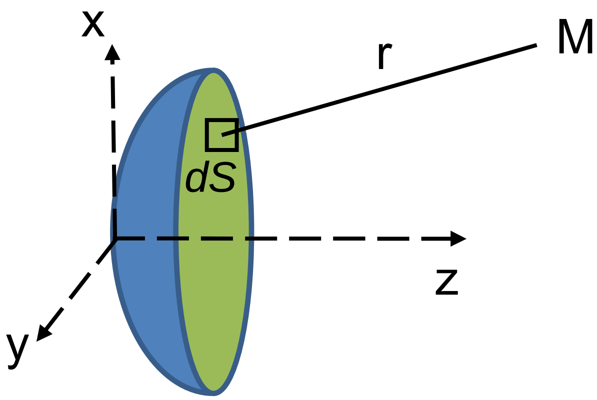


Path from below the ribs

Acoustic model

- Based on the Rayleigh-Sommerfeld diffraction integral:

$$P(r) = j\rho_0 f \iint_S V_n \frac{e^{-jkr}}{r} dS$$



=> complex-shaped transducer can be considered

- Division of the transducers into M small elements:

$$P(r) = j\rho_0 f \sum_{m=1}^{M} V_{n,m} \frac{e^{-jkr_m}}{r_m} \Delta S_m$$

- Attenuation in the tissue layers:

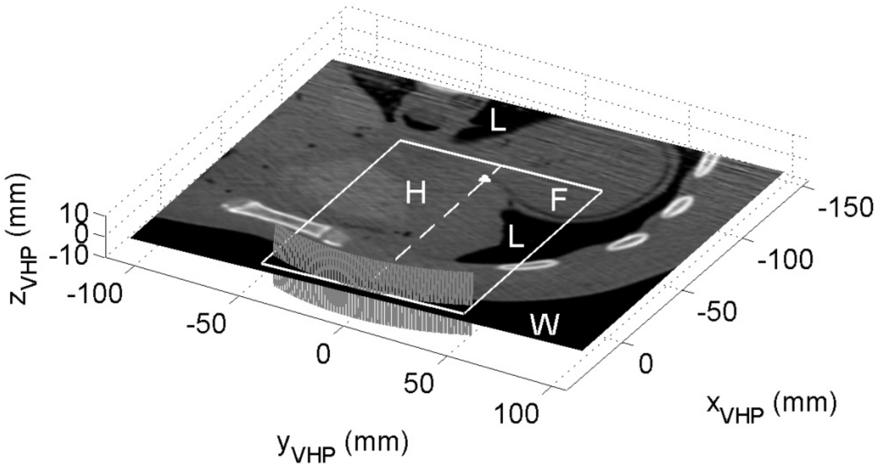
complex wave number: $k = k_0 - j\alpha$ $\qquad \alpha = \sum_{n=1}^{N} \alpha_i r_i$

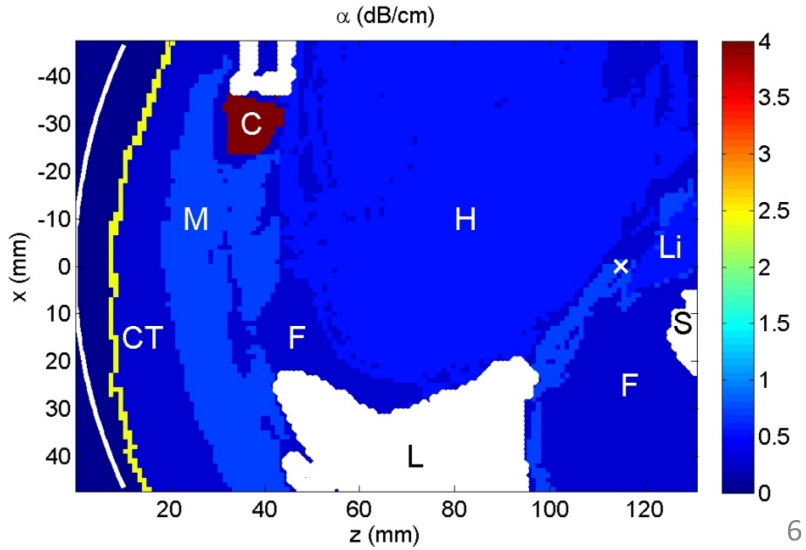
attenuation coefficient in layer (i)

Acoustic model

- Two types of tissue layers:
  - Blocking tissues: lungs, bones and stomach
  - Soft tissue
- Example for a horizontal plane with a 64-element spherical linear array:

Tissue layer	ρ (kg/m³)	c (m/s)	α at 1MHz (dB/cm)
Cartilage	1100	1600	4.0
Connective tissue	1040	1540	0.3
Fat	950	1450	0.3
Liver	1060	1595	0.5
Muscle (cardiac)	1060	1570	0.5
Muscle (skeletal)	1050	1580	0.7
Skin	1090	1615	2.4



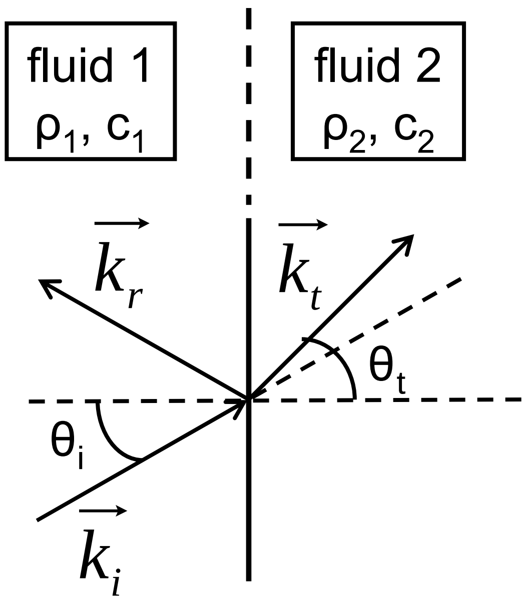


Acoustic model

- Main assumptions of the model:
  - Linear acoustics
  - No cavitation
  - Transducer surface planar or slightly curved
  - Refraction and reflection effects neglected:

- Snell – Descartes law:

$$\frac{\sin\theta_t}{c_2} = \frac{\sin\theta_t}{c_1}$$



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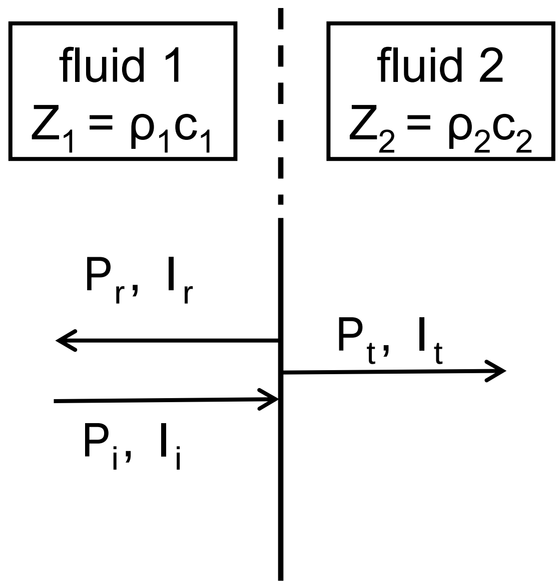


- Reflection coefficients under normal incidence:

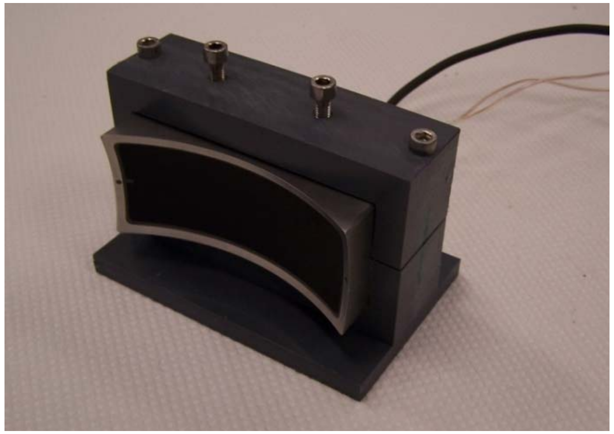
for pressure: $$R_P = \frac{P_r}{P_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

for intensity: $$R_I = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

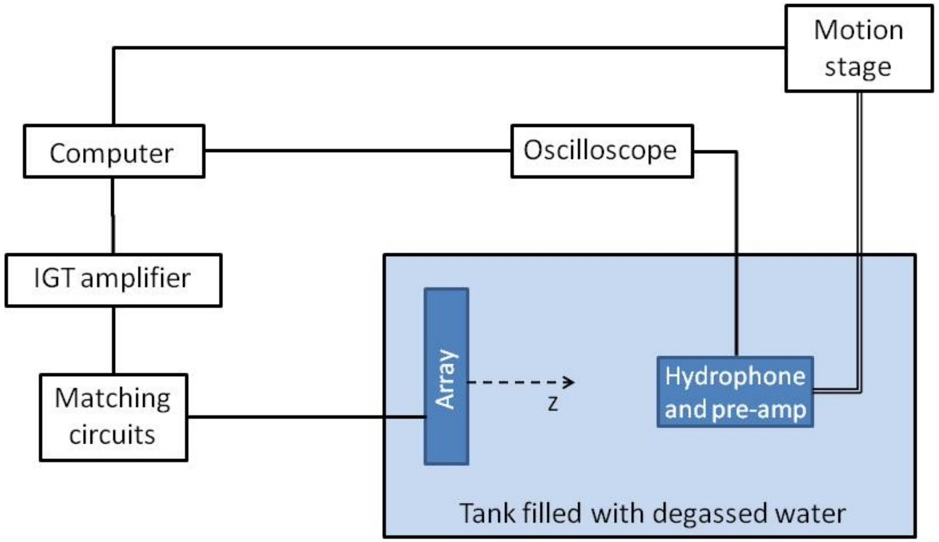
$$I = \frac{|P|^2}{2\rho c}$$

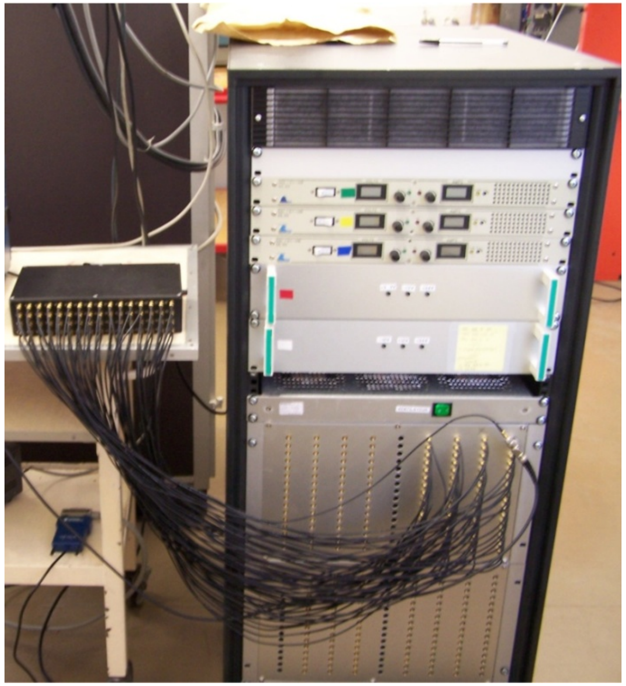
Experimental validation in water

- 64-element spherical linear array with curvature of 11cm
  => beamforming is used to shift the focal point at $(x_F,0,z_F)$



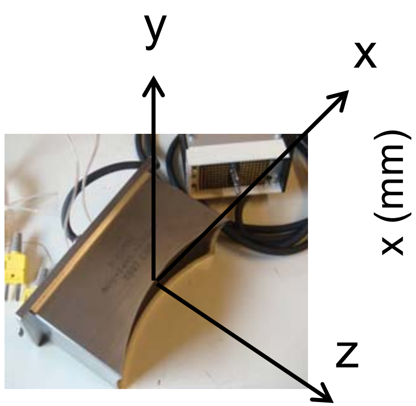
- Experimental setup:

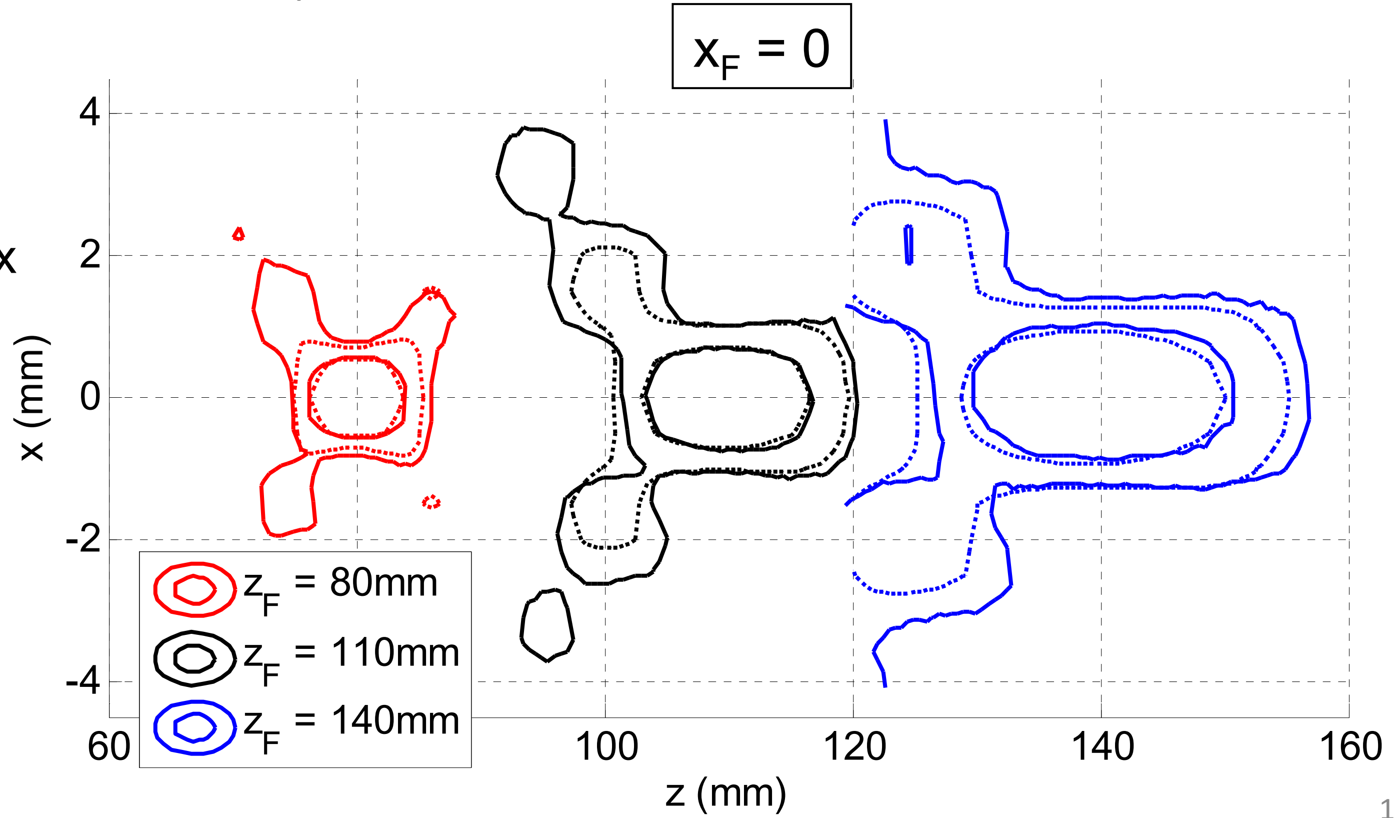




Experimental validation in water

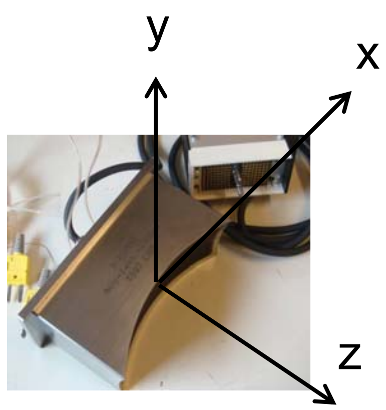
- Contours at -3dB and -6dB in the horizontal plane y = 0:
  - Solid lines: measurements
  - Dashed lines: model predictions

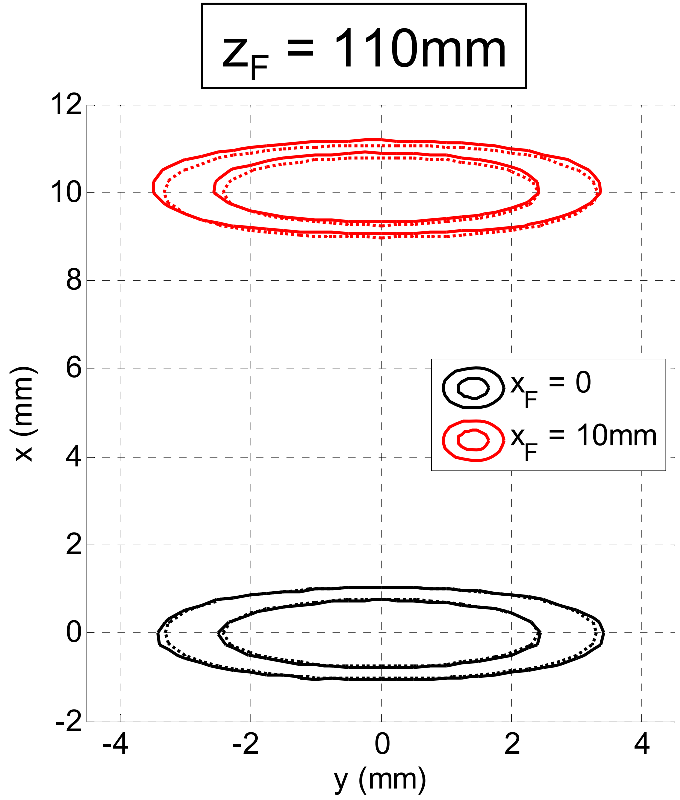




Experimental validation in water

- Contours at -3dB and -6dB in the focal plane z = 110mm:
  - Solid lines: measurements
  - Dashed lines: model predictions

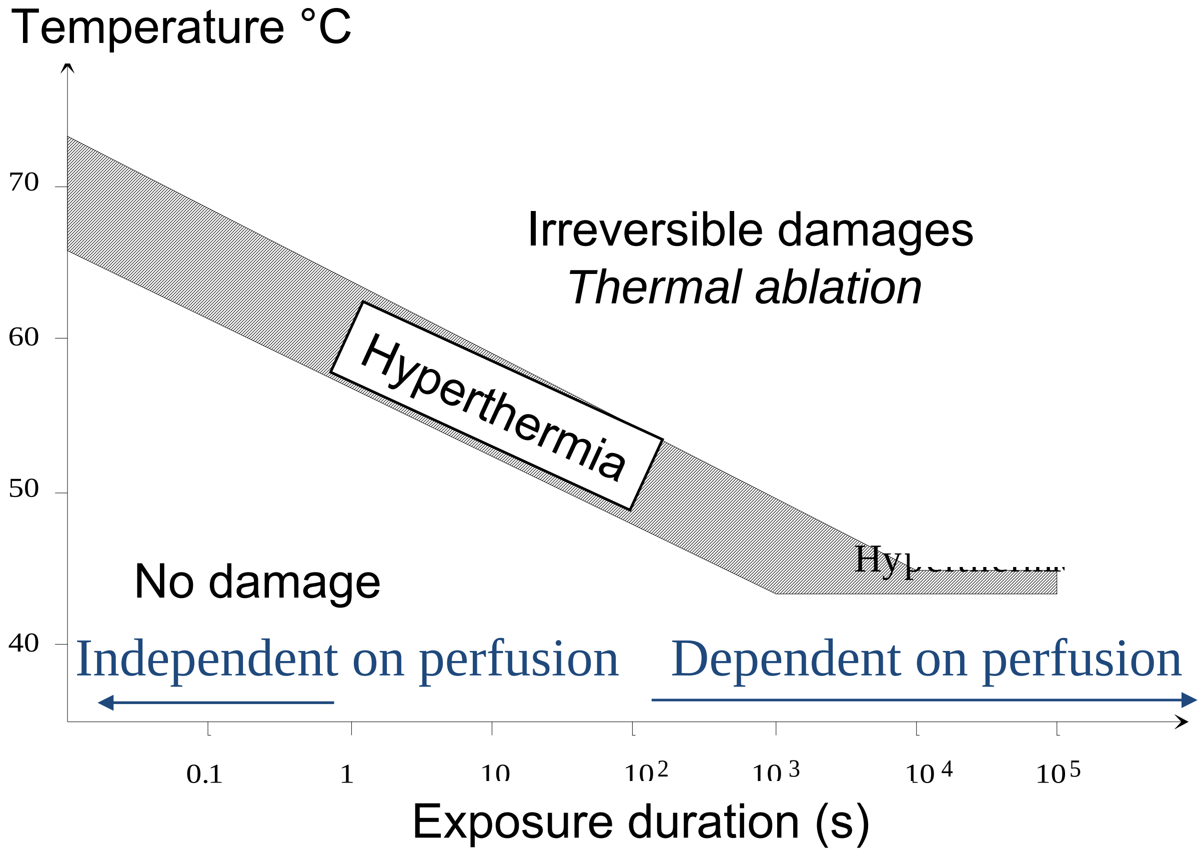




- Experiments are currently led with phantoms whose sound speed is between 1450m/s and 1600m/s

Bioeffects due to ultrasound: tissue heating

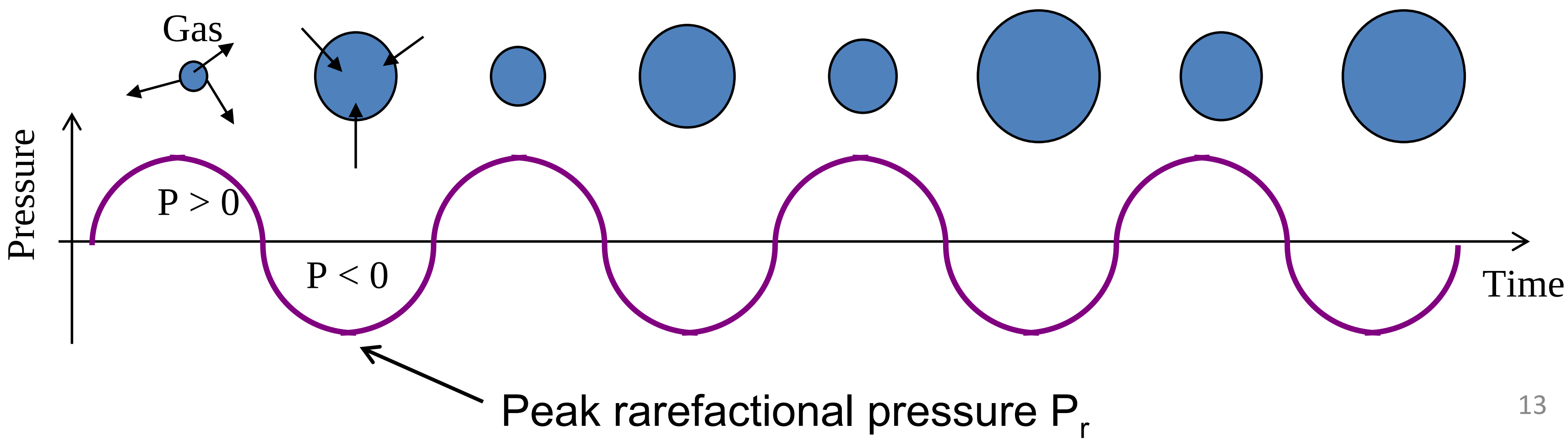
- Threshold for thermal damage as a function of exposure duration and temperature (Lele 1977)



Bioeffects due to ultrasound: cavitation

- Interaction of ultrasound with bubbles
- When a medium that hosts gaseous nuclei is sonicated, micro-bubbles start to expand and contract in a way inversely proportional to the acoustical pressure.

  => mechanical effect on tissue



Bioeffects due to ultrasound: therapy by ultrasound

Different effects can be used for different applications

Thermal effects → Non thermal effects

Physiotherapy
T < 42°C

Hyperthermia
42°C < T < 60°C

Lithotripsy
(Cavitation – Mechanical stress : shocks, etc.)

Thrombolysis
(Cavitation – micro-flows)

Drug delivery – Transfection
(Heat and/or Cavitation)

HIFU or Focused Ultrasound Surgery
T > 60°C + *Cavitation*

Minimization of adverse bioeffects

- Limit the incident acoustic power to avoid these bioeffects (FDA, 2008):
  1. Criterion on the derated spatial-peak time-average intensity $I_{spta.3}$:

     $\mathbf{I_{spta.3} \leq 0.72W/cm^2}$

  2. Criterion on the mechanical index: $MI = \frac{P_{r.3}}{\sqrt{f_c}}$

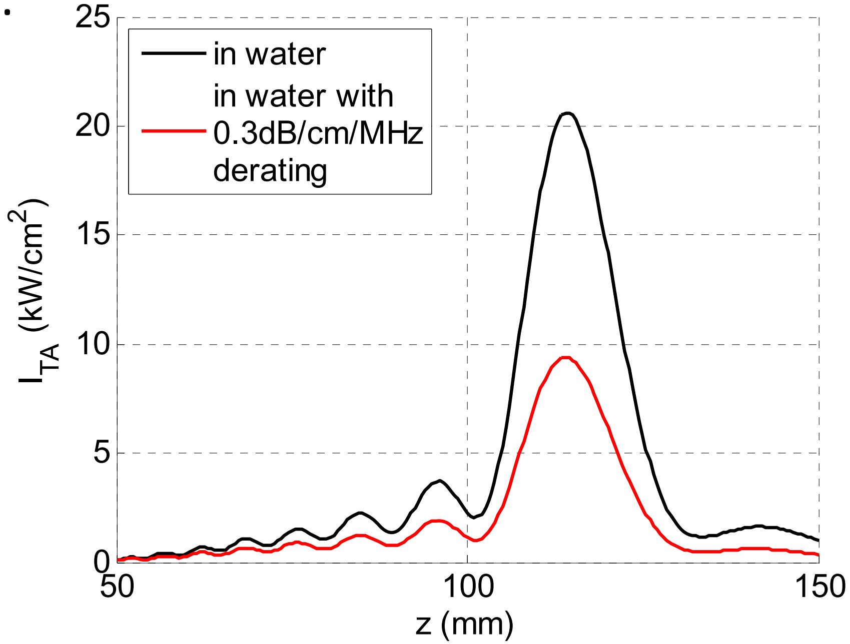
     $\mathbf{MI \leq 1.9}$

- Continuous wave (CW) signals are considered:

=> $V_n \leq 8.8$mm/s to meet these criteria with $x_F = 0$ and $z_F = 115$mm

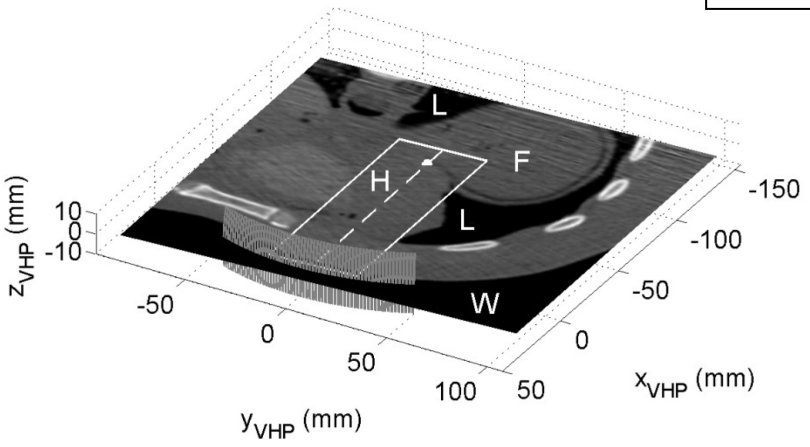
Calculation in water with an arbitrary normal velocity V_n of 1m/s

I_{ta} : time-average acoustic intensity

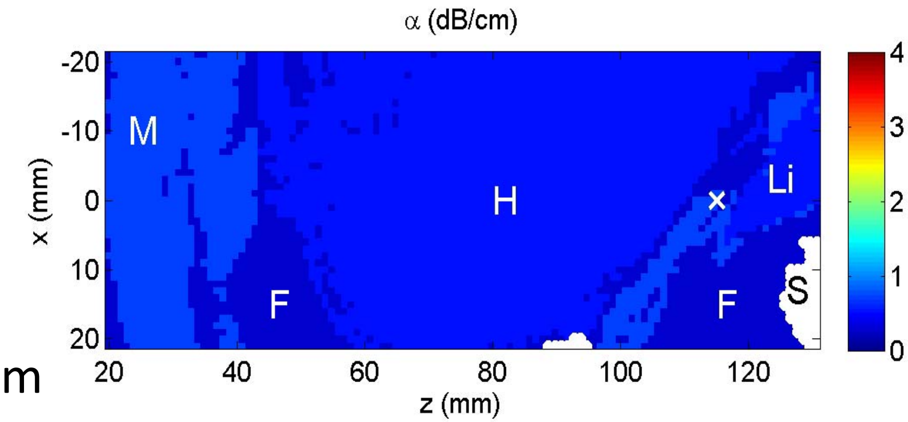


Model results in the horizontal plane

Path between the ribs

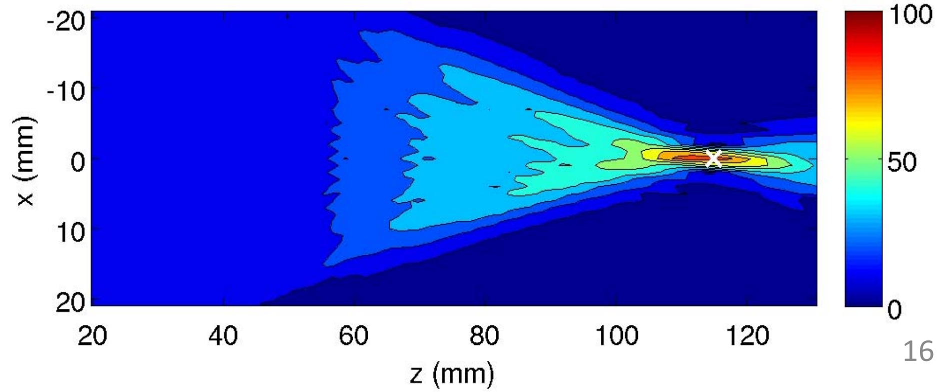


Map of the attenuation coefficient in dB/cm

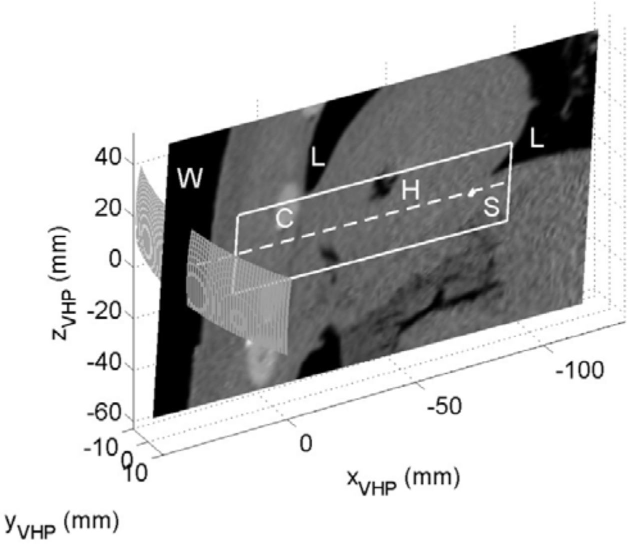


- Focal point at $x_F = 0$ and $z_F = 115$mm
- $V_n = 8.8$mm/s, i.e. for CW signal :
  - $I_{spta,3} = 0.72 W/cm^2$
  - MI = 0.15
- At the transponder position:
  - $|P| = 87$kPa
  - $I_{ta} = 0.26 W/cm^2$

Map of the peak pressure in kPa



Model results in the vertical plane



Path between the ribs

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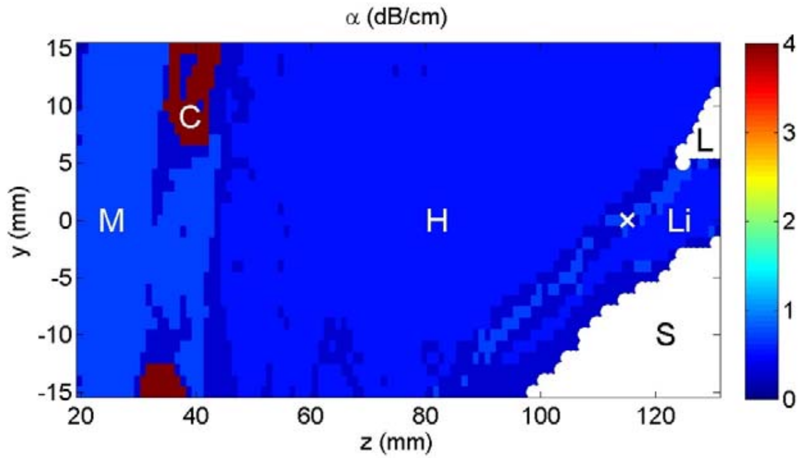

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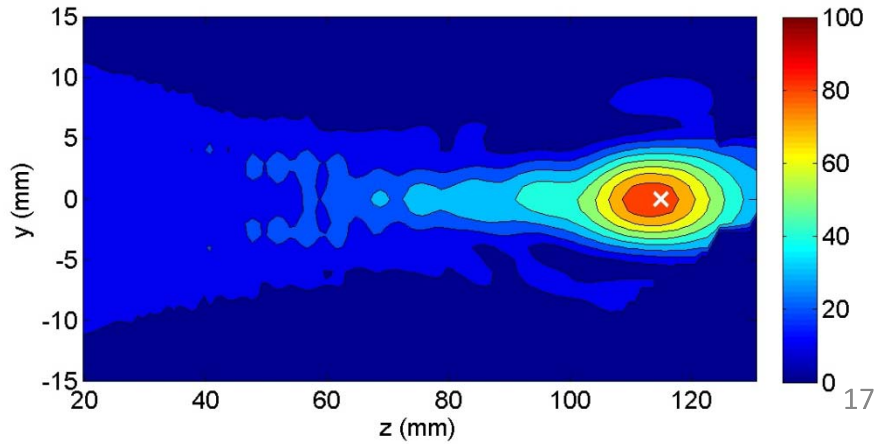

Conclusion and future work

- An acoustic model has been presented that is able:
  - to account for a realistic tissue geometry
  - to calculate the energy transferred to a transponder located deep in the body
  - to minimize adverse bioeffects
- It can be used to select suitable acoustic paths for a given transponder position
- Experiments are currently performed with tissue phantoms to further validate the model
- In the future, calculation of temperature elevation in tissue could be performed based on this model

Acknowledgements

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