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HIFU Induced Heating Modeling by using the Finite Element Method

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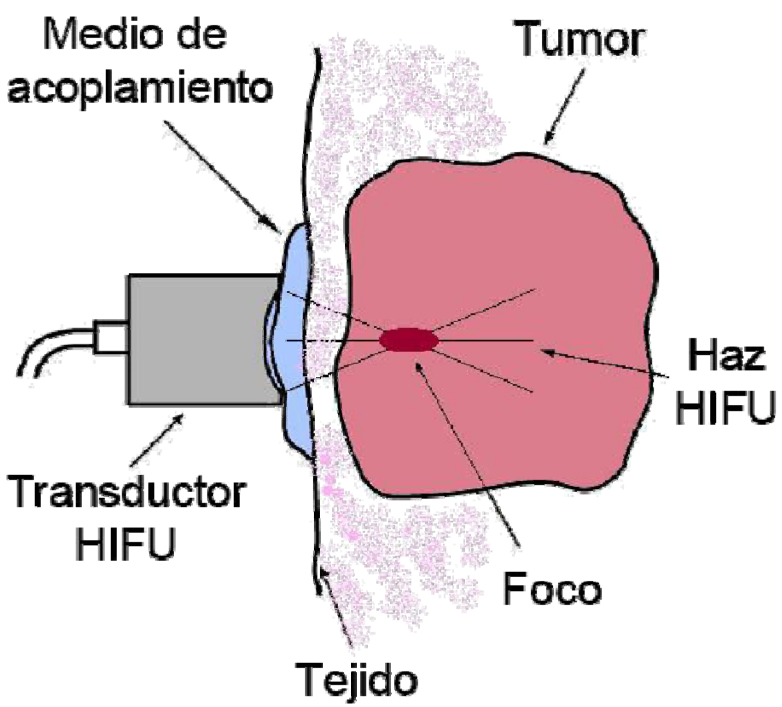
Contents

Introduction

What is HIFU*?



- Ellipsoidal shaped focal zone.
- Focus location depends on tranducer geometry and operating frequency.
- Acoustic energy concentrartion at the focus.
- Quick temperature elevation over 56°C which produces coagulative necrosis.
- Treatment of benign and malign tumors
- Non-invasive technique.
- Exposure time < 10 s.

* High-intensity focused ultrasound

Heating modeling

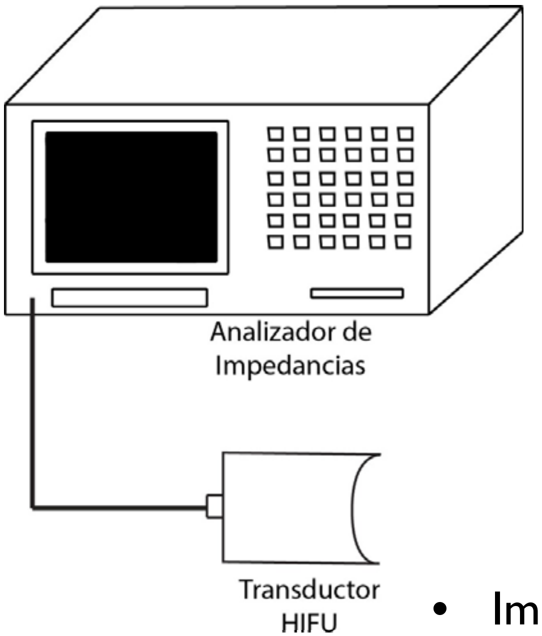
- Exposure time to HIFU for lesion formation.
- Tissue/phantom thermal properties temperature dependence.
- Temperature gradient around focal region.
- Media changes due to HIFU and heating.

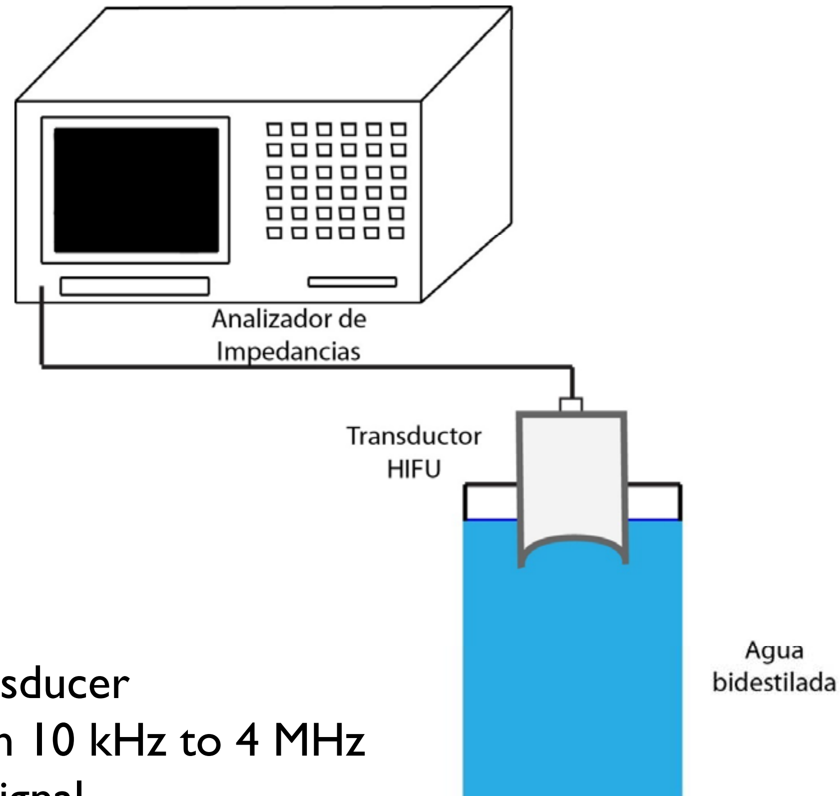
Objective

To model the HIFU induced heating by means of Finite Element Method as a function of the applied electric potential to the transducer.

Methods

HIFU transducer electric impedance measurement

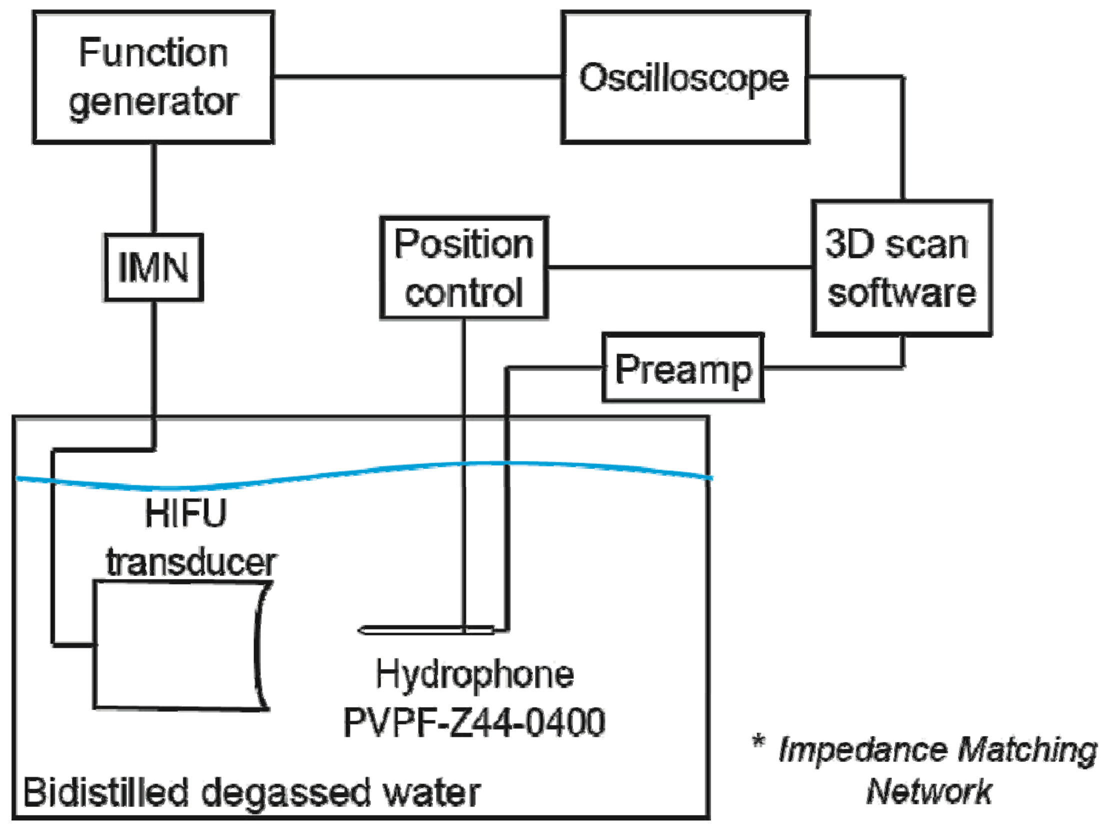




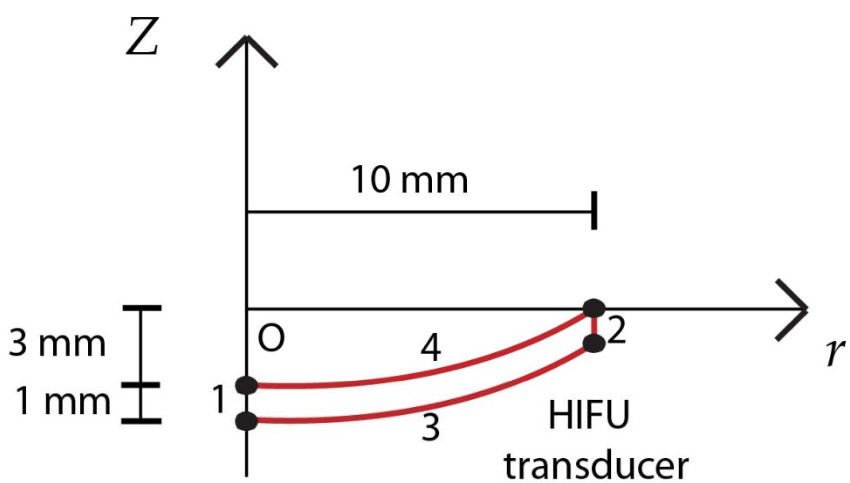
- Impedance analyzer
- 2 MHz concave transducer
- Frequency scan from 10 kHz to 4 MHz
- 500 mV excitation signal
- Measurements in **air** and **bidistilled water**

HIFU acoustic field characterization

- Low power measurements using a PVPF-Z44-0400 hydrophone.
- 1.965 MHz/ 10 Vpp burst with a repetition frequency of 10 Hz.
- X and Y axis resolution of 0.1016 mm.
- Z-axis resolution of 1 mm.



HIFU transducer FEM electric impedance modeling



Piezoelectric material:
PZT-8

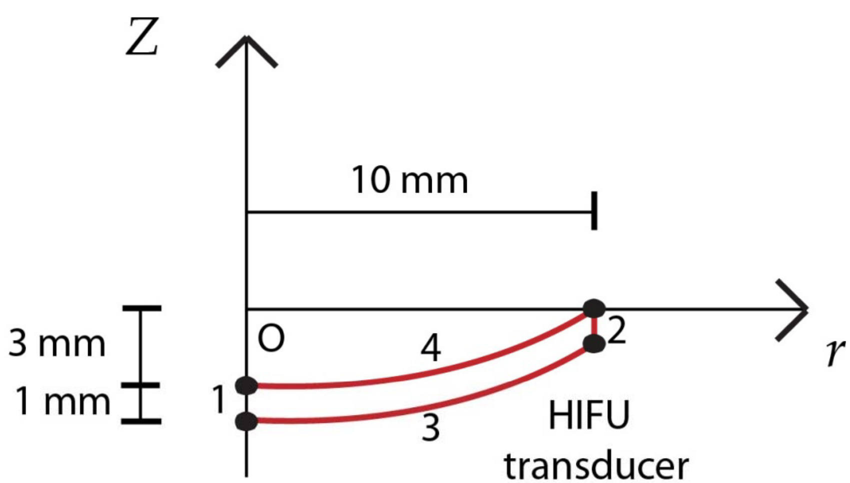
System equations

$\sigma = c_E \varepsilon - e^T \mathbf{E}$
$\mathbf{D} = e\varepsilon + \varepsilon_0 \varepsilon_{rT} \mathbf{E}$

where,

σ, stress tensor
c_E , elasticity matrix
e_T , electro-mechanic coupling matrix
E, electric field
D, displacement vector
e, deformed tensor
ε_0, vaccum permitivity
ε_{rT} , relative permitivity

HIFU transducer FEM electric impedance modeling



Element material:
PZT-8

Boundary constrains:
- 1, axial symmetry
- 2, fixed
- 3 and 4, free

Electric boundary conditions:
- 1 and 2, zero charge/symmetry
- 3, ground
- 4, electric potential of 500 mV

Mesh:
- 2794 triangular elements

Frequency response:
- 100 kHz to 4 MHz

HIFU transducer electric impedance

- Electric impedance in transducer face

$$I=\int_S \boldsymbol{J}\cdot d\boldsymbol{A}$$

$$Z_e=V_{B\text{-}A} / I$$

where,

J, current density in transducer's face

A, transducer face area

$\boldsymbol{V_{B\text{-}A}}$, electric potential between both electrodes A and B

I, current

$\boldsymbol{Z_e}$, electric impedance

2D axisymmetric FEM equations

Wave equation for time-harmonic analysis

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

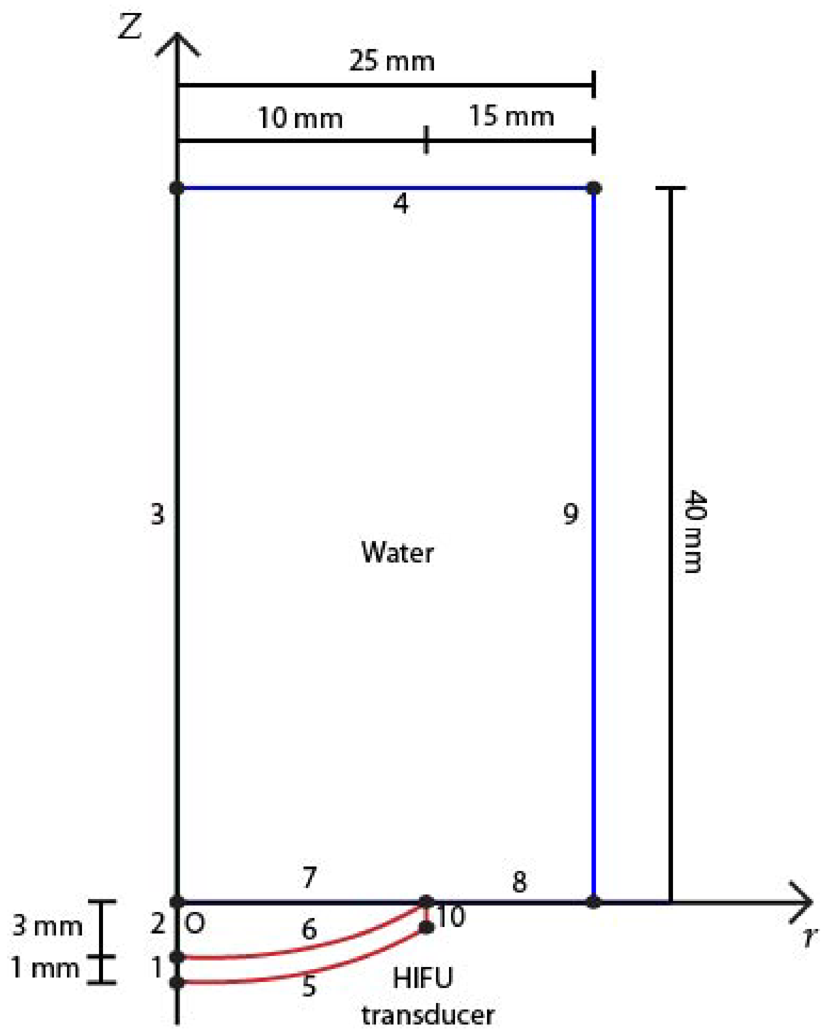
Reduced Bio-heat equation for transient response

$$\rho_0 C \frac{\partial T}{\partial t} - \bar{k}\nabla^2 T = Q_{ext}$$

Acoustic pressure and heat relation

$$Q_{ext} = \frac{\alpha p^2}{\rho_0 c}\left[\frac{W}{m^3}\right]$$

HIFU field FEM modeling



Boundary conditions

Axial symmetry: 1, 2 and 3

Continuity: 7

Impedance: 4 and 9

Sound hard wall: 8

Normal acceleration: 6

Subdomain properties

Water:

Density: 1000 kg/m^3

Sound speed: 1500 m/s

Piezoelectric excitation voltages

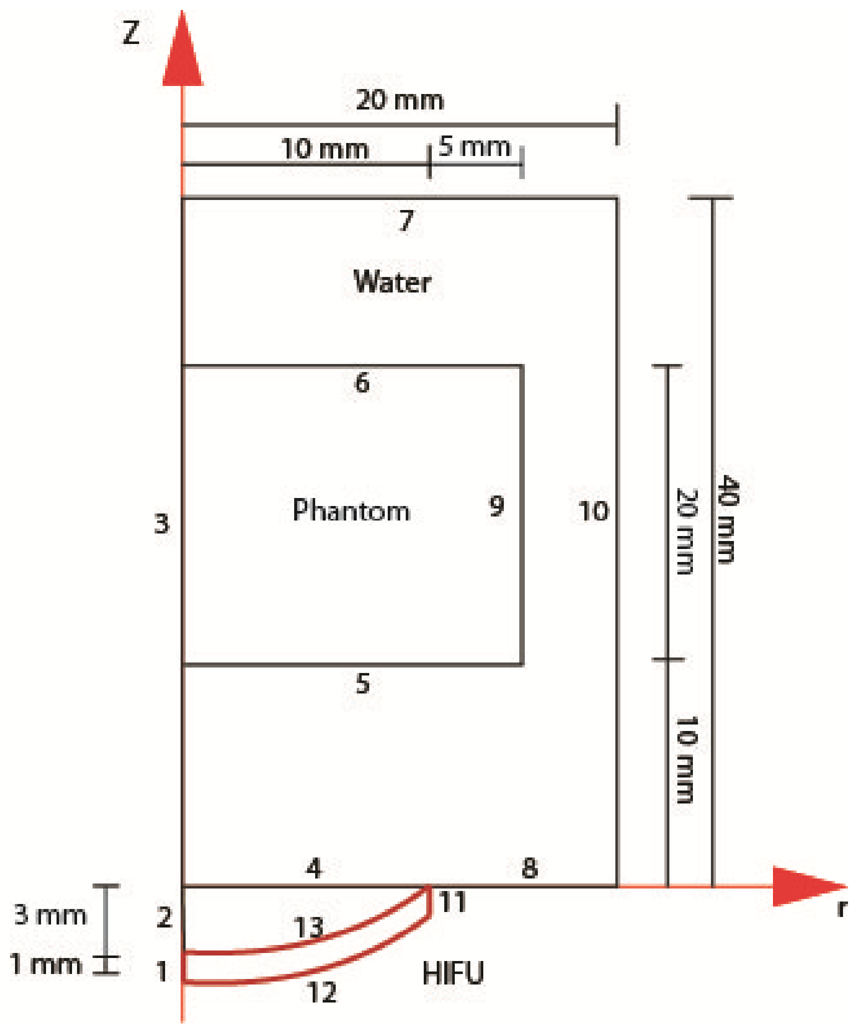
5 V, 10 V, 15 V, 20 V

Mesh

5494 triangular elements

39589 quad elements

HIFU induced heating modeling



Boundary conditions

- Axial symmetry: 1, 2 and 3
- Continuity: 4, 5, 6, and 9
- Temperature: 7, 8 and 10
- Thermal insulation: 13

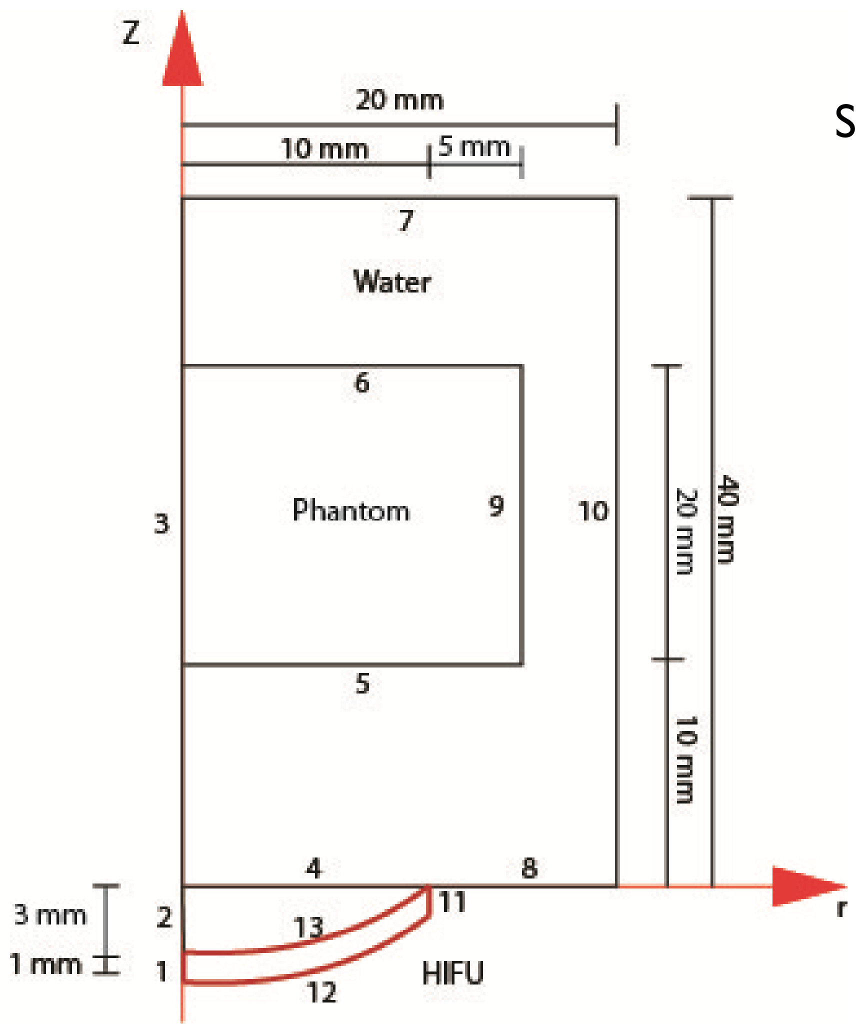
Subdomain properties

- Water:
  - Density: 1000 kg/m^3
  - Sound speed: 1500 m/s
- Phantom:
  - Density: 1045 kg/m^3
  - Sound speed: 1540 m/s

Mesh

5494 triangular elements
39589 quad elements

HIFU induced heating modeling



Subdomain properties

Water:
Specific heat capacity: 4000 J/(kg*K)
Thermal conductivity: 0.58 W/(m*K)

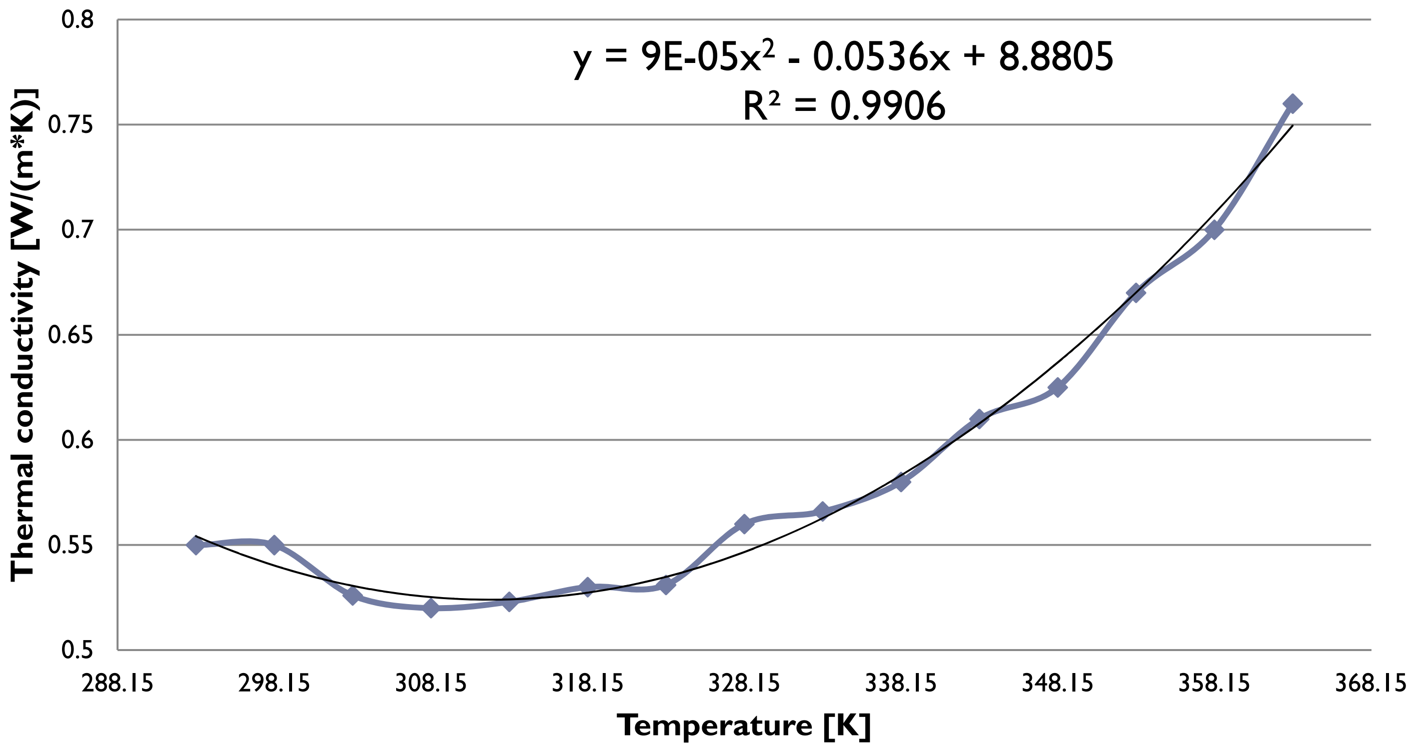
Phantom:
Specific heat capacity: 3411 J/(kg*K)

Thermal conductivity: W/(m*K)
Fixed and temperature dependent

External heat source: *Qext*

Phantom thermal conductivity

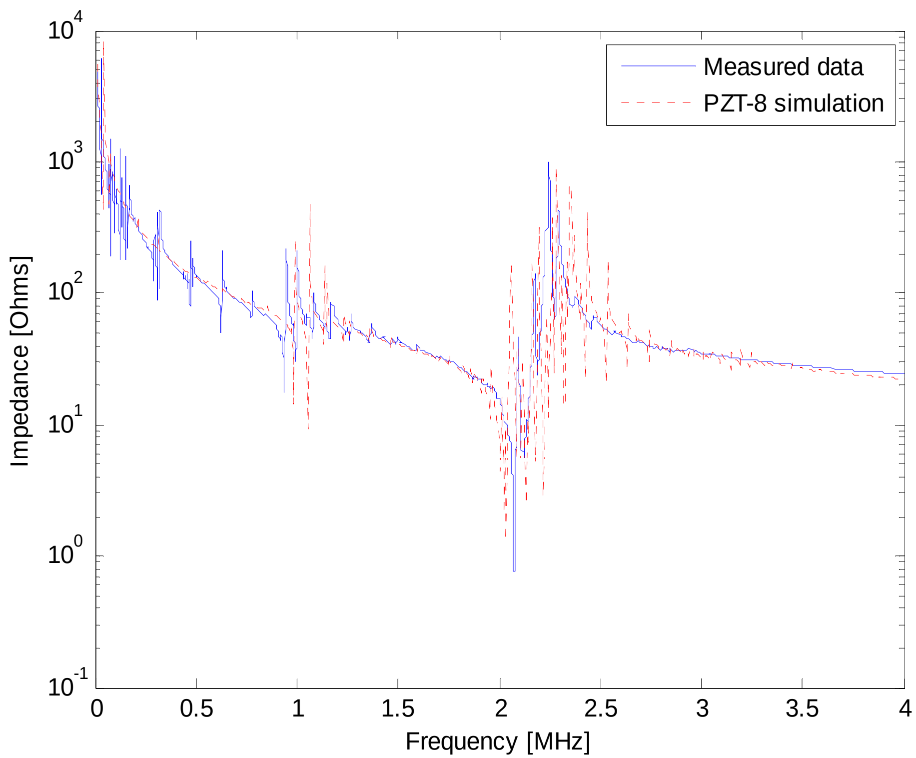
- Fixed: 0.5 W/(m*K)
- Temperature dependent **



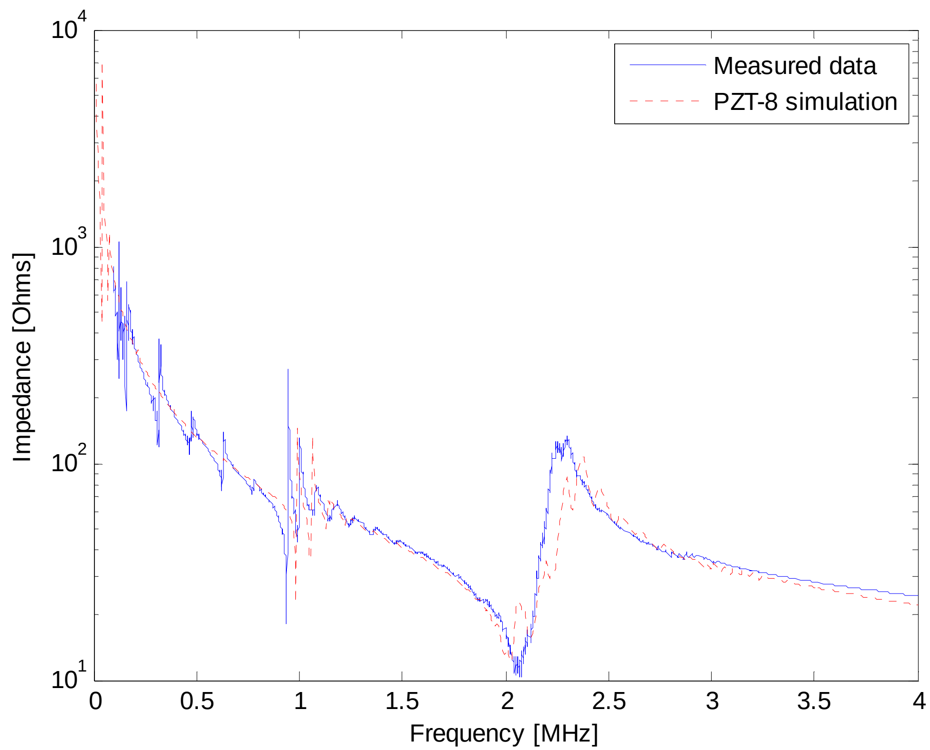
** Guntur S. R., Lee K. I., *et al*, "Temperature-dependent thermal properties of ex vivo liver undergoing thermal ablation". *Ultrasound in Med. & Biol.*, Vol. 39, No. 10, pp. 1771-17184, 2013

Results

HIFU transducer electric impedance measurement and modeling

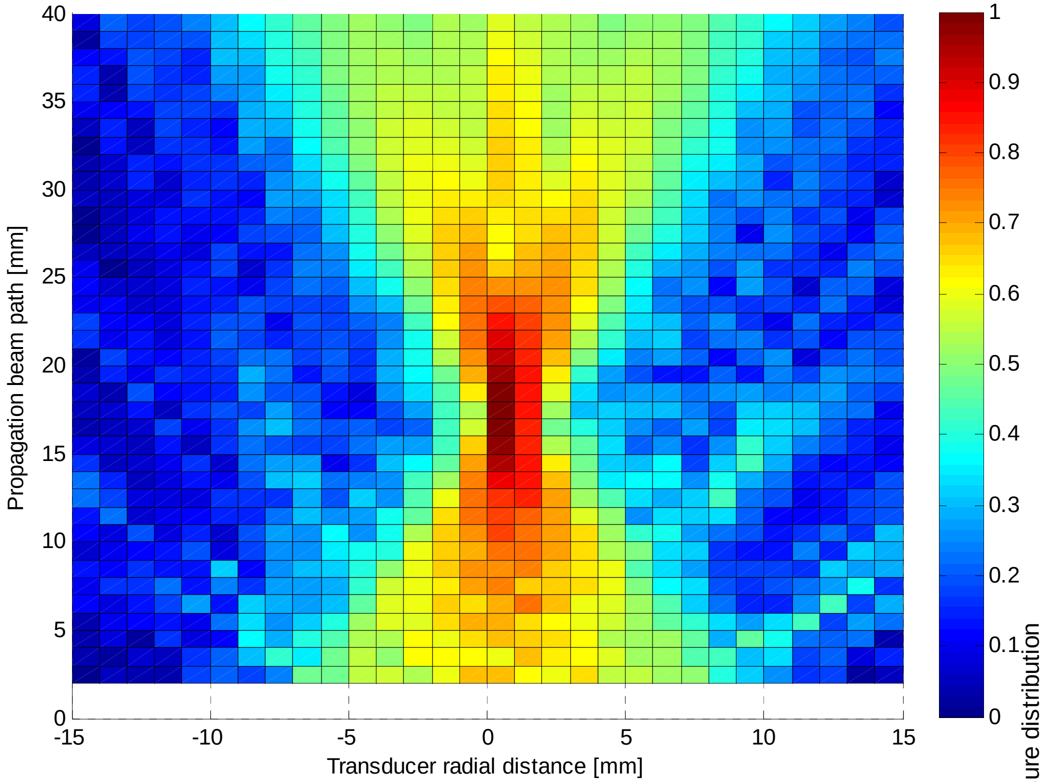


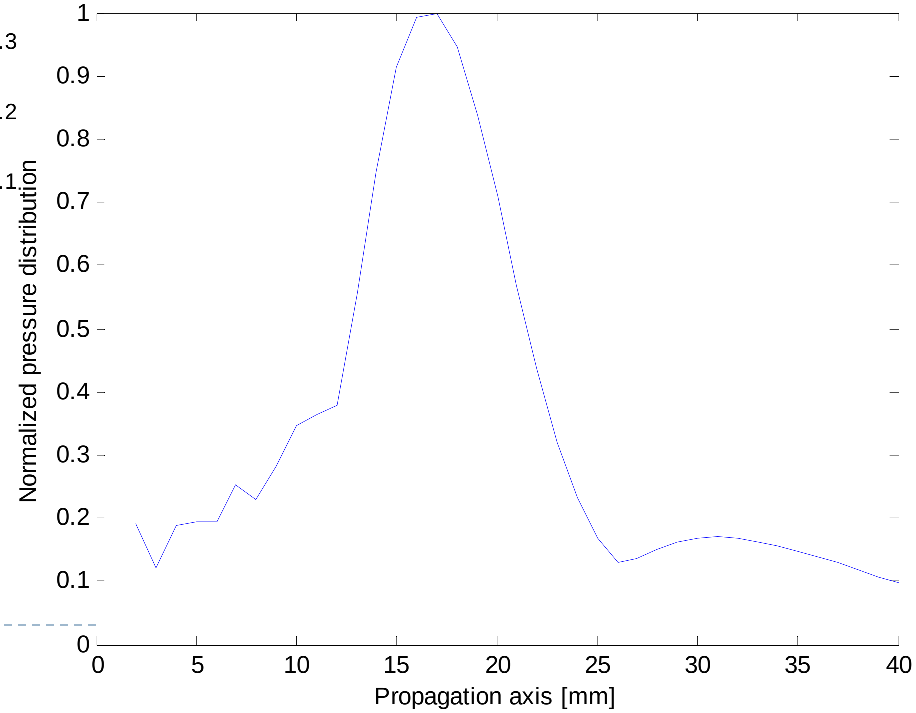
Electric impedance when transducer was emitting in air



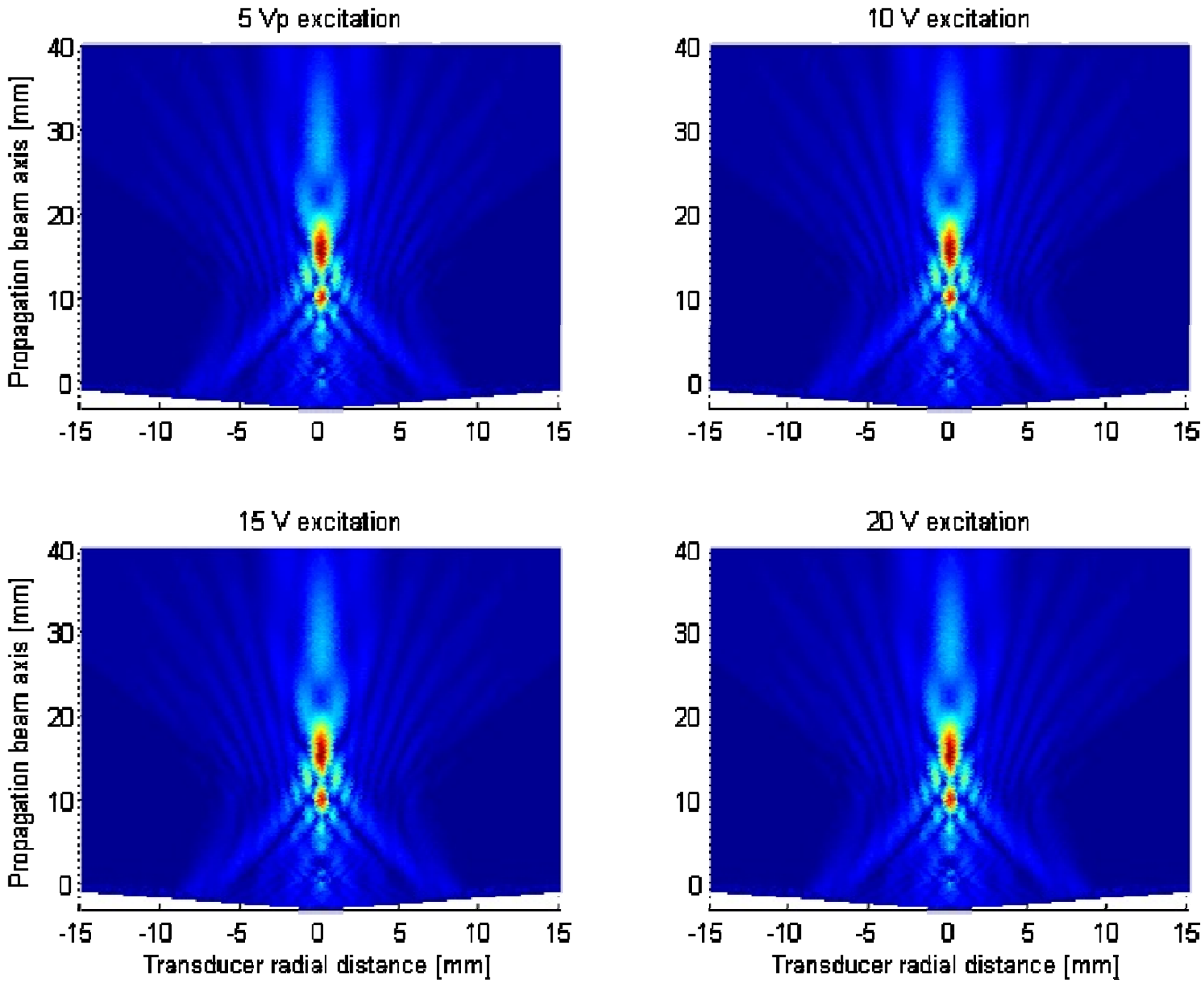
Electric impedance when transducer was emitting in water

HIFU acoustic characterization

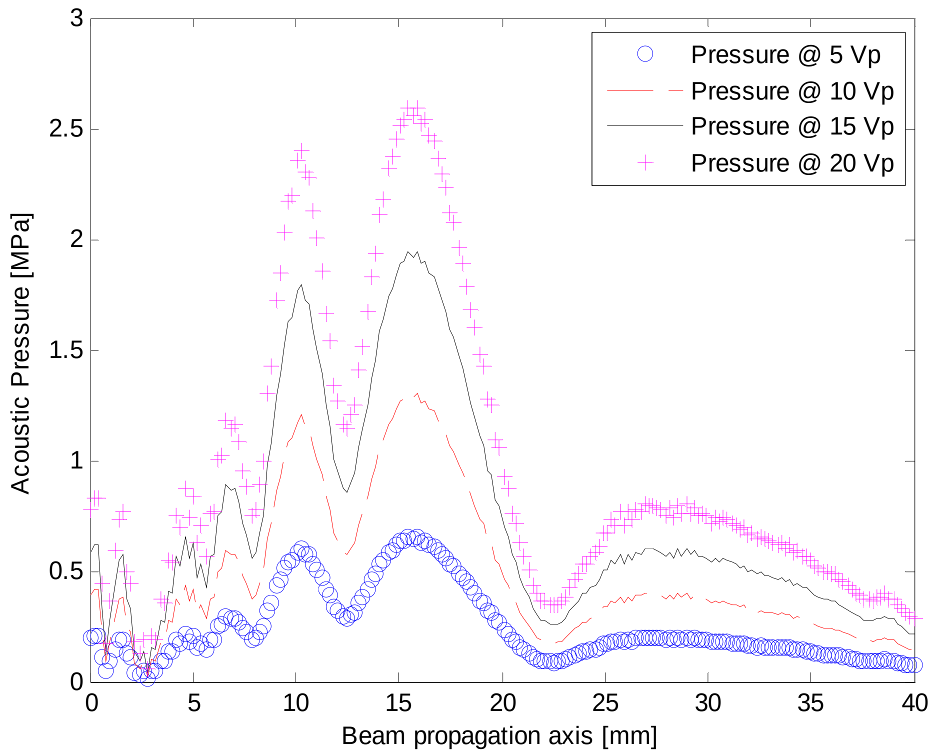


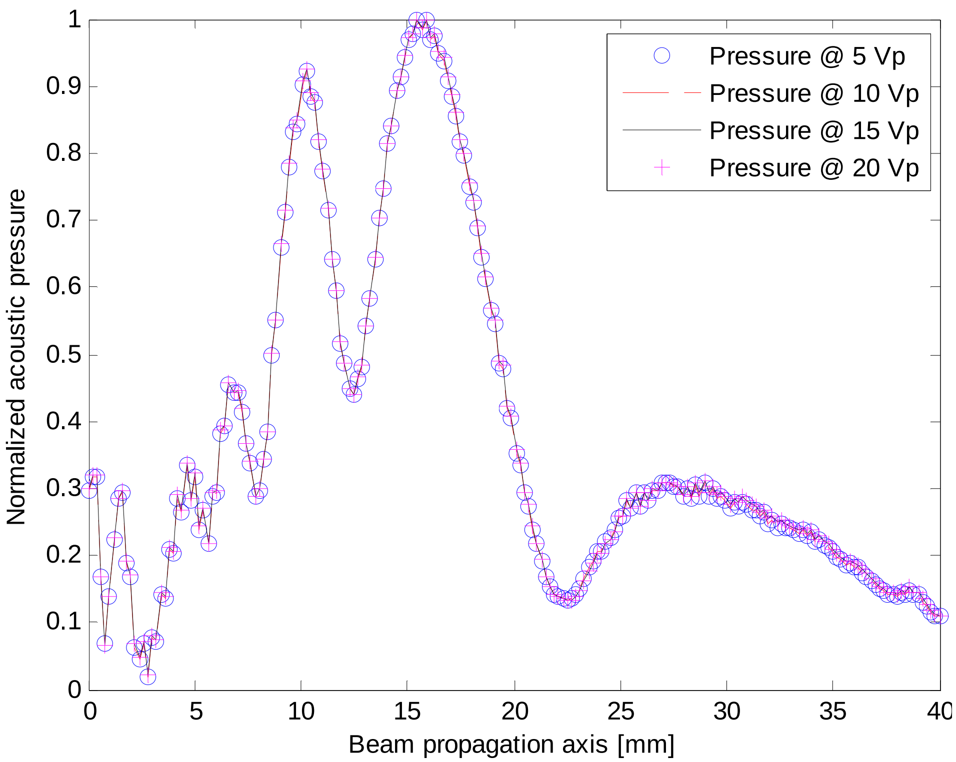


HIFU field modeling

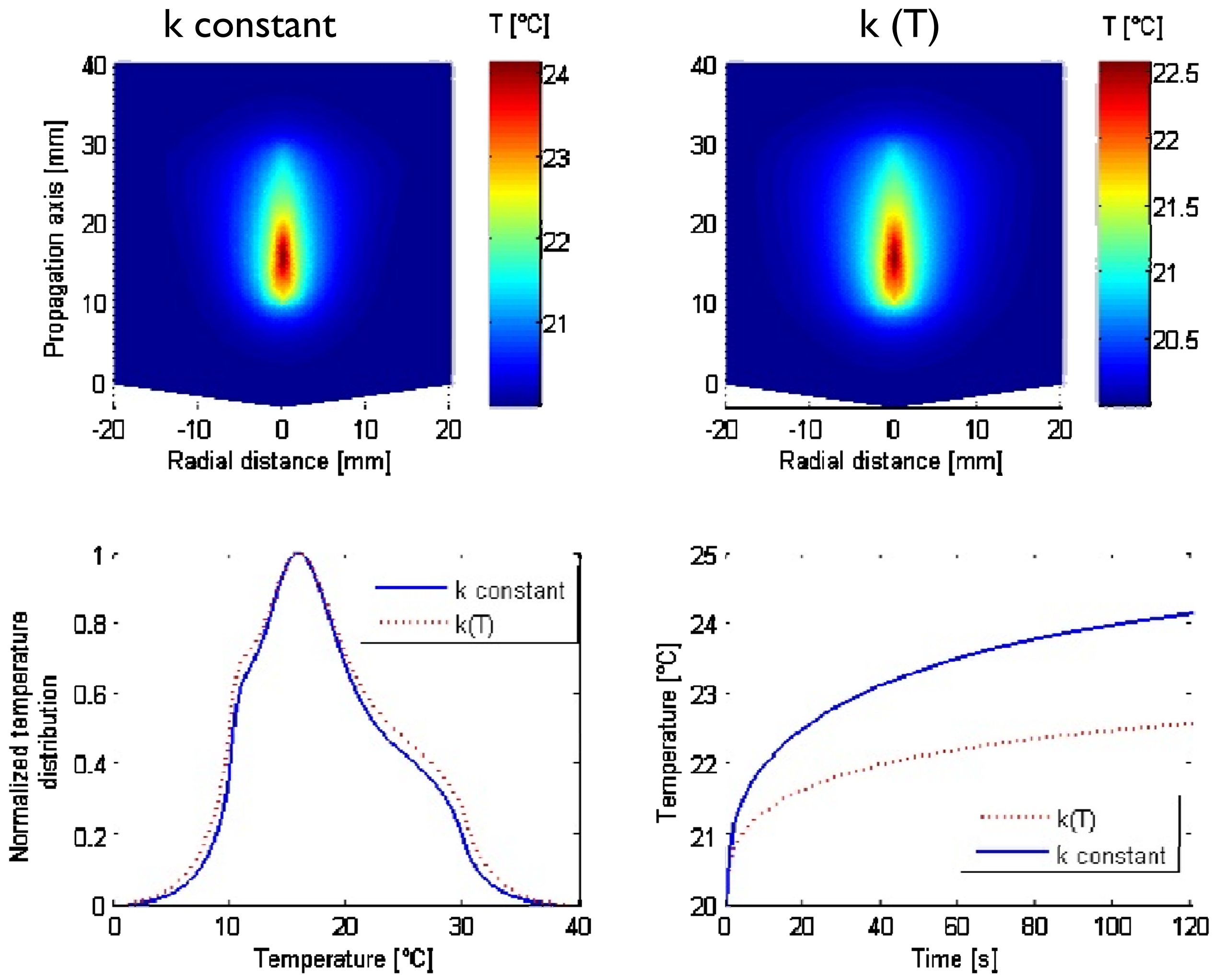


HIFU field modeling

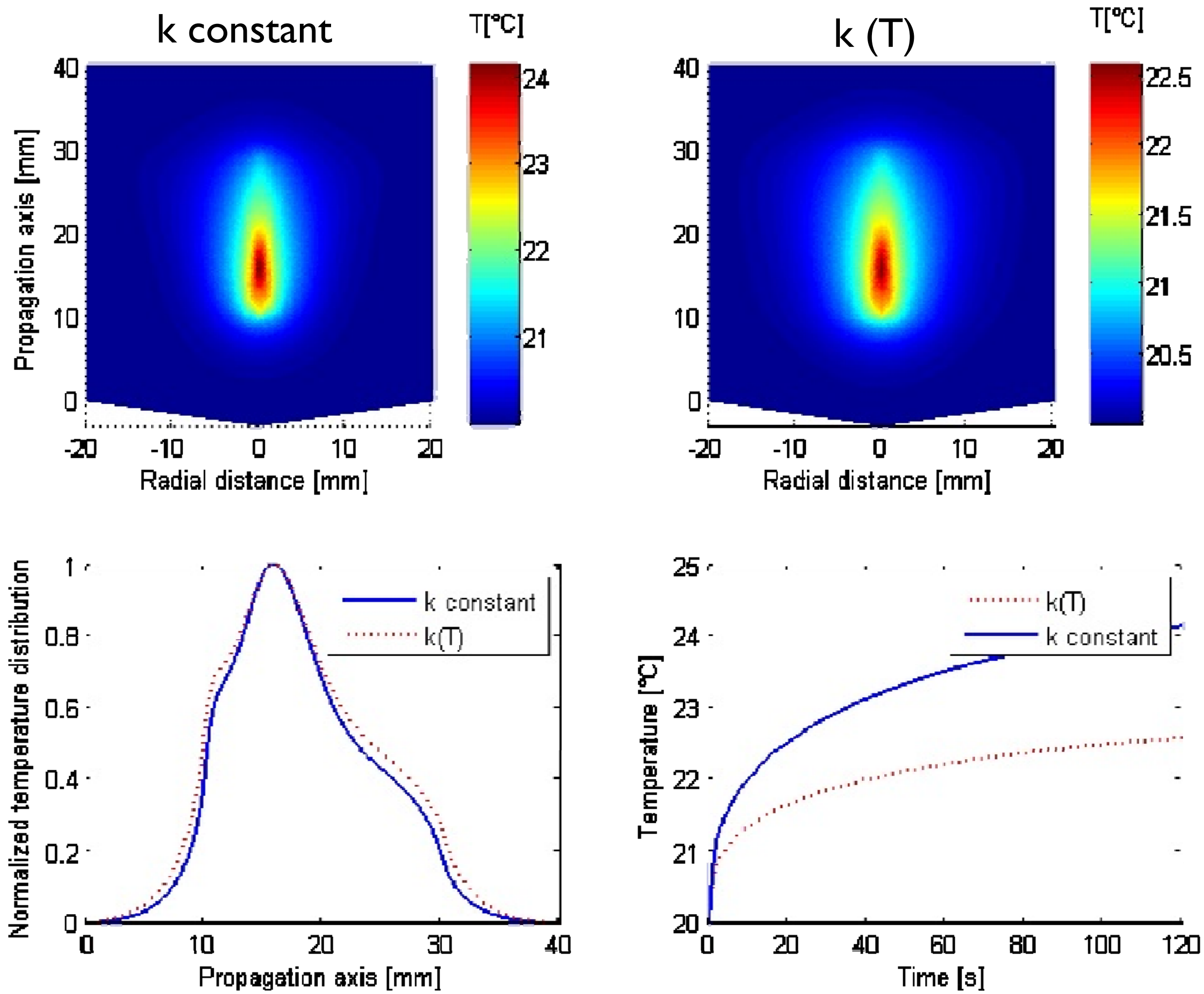




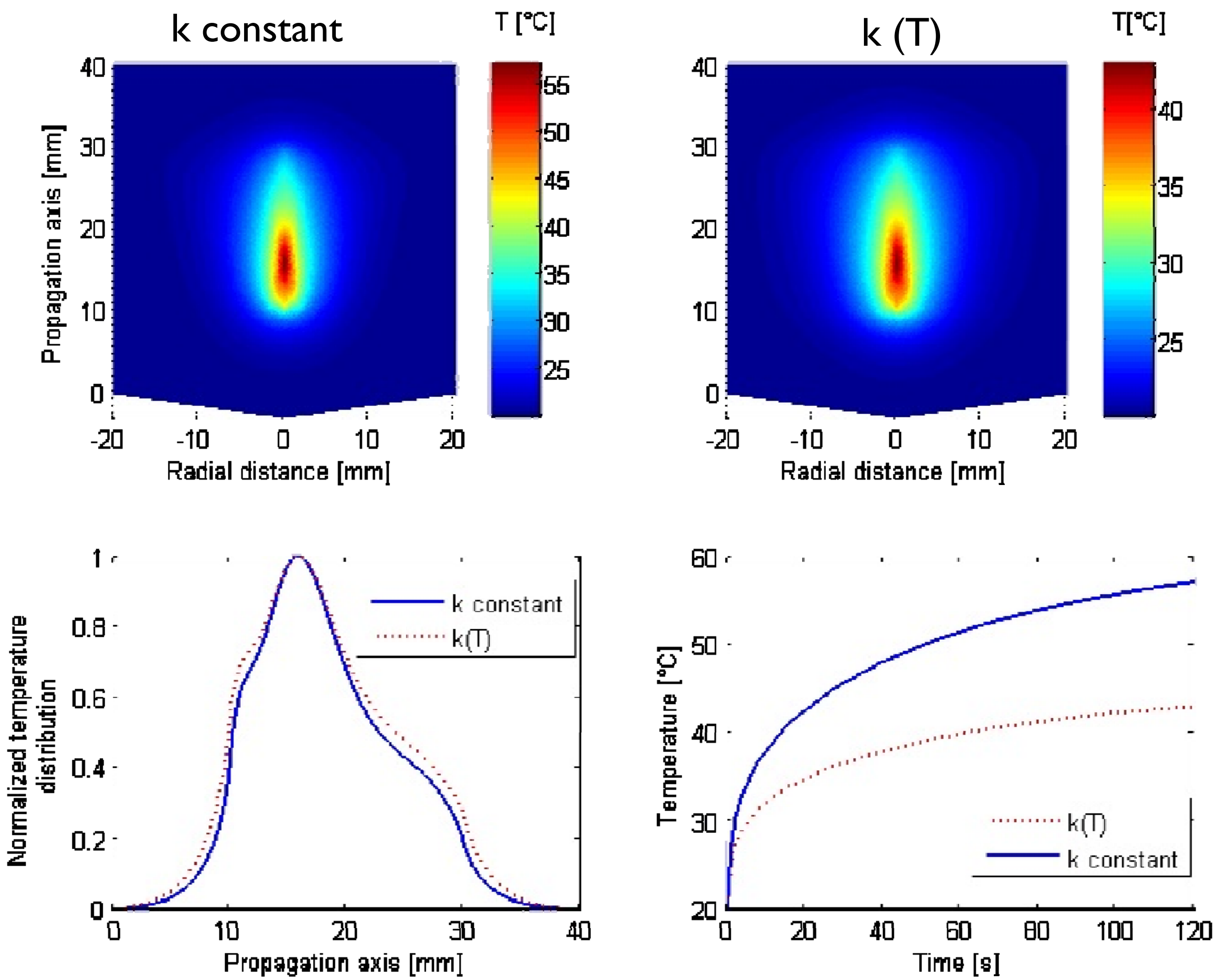
Heating modeling @ 5 Vp excitation



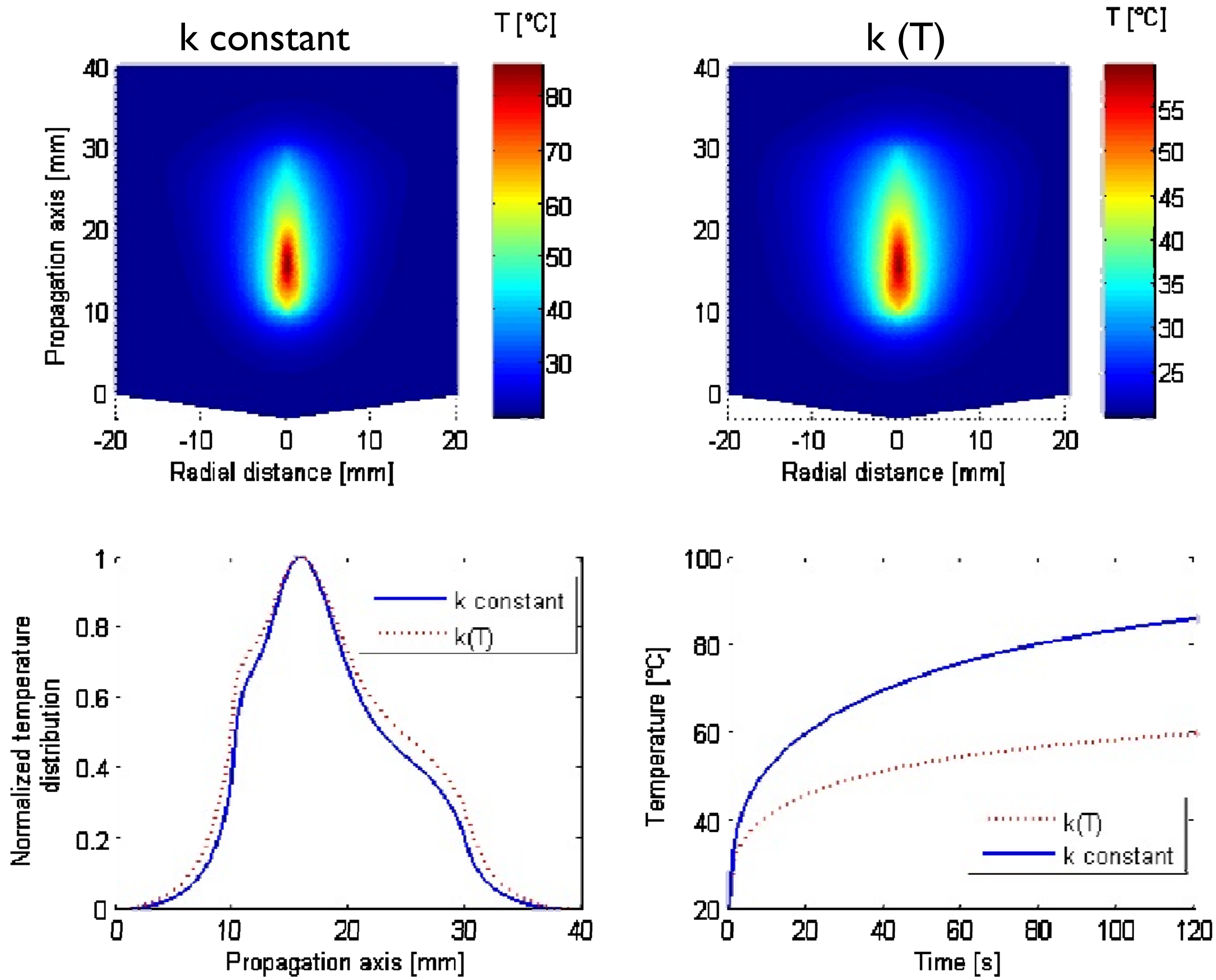
Heating modeling @ 10 Vp excitation



Heating modeling @ 15 Vp excitation



Heating modeling @ 20 Vp excitation



Discussion

- Nonlinearity propagation was neglected.
- Inclusion of temperature dependent tissue/phantom properties.
- Electric power loss: transducer efficiency.
- Pressure acoustic propagation at beam path difference with measured data.
- Heat model validation with measurements in phantom.

Conclusions

- Concave radiator electric impedance model show great concordance with measurements in both air and water media.
- Focused acoustic field depend on piezoelectric element properties which vary according on its fabrication.
- As nonlinearity propagation was neglected, pressure distribution along beam path and the acoustic field did not showed differences.
- Maximum temperature increment was expected on heating modeling with thermal conductivity as a function of temperature.
- Normalized heating along beam path with thermal conductivity as a function of temperature showed a bigger heating area than heating with constant thermal conductivity.
- Model improvement.

Thanks for your attendance

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