Simulation of a Piezoelectric Catheter-based Acoustic Ablation Device

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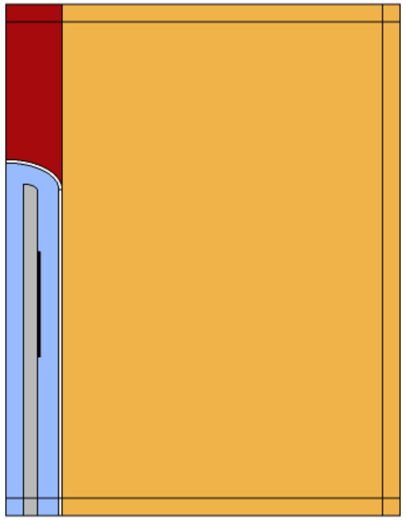
Introduction

- Thermal ablation allows for bulk removal of tissue by inducing coagulative necrosis
- Acoustic ablation can be used to target tissue selectively while being minimally invasive
- Veryst used COMSOL Multiphysics to simulate a device which heats tissue through the propagation of acoustic waves
  - Piezoelectric transducers used to generate acoustic waves
  - Pressure losses in tissue created an acoustic heat source
- Coupled finite element model included
  - Piezoelectric Effect
  - Pressure Acoustics (Frequency Domain)
  - Laminar Flow
  - Bioheat Transfer

Device Geometry

- Simulated ablation device consisted of
  - Rigid stainless-steel shaft
  - Array of annular PZT transducers
- Transducers were held to shaft with an acoustic insulating epoxy
- Device was encased in a polycarbonate bag with cooling fluid
- Model was created using a 2D axisymmetric geometry to reduce complexity

a) 3D geometry of ablation device



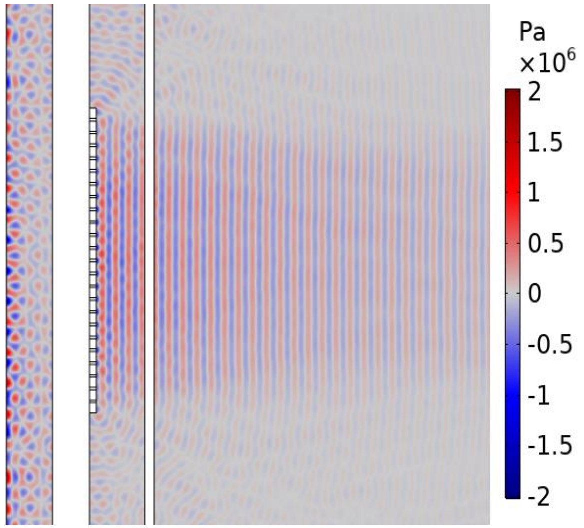
b) 2D geometry of ablation device, surrounding tissue (yellow), and blood (red)

Material Properties

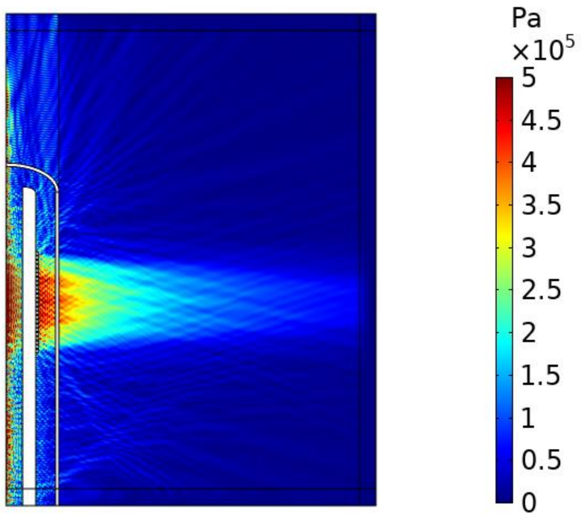
Parameter	Symbol	Value	Reference
Tissue Density	ρ	1.050 g/cm^3	[8]
Tissue Specific Heat Capacity	c_{pt}	3540 J/kg/K	[9]
Tissue Thermal Conductivity	k_t	0.469 W/m/K	[9]
Blood Perfusion Rate	ω_b	6.4e-3 1/s	[10]
Blood Specific Heat Capacity	c_{pb}	3594 J/kg/K	[11]
Water Acoustic Absorption Coefficient	α_w	3590.694 1/m at 5.27 MHz	[7]
Tissue Acoustic Absorption Coefficient	α_t	54.5 1/m at 5.27 MHz	[7]

Pressure Acoustics (Frequency Domain)

- Eigenfrequency study identified 5.27 MHz as the optimal transducer frequency
  - Mode shape that would produce pressure waves in the radial direction
- PML was used to resolve waves not completely attenuated by tissue and blood
- Lossy elastic behavior of tissue acted as a heat source in this study
  - Attenuation in tissue was used as a heat source in subsequent heat transfer studies



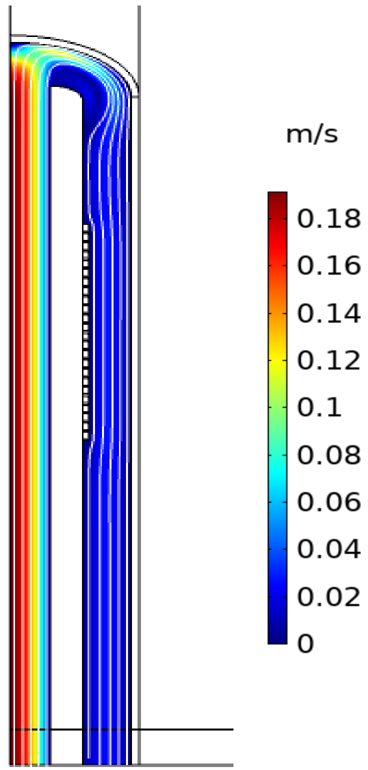
a) Acoustic pressure near transducer array



b) Absolute acoustic pressure in device, tissue, and blood

Laminar Flow

- Modeled aqueous cooling fluid flowing around ablation device
- Fluid at a temperature of 25°C
- Conjugate heat transfer was considered (non-isothermal flow)
- Circulation of the fluid was through the center of the hollow central shaft supporting piezoelectric transducers
- If flow pattern of the coolant fluid is not axisymmetric, a 3D CFD simulation would be required
- In some cases, we can ignore the CFD simulation completely, and assume a suitable heat transfer coefficient at the boundaries involving the coolant fluid



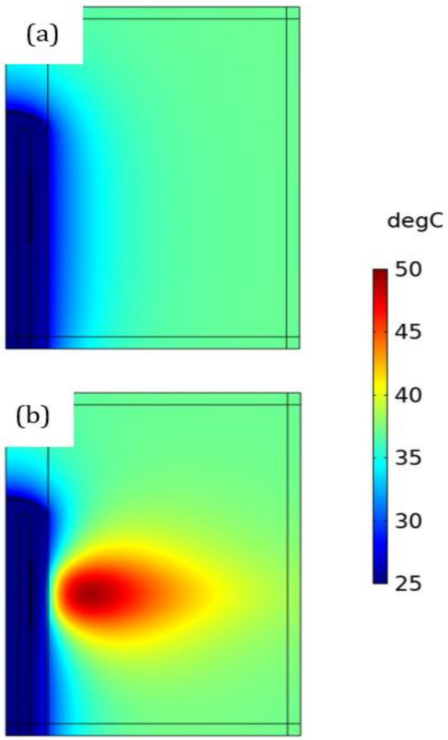
Fluid velocity and streamlines in a cross section of the ablation device

Bioheat Transfer

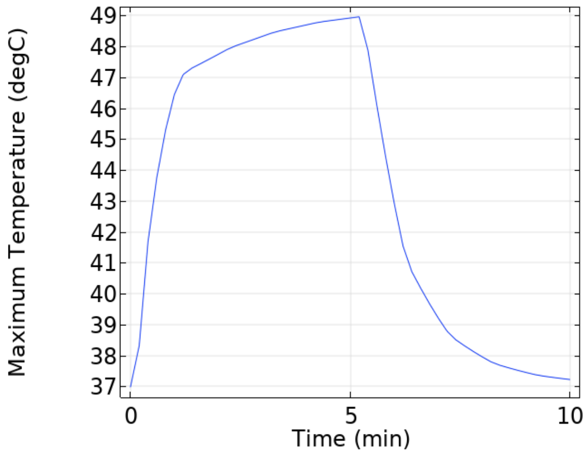
- Pennes Bioheat Transfer Model was used with an acoustic heat source considering blood perfusion:

$$\rho c_{pt}\frac{\partial T'}{\partial t} = \nabla[k_t \nabla T'] - \omega_b c_{pb} T' + Q_{ac}$$

- The acoustic heat source was determined from the heat generated by the attenuation of acoustic wave
  - Due to lossy elastic behavior of tissue
- Transient heat transfer model over a 10-minute period
  - 6 minutes active heating
  - 4 minutes with transducers switched off

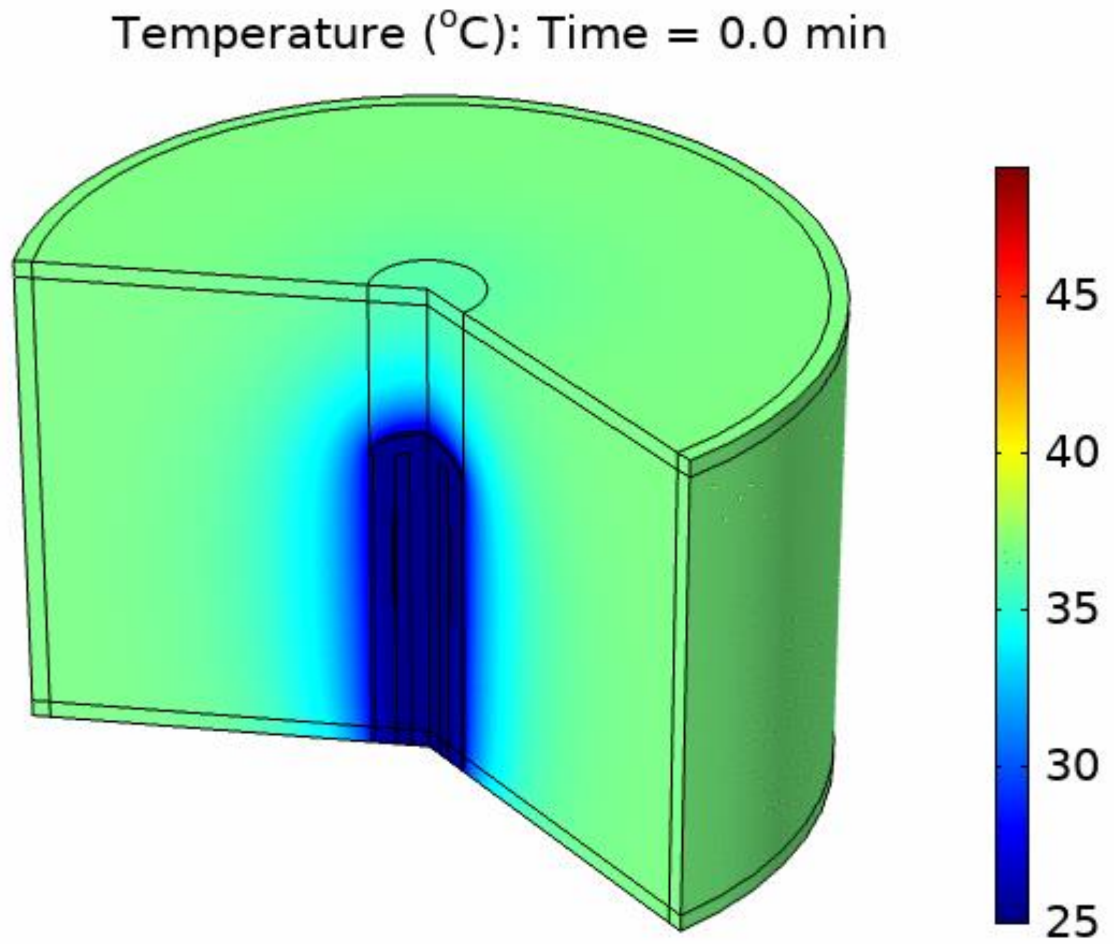


Temperature distribution in ablation device, tissue, and blood (a) at initial state before the start of ablation (b) after 5 minutes of heating



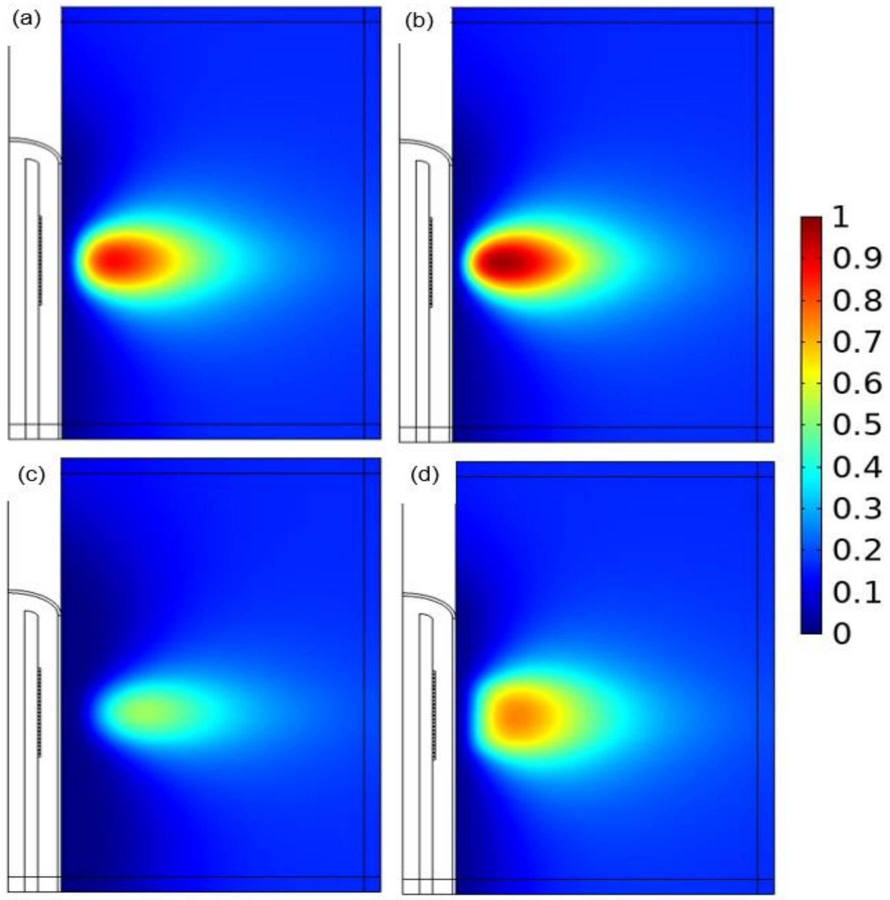
Maximum temperature in the tissue over the ablation period

Transient Heat Transfer



Temperature distribution in ablation device, tissue, and blood for a 10-minute treatment

Resulting Damage



- Fraction of damaged tissue from Arrhenius kinetics damage integral was evaluated after 10 minutes (6 minutes of heating and 4 minutes with the with transducers switched off) in:
  a) original model with uniform power distribution along transducer array
  b) model with transducer power maximized in central transducers of the array
  c) model with cooling fluid at a temperature of 10°C
  d) model with transducer power maximized in upper and lower regions of the transducer array
- Arrhenius damage model considered typical necrosis values for liver tissue [9]

Conclusions

- Acoustic tissue ablation devices can be modeled easily and accurately with simulation tools such as COMSOL Multiphysics
- Important factors to consider in designing ablation devices:
  - Temperature
  - Shape of ablation zone
- Changing the power distribution in the array of piezoelectric transducers can produce targeted ablation zones
- Computational models allow for the rapid iteration of various geometries and parameters and reduce the need for in vivo experimental studies
  - Simulation tools can provide a great starting point for the design of complex medical devices

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