HIFU Induced Heating Modeling by using the Finite Element Method

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Introduction
What is HIFU*?

- Ellipsoidal shaped focal zone.
- Focus location depends on transducer geometry and operating frequency.
- Acoustic energy concentration at the focus.
- Quick temperature elevation over 56°C which produces coagulative necrosis.
- Treatment of benign and malignant 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**
Low power measurements using a PVPF-Z44-0400 hydrophone.

1.965 MHz/ 10Vpp burst with a repetition frequency of 10 Hz.

X and Y axis resolution of 0.1016 mm.

Z-axis resolution of 1 mm.
**System equations**

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

where,

- \( \sigma \), stress tensor
- \( c_E \), elasticity matrix
- \( e_T \), electro-mechanic coupling matrix
- \( E \), electric field
- \( D \), displacement vector
- \( \varepsilon \), deformed tensor
- \( \varepsilon_0 \), vacuum permittivity
- \( \varepsilon_{rT} \), relative permittivity

Piezoelectric material: 
**PZT-8**
HIFU transducer FEM electric impedance modeling

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

Element material: PZT-8
HIFU transducer electric impedance

- Electric impedance in transducer face

\[
I = \int_S J \cdot dA
\]

\[
Z_e = \frac{V_{B-A}}{I}
\]

where,

\(J\), current density in transducer’s face
\(A\), transducer face area
\(V_{B-A}\), electric potential between both electrodes A and B
\(I\), current
\(Z_e\), electric impedance
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

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

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: Q_{ext}
**Phantom thermal conductivity**

- **Fixed:** $0.5 \text{ W/(m*K)}$
- **Temperature dependent**:

\[
y = 9 \times 10^{-5}x^2 - 0.0536x + 8.8805
\]

\[R^2 = 0.9906\]

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

5 Vp excitation

10 V excitation

15 V excitation

20 V excitation
Heating modeling @ 5 Vp excitation

![Graphs showing temperature distribution and comparison between k constant and k(T).]
Heating modeling @ 10 Vp excitation

Graphs showing heat distribution and temperature changes under constant and temperature-dependent thermal conductivity conditions.
Heating modeling @ 15 Vp excitation

- k constant
- k (T)

Normalized temperature distribution

Temperature vs. Time
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 shows great concordance with measurements in both air and water media.

- Focused acoustic field depends on piezoelectric element properties which vary according to its fabrication.

- As nonlinearity propagation was neglected, pressure distribution along beam path and the acoustic field did not show 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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