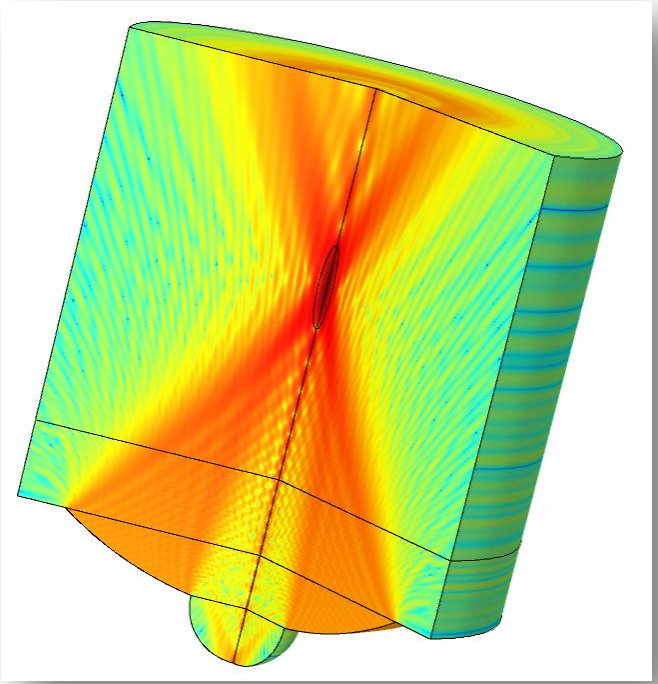
Focused Ultrasound Induced Heating in Tissue Phantom



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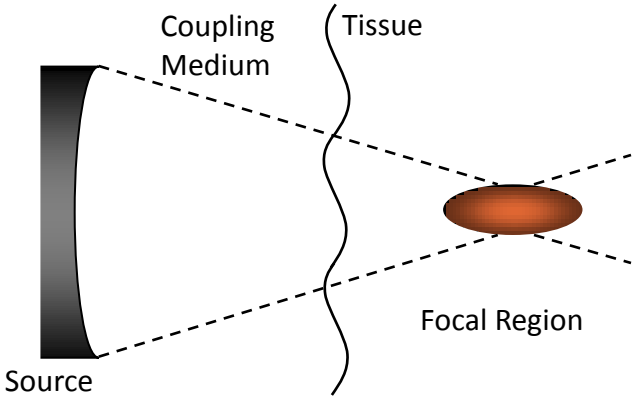
Introduction

- This model example shows how to model tissue heating induced by focused ultrasound.
- The pressure acoustic field is solved in the frequency domain and the tissue heating is solved in the time domain.
- The acoustic intensity field is calculated from the pressure field, and the absorbed energy is then used as the heat source for the Bioheat Transfer thermal model.
- This model is suitable for tissue heating when the acoustic pressure at the focus is well below the acoustic cavitation threshold.
- This model is inspired by the experimental work of Huang [Huang *et al.*, *J. Acoust. Soc. Am.*, **116** (2004)] that consisted in measuring focused ultrasound induced heating in a tissue phantom.
- The model uses the same geometry and material properties as in the reference. The simulation results are compared to the experimental data in the reference.



Focused ultrasound makes selective and targeted heating possible: heating of tissues lying within the focal volume can be achieved with minimal damage to nearby healthy tissue and other structures lying elsewhere in the path of the beam.

Model assumptions

- Pressure Acoustics:
  - Linear Acoustic wave propagation in frequency domain (2D axi-symmetric)

$$\frac{\partial}{\partial r}[-\frac{r}{\rho_c}(\frac{\partial p}{\partial r})]+r\frac{\partial}{\partial z}[-\frac{1}{\rho_c}(\frac{\partial p}{\partial z})]-[(\frac{\omega}{c_c})^2]\frac{rp}{\rho_c}=0$$

    Where *r, z* are radial and axial coordinates, *p* is the acoustic pressure, ω is the angular frequency, and r_c and c_c are the complex density and speed of sound.

  - Shear waves in tissue domain are assumed much smaller than the compressional wave and so are neglected.

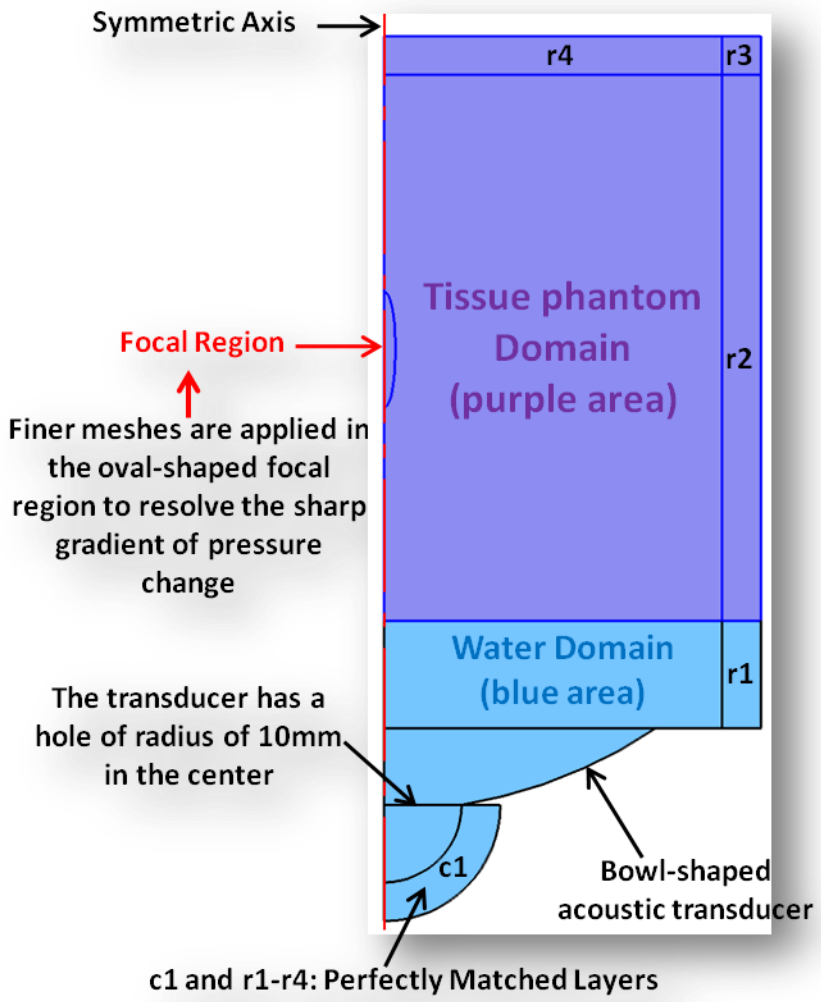
Model assumptions

- Bioheat Transfer:
  - The Pennes' Bioheat Transfer equation models heat transfer within biological tissue

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) - \rho_b C_b w_b (T - T_b) + Q + Q_{met}$$

    where T is the temperature, ρ is the density, C_p is the specific heat, K is the thermal conductivity, ρ_b is the density of blood, C_b is the specific heat of blood, w_b is the blood perfusion rate, T_b is the temperature of the blood, Q is the heat source (e.g. absorbed ultrasound energy), and Q_{met} is the metabolic heat source.
  - Tissue properties do not change with temperature rise
  - Blood perfusion is not included but can be added in easily

Model Definition



- **Pressure Acoustics**
  - The bowl-shaped acoustic transducer (with a hole of radius of 10 mm in the center) and the tissue phantom are immersed in water
  - 2D axi-symmetric simulation
  - Frequency domain study to get the steady state pressure field
- **Bio-heat Transfer Model**
  - The heat source for thermal simulation is a function of acoustic intensity:

$$Q = 2\alpha_{ABS} I = 2\alpha_{ABS} \left| \mathrm{Re}\left(\frac{1}{2} p\mathbf{v}\right)\right|; \quad I = \left|\mathrm{Re}\left(\frac{1}{2} p\mathbf{v}\right)\right|$$

α_{ABS} - Acoustic absorption coefficient

p - Acoustic pressure

ρ - Density

I - Acoustic intensity

c - Speed of sound

  - In COMSOL, the intensity is a derived variable whose magnitude can be accessed as acpr.I_rms
  - The acoustic source is turned on for one second and the tissue is then left for cooling
  - Time-dependent analysis to model temperature field as a function of time

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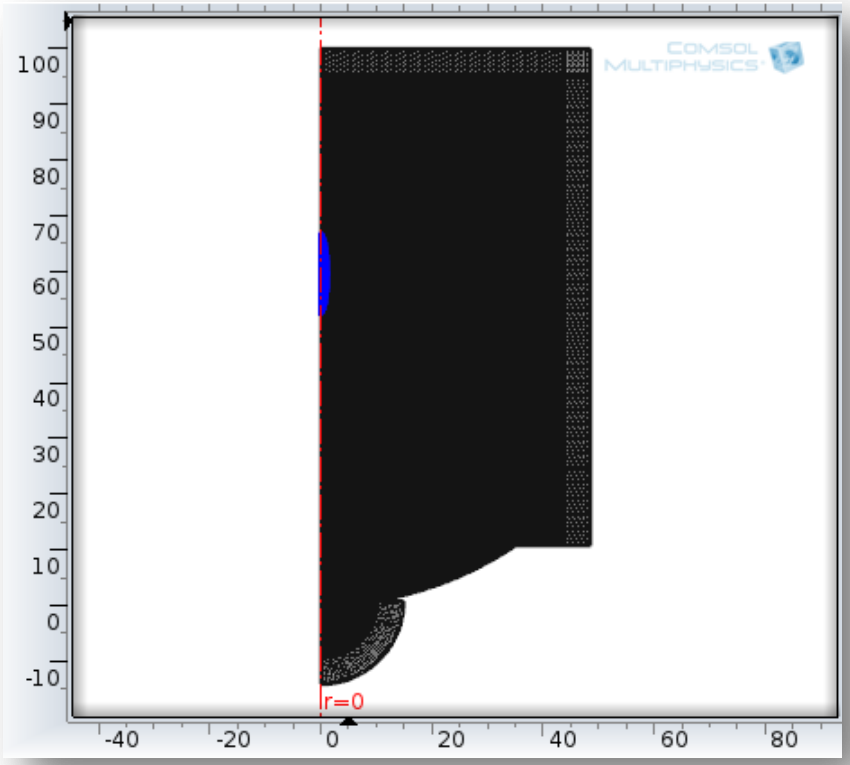
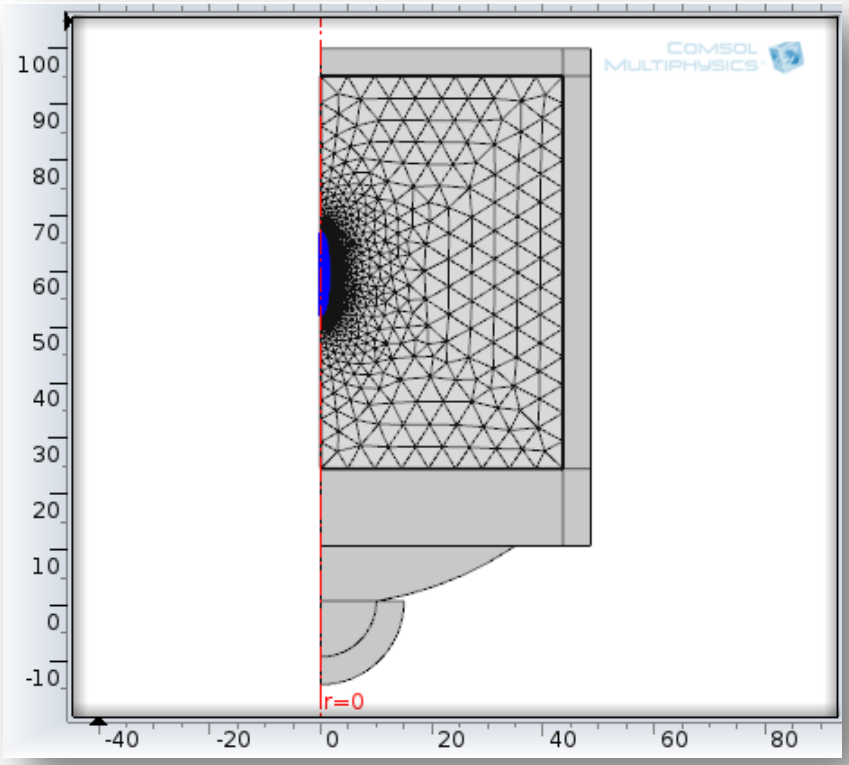
Meshing

A finer mesh was used in acoustic simulation



Quartic (4th order) elements were used to discretize pressure. Maximum element size of λ/6 was used in the focal region to resolve the high gradient of pressure change; Maximum element size of λ/4 was used elsewhere.

A coarser mesh was used in thermal simulation



Quadratic (2nd order) elements were used to discretize temperature. The same mesh as used in acoustic simulation was applied to the focal region to resolve the high gradient of temperature change; A coarser mesh was used elsewhere (maximum element size of 5 mm).

Material Properties

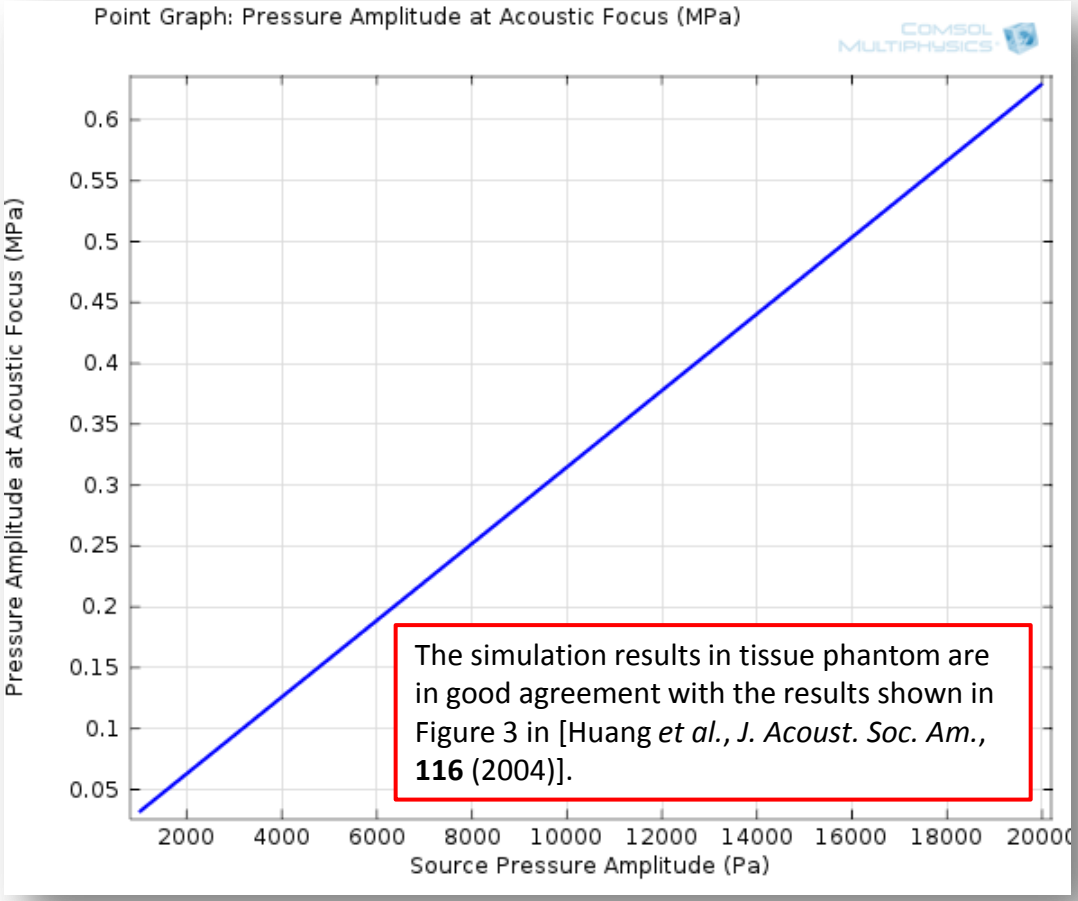
Property	Density (kg/m^3)	Sound Speed (m/s)	Attenuation (Np/m/MHz)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)
Water (@293.7K)	1000	1483	0.025	N/A	N/A
Tissue Phantom*	1044	1568	8.55	3710	0.59
Human Tissue**	1000-1100	1450-1640	4.03-17.27	3600-3890	0.45-0.56

* The properties of the tissue phantom are the measured data described in [Huang *et al.*, *J. Acoust. Soc. Am.*, **116** (2004)].

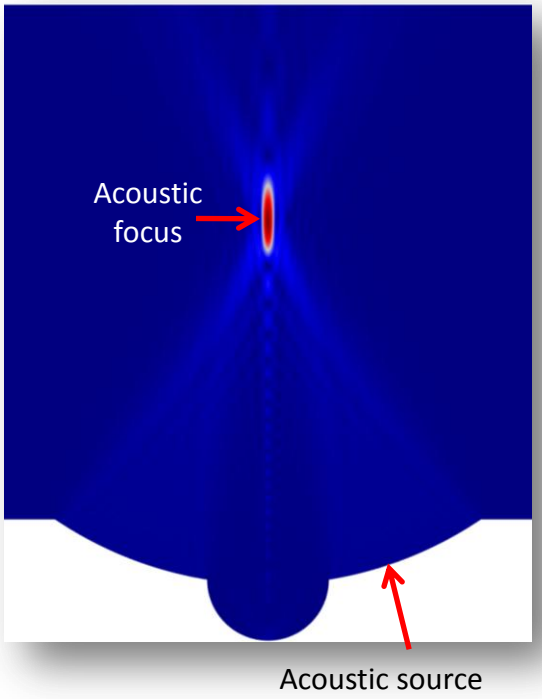
** The properties of human tissue are from [F. A. Duck, *Physical properties of tissue*, Academic Press (1990)].

Results

Pressure amplitude at the acoustic focus in tissue phantom vs. source pressure.

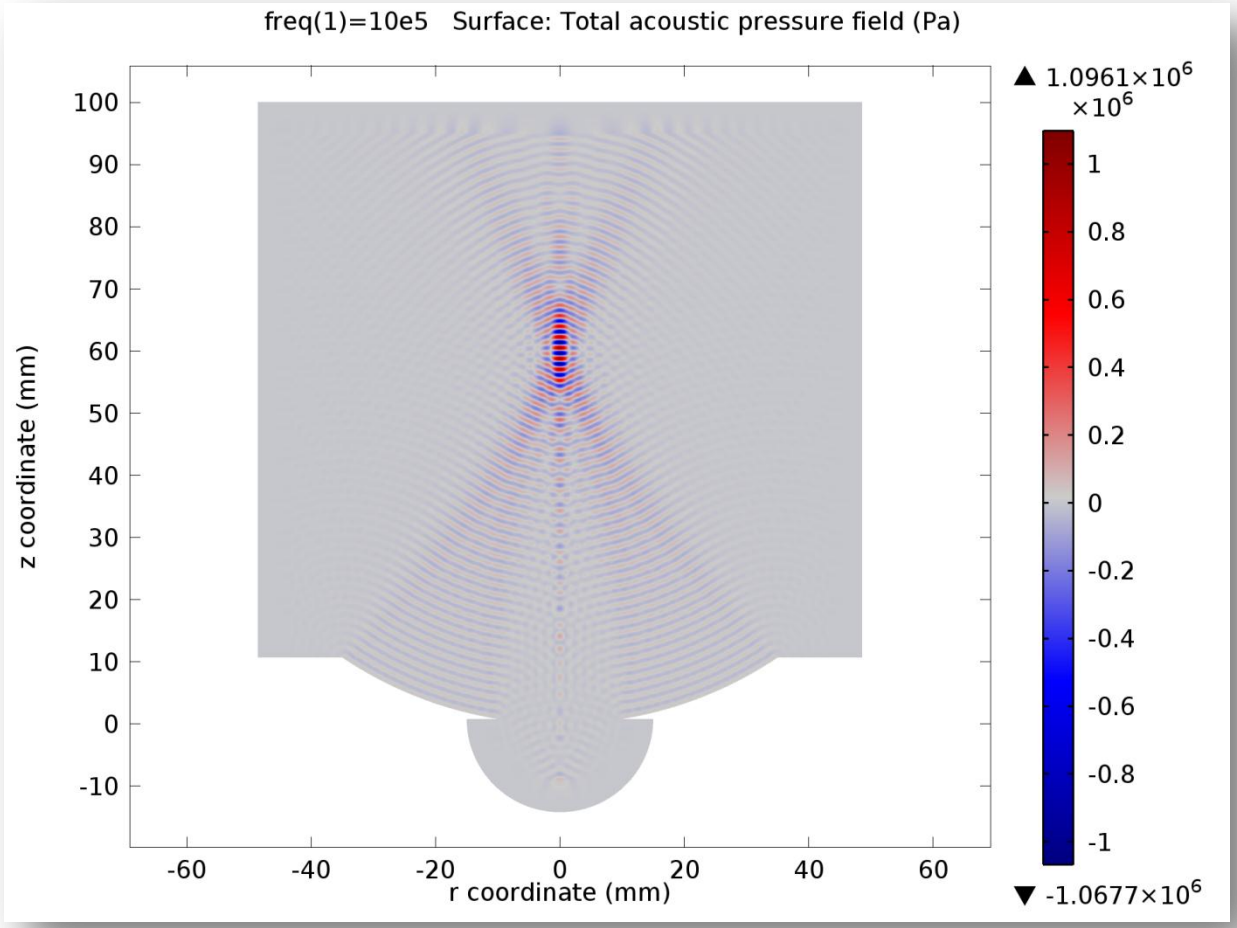


The simulation results in tissue phantom are in good agreement with the results shown in Figure 3 in [Huang *et al.*, *J. Acoust. Soc. Am.*, **116** (2004)].



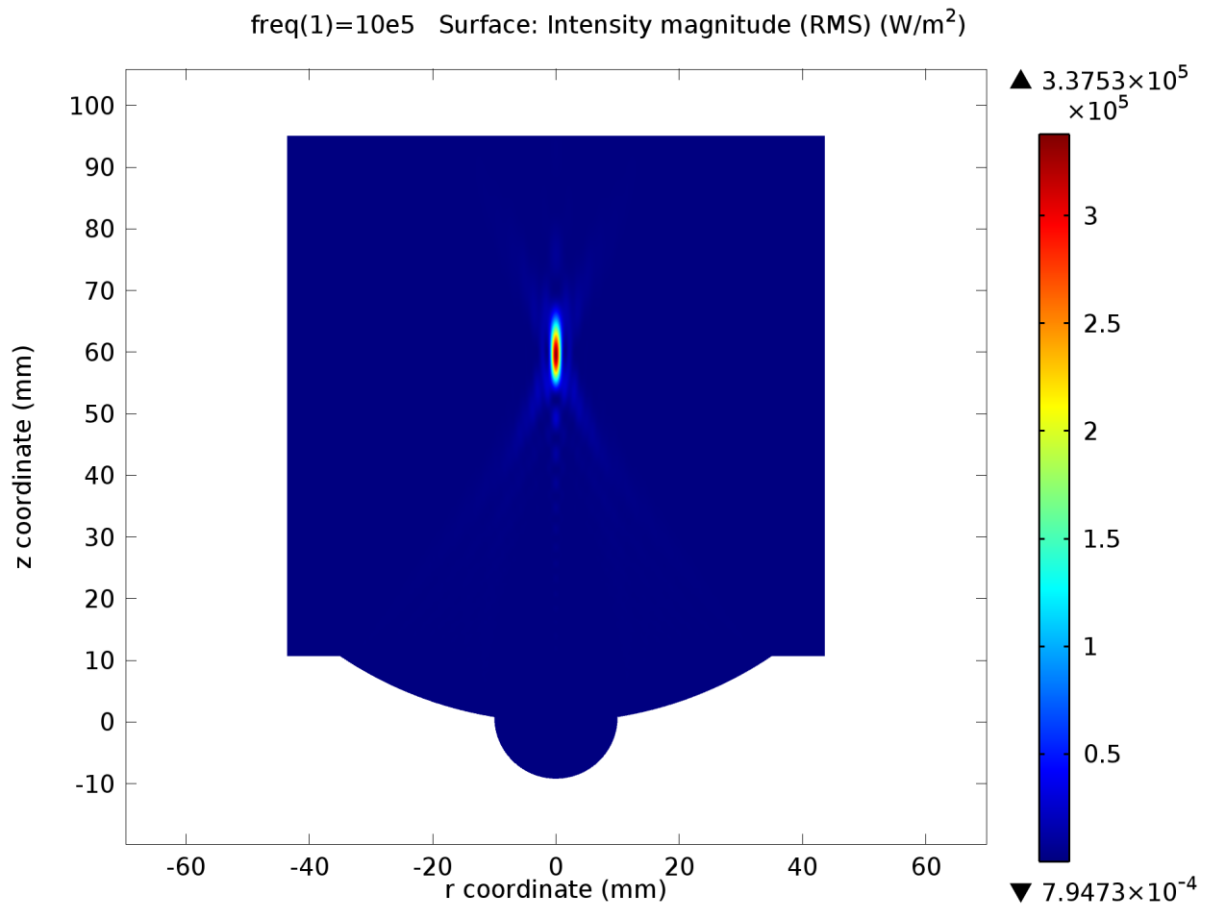
Results

The acoustic pressure field in the water and tissue phantom domains (focal pressure amplitude 1.11 MPa).



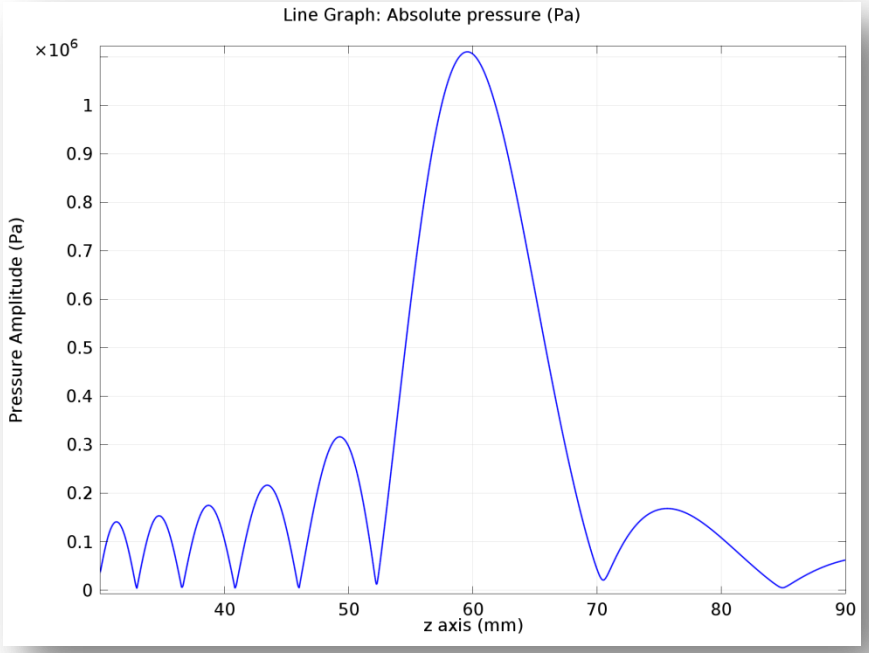
Results

The acoustic intensity field, showing the acoustic energy to be concentrated in the focal region (focal pressure amplitude 1.11 MPa).

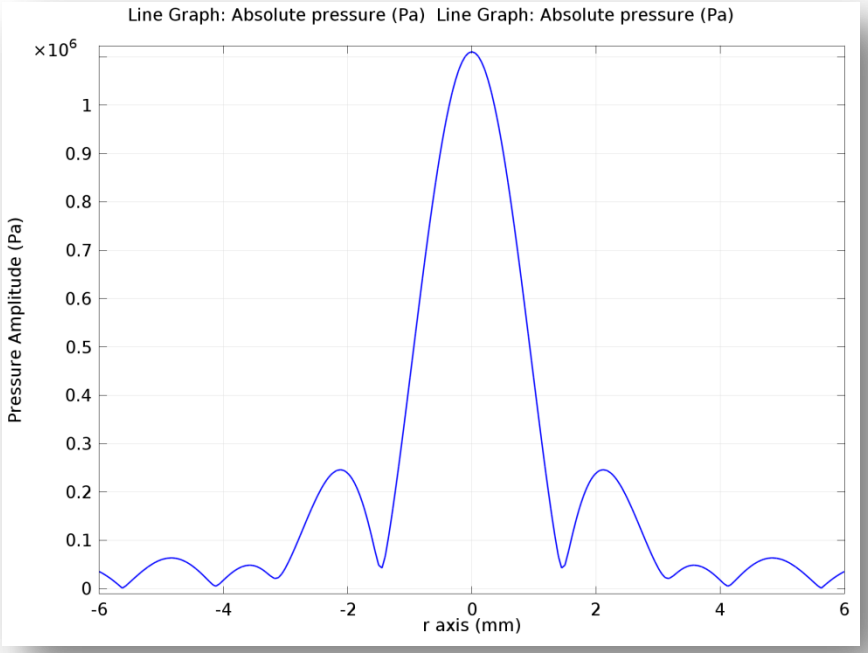


Results

The acoustic pressure amplitude profile along the axis of symmetry (r = 0) and the radial direction in the focal plane (focal pressure amplitude 1.11 MPa).



Acoustic pressure amplitude profile along the acoustic axis (r = 0)



Acoustic pressure amplitude profile along the radial direction in the focal plane

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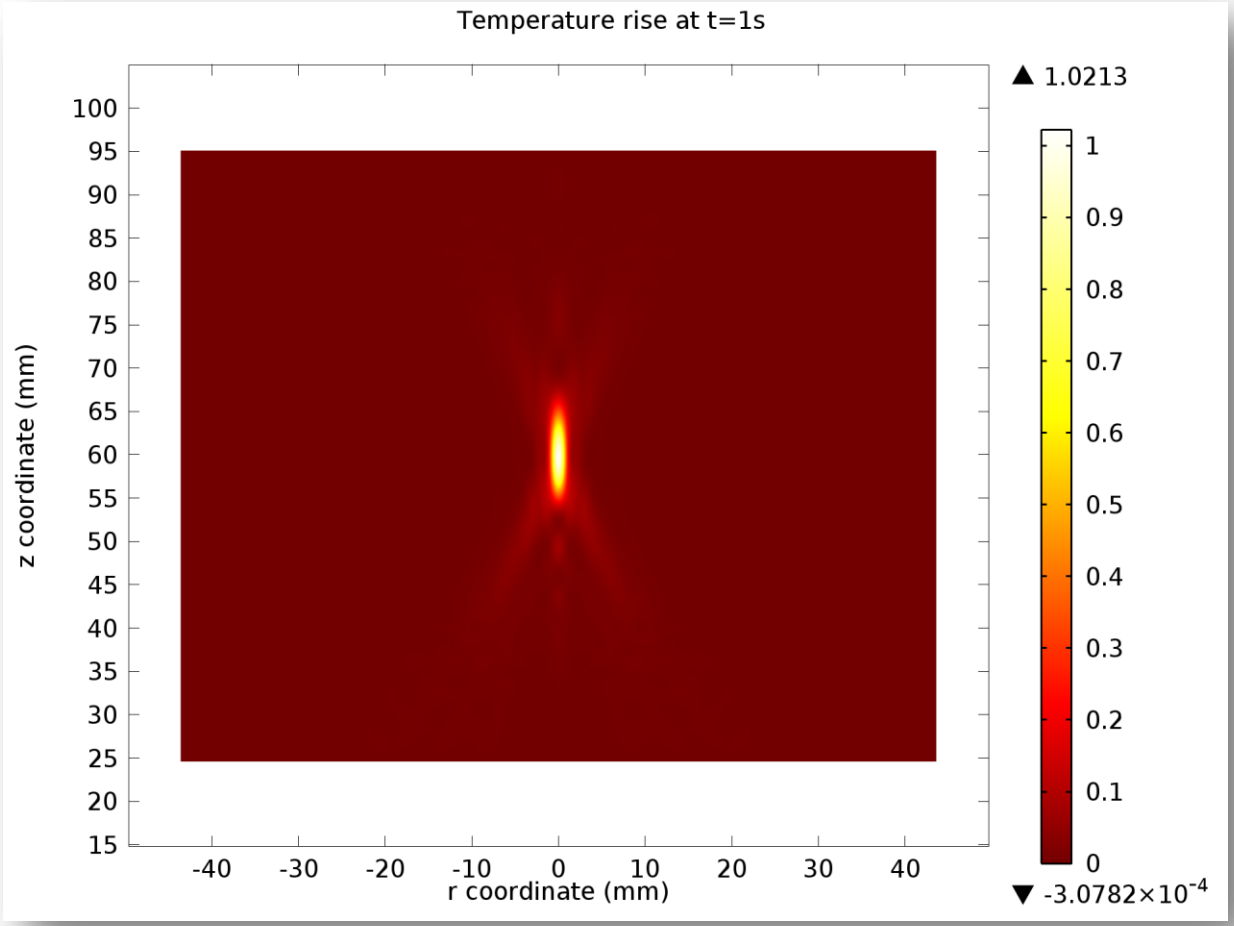
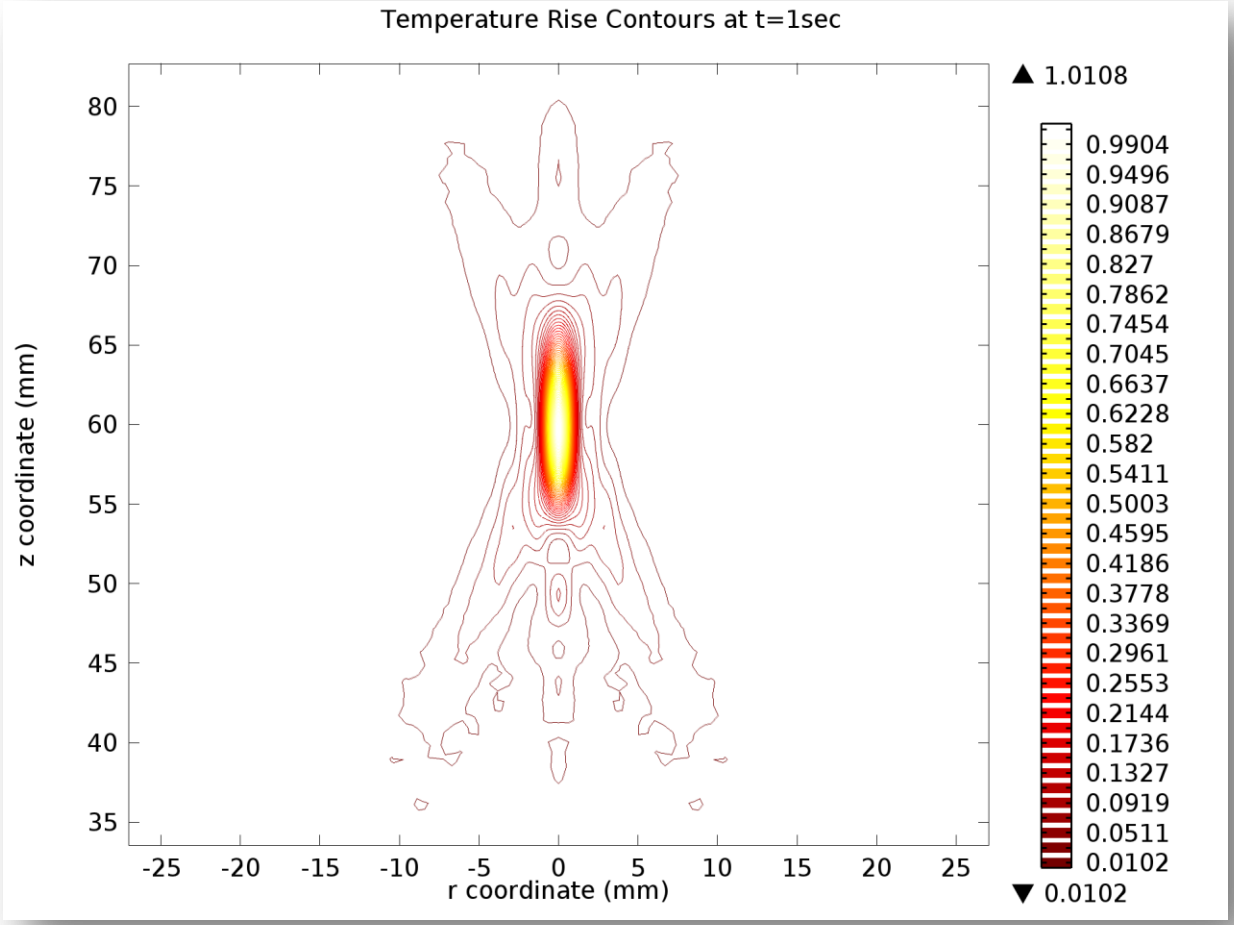
Results

Temperature rise in tissue phantom after one second insonation (focal pressure amplitude 1.11 MPa).



Results

Isothermal contours in tissue phantom after one second insonation (focal pressure amplitude 1.11 MPa).



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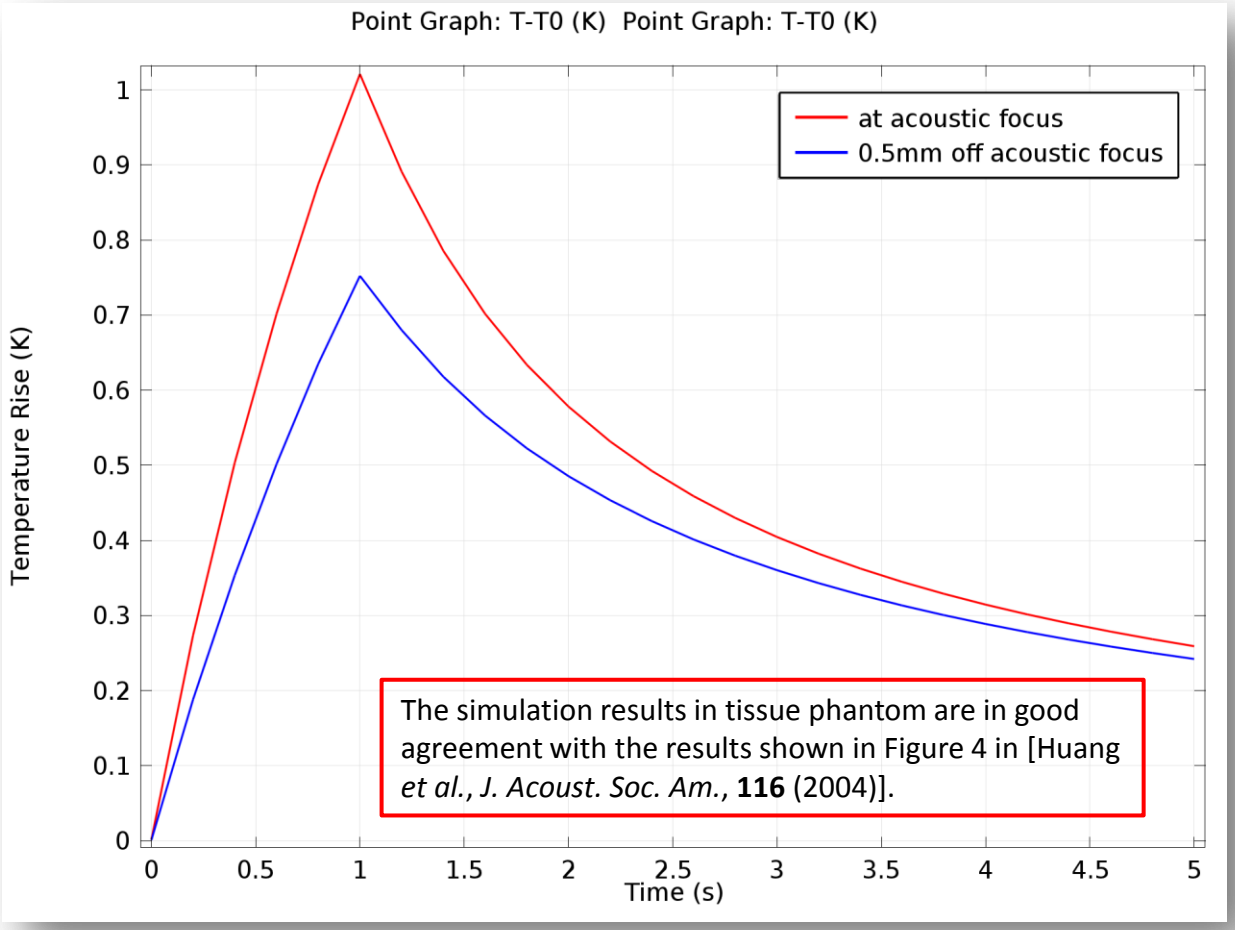
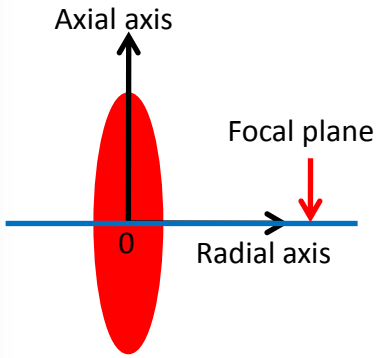
Results

Heating and cooling curves at the acoustic focus and 0.5 mm away from the acoustic focus (focal pressure amplitude 1.11 MPa).





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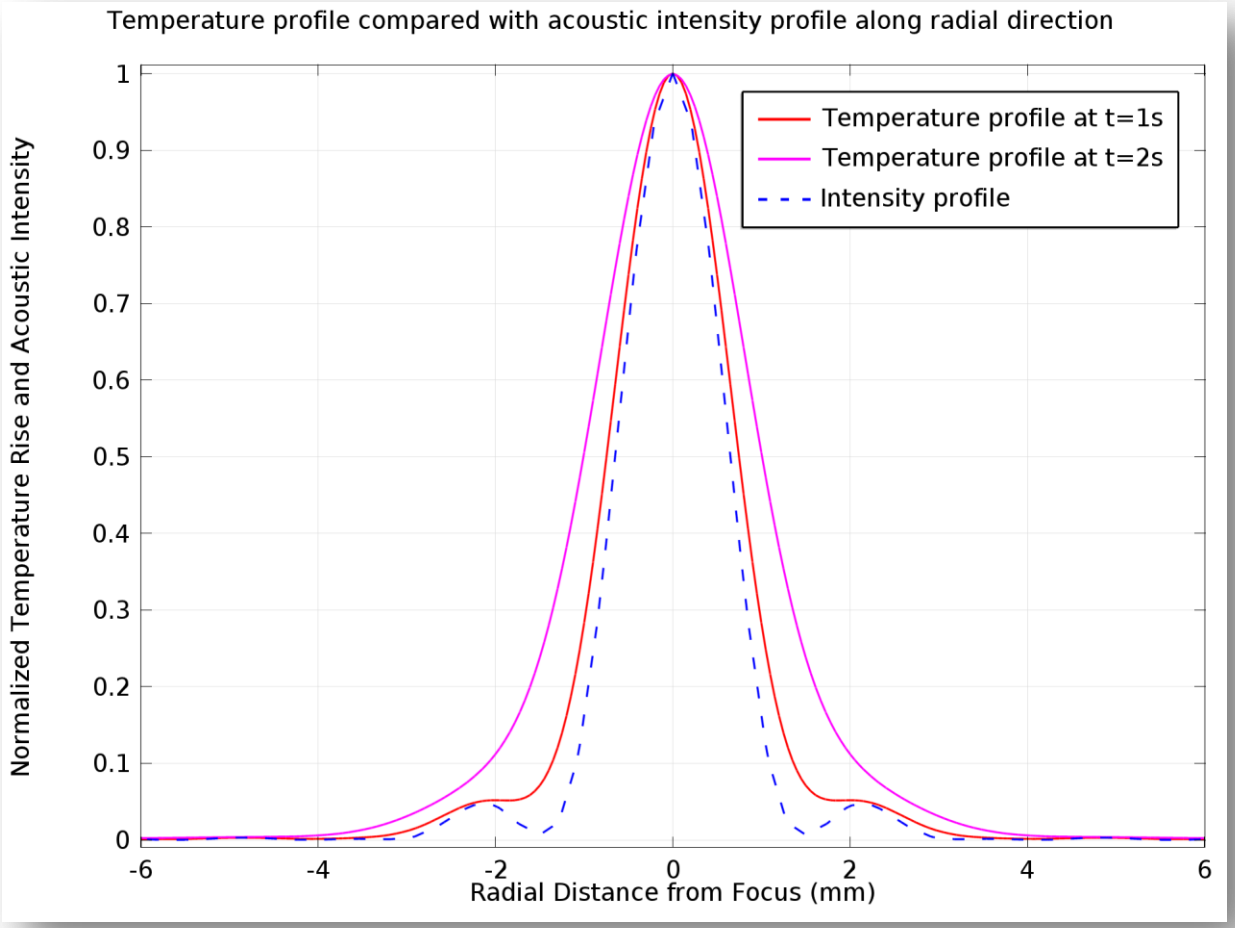
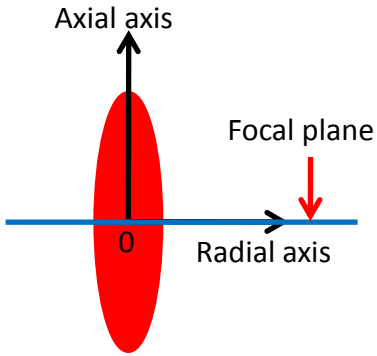
Results

The temperature and intensity profiles show that the side lobes in the intensity field are mitigated in the temperature response due to the smoothing effect of the thermal conduction.





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