Optimizing Performance of Equipment for Thermostimulation of Muscle Tissue using COMSOL Multiphysics

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Introduction

Thermostimulation = Heating therapy + Electric stimulation of muscles

- Optimal stimulation: Electric field in muscles must be above **stimulation threshold**
- Painless treatment: Electric field in nerve region must be below **pain threshold**
- Thermotherapy: **High temperature** required in muscles for hyperthermia
- Avoid overheating: Upper temperature limit of **42 ºC** at skin surface / inside body

Project target: Build simulation models which can be used to make optimal design choices for thermostimulation equipment: electrode layout and electrode material, heat pad layout, alternative heating methods, effect of body composition on stimulation effect, etc.

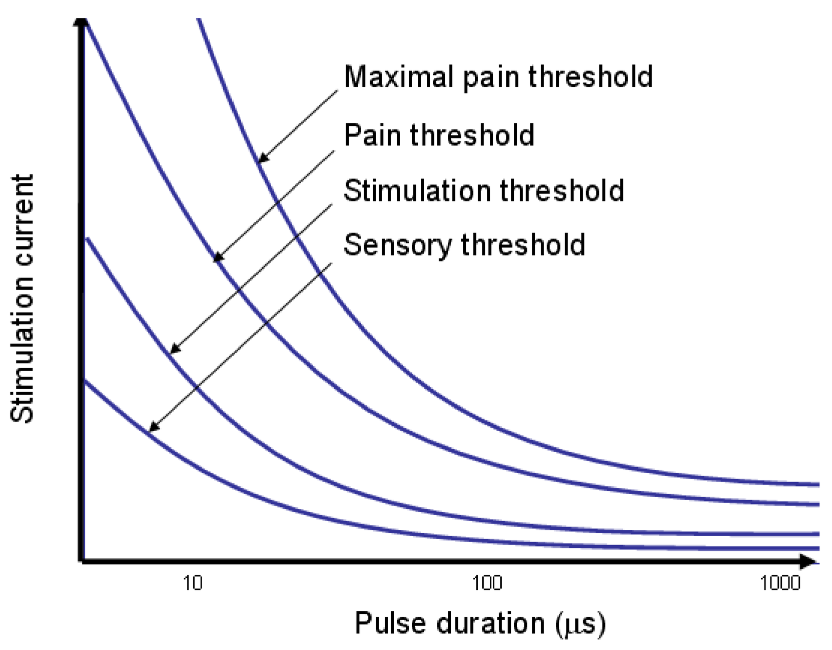

Figure 1: Pain & Stimulation thresholds.
Relationship between pulse duration and stimulation current based on data from Nelson et al. (1999).

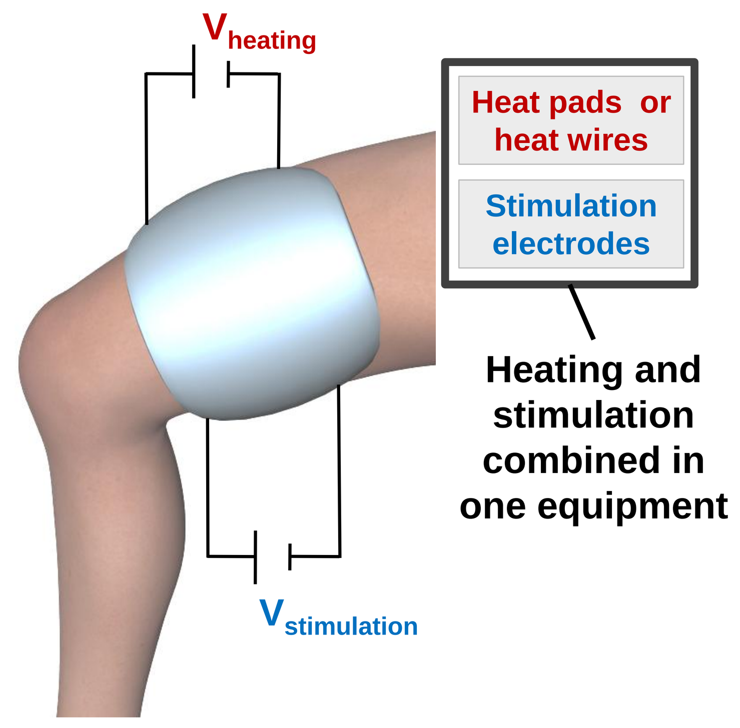

Figure 2: Thermostimulation equipment
Thermostimulation equipment combines heating and electrical stimulation into one piece of medical equipment.

Use of COMSOL Multiphysics

Model setup: Heating and heat transfer simulations

- Body tissue modelled as layered structure - bone, muscle, fat, skin
- Heat pads modelled as additional outer layers of silicone rubber and heat wire layer
- AC/DC module used for heat wires. Heat Transfer module with Penne's Bio-heat equation for heat transfer into body

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met}$$

ρ	tissue density [kg/m3]
C_p	tissue heat cacpacity [J/kgK]
T	tissue temperature [K]
k	tissue thermal conductivity [W/mK]
ρ_b	density of blood [kg/m3]
C_b	heat capacity of blood [J/kgK]
ω_b	blood perfusion rate [1/s]
T_b	arterial blood temperature [K]
Q_{met}	metabolic heat generation [W/m3]

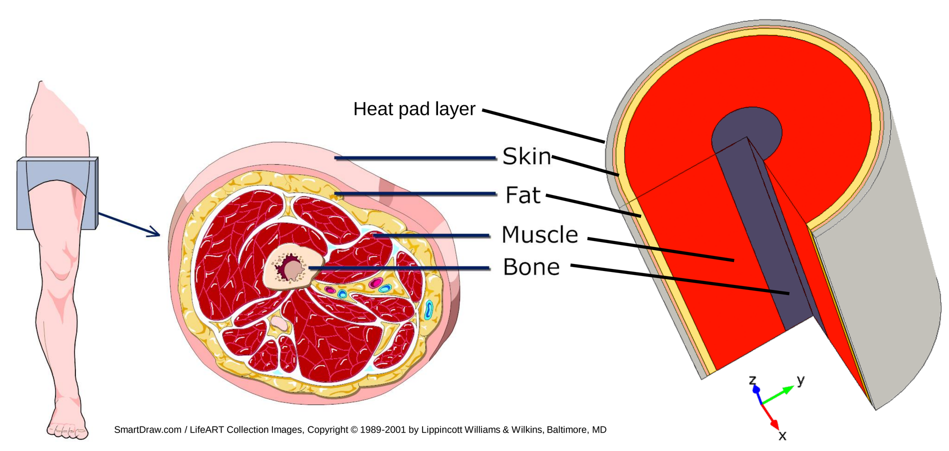

Figure 3: Heating and heat transfer model

- Heat wires modelled as layer with varying electrical conductivity using a step function – heat wire separation and number of wires varied by varying step function period
- Model built up using COMSOL LiveLink for Matlab
  - Sensitivity analysis to investigate different sets of tissue parameters in literature
  - Iterative analysis to adjust skin temperature to 42 ºC
  - Axisymmetric model for basic analysis – 3D model for individually shaped layers
- Model also extended to alternative heating methods (Microwave/IR heating – not shown here)

Model setup: Electrical stimulation simulations

- Body tissue modelled as layered structure
- Electrodes and heat pads modelled as separate thin layers on top of skin layer
- Model variants:
  - Finite thickness electrodes with varying electrical conductivity
  - Thin high-conductivity electrode wires below electrodes
  - Conductive gel layer with "gel leakage" between electrodes
  - Non-conductive air-layer between electrodes
- Simulation results evaluation:
  - Electric field / electric current evaluated along lines at muscle/fat layer boundary
  - Area in muscle cross section with electric field above certain threshold value identified
  - 3D contour plots to visually investigate difference in electric field

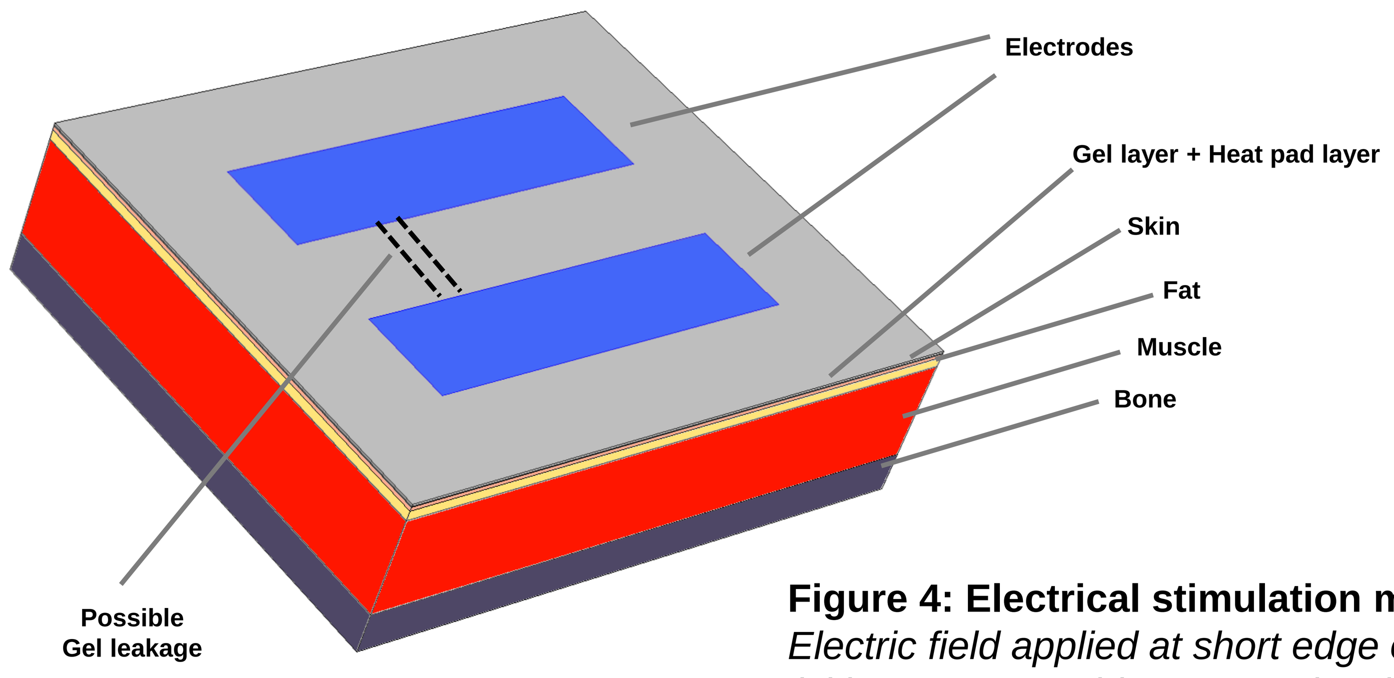

Figure 4: Electrical stimulation model
Electric field applied at short edge of electrodes (either on same side or opposite sides)

Results

1. Heating for different body compositions

- Fat layer thickness influences significantly on both pre-heating time and final temperature
- Need to plan long pre-heating for patients with thick fat layers

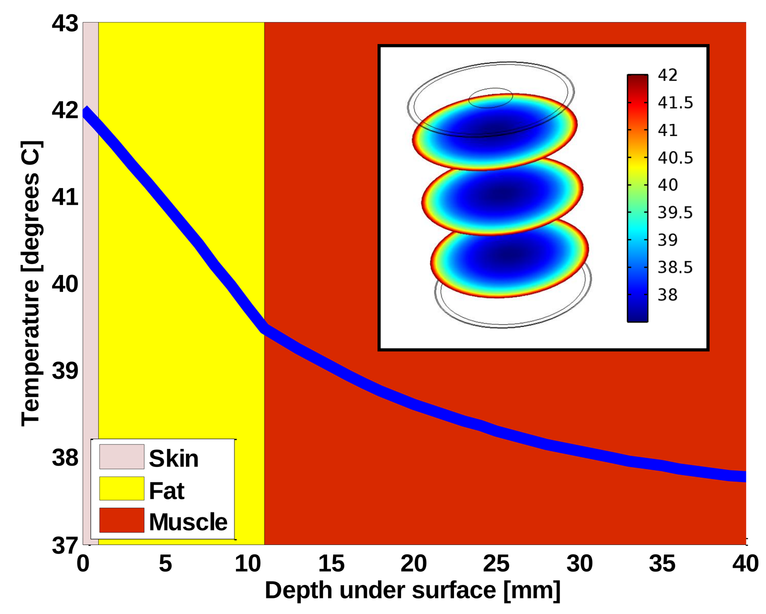

Figure 5: Temperature distribution in tissue
Temperature distribution as a function of depth under skin surface for a fat layer thickness of 10 mm

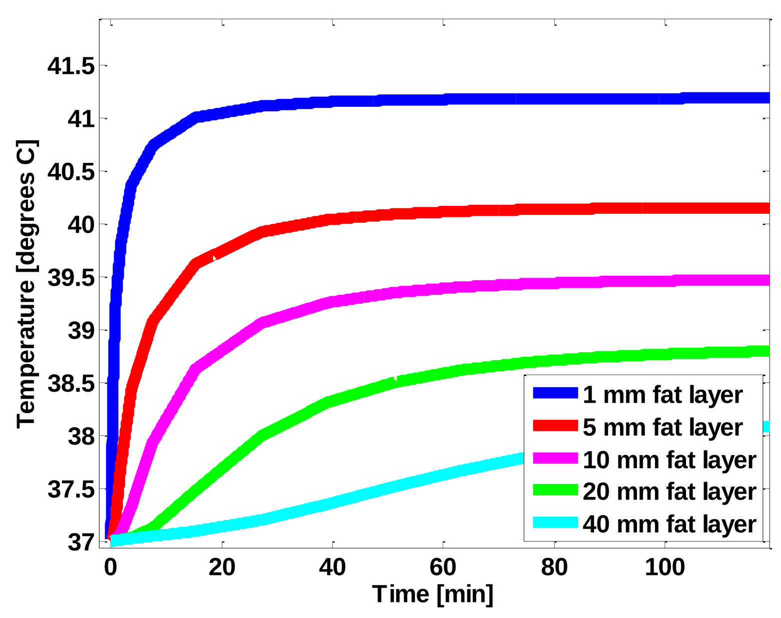

Figure 6: Influence of fat layer thickness
Temperature at muscle/fat layer interface as a function of time for fat thickness of 1-40 mm

2. Effect of heat wire separation

- Heat wire separation critical design parameter – large spacing gives uneven heat
- 5 mm heat wire spacing leads to significant lowering of heat in the muscle tissue

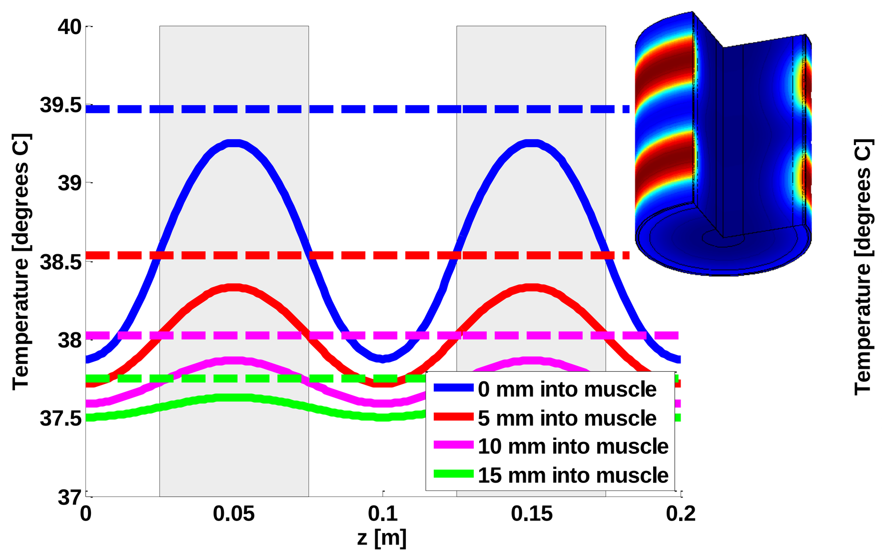

Figure 7: 5.0 mm heat wire separation

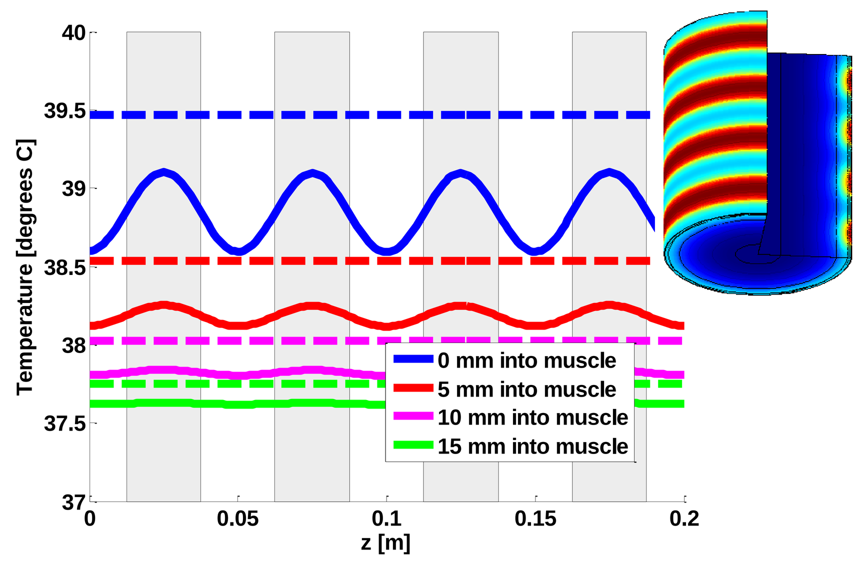

Figure 8: 2.5 mm heat wire separation

3. Effect of electrode conductivity

- Low electrode conductivity better from production point of view – gives uneven stimulation
- Either conductivity σ > 40 S/m required for even stimulation
- Alternative: Use conductive wire under electrode (not shown, see Kocbach et al 2011)

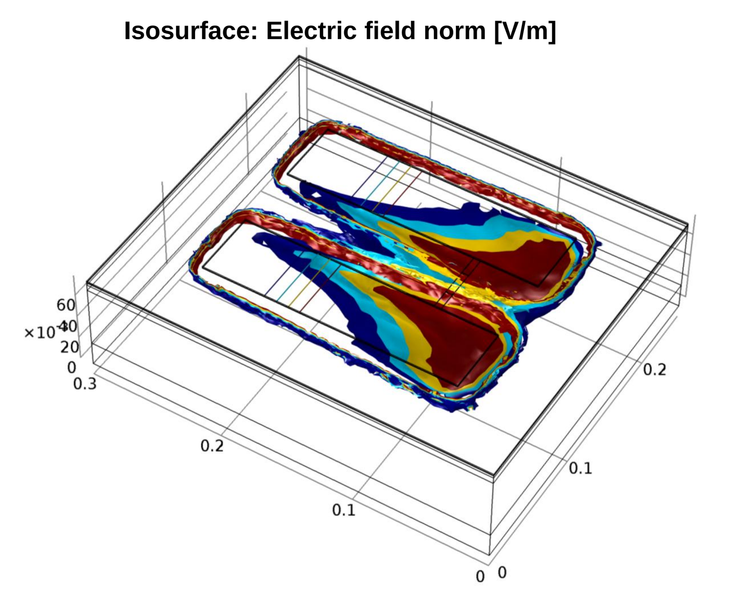

Figure 9: E-field distribution for σ=10 S/m

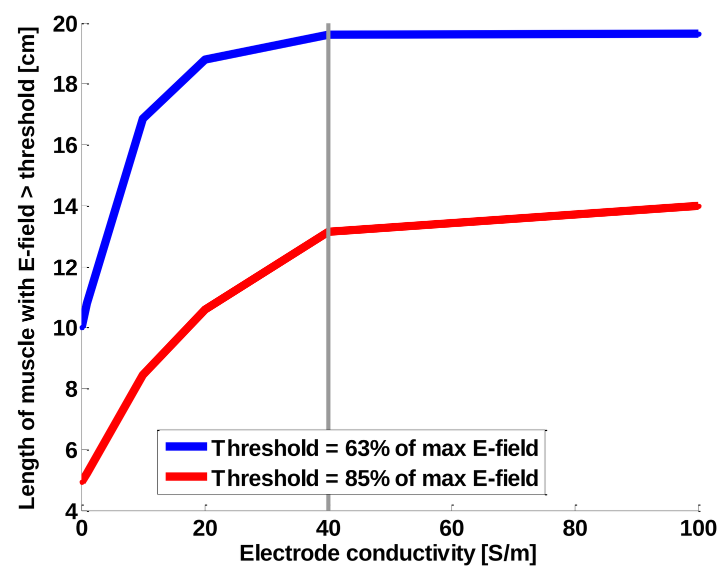

Figure 10: E-field uniformity as function of σ

4. Focusing of electric field due to gel leakage

- Leakage of gel to gap between electrodes leads to strong focusing effects
- 100% gel with case gives significantly reduced electric field in muscle (Kocbach et al 2011)

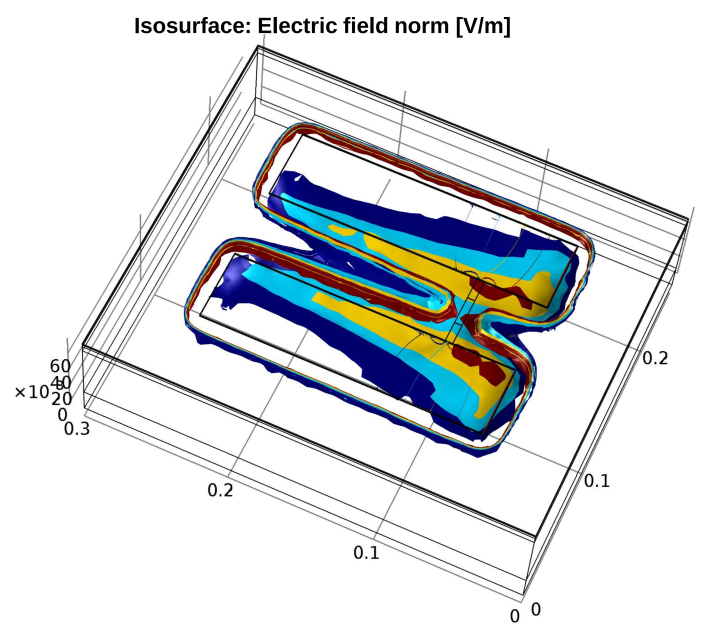

Figure 11: E-field distribution with gel leakage

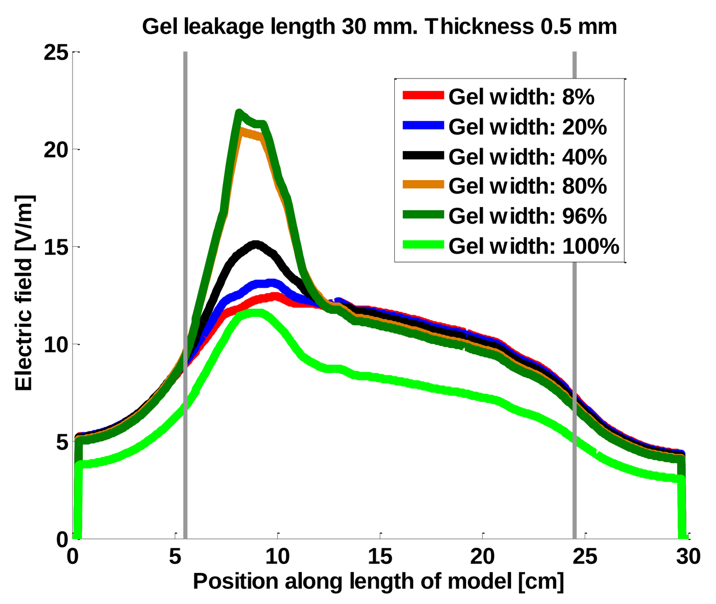

Figure 12: Focusing due to gel leakage

References

- Nelson, R. M., Currier, D. P. and Hayes, K. W. (1999). *Clinical Electrotherapy*. 3rd. Edition, Appleton & Lange
- Kocbach J., Folgerø K., Mohn L., Brix O. (2011). *A Simulation Approach to Optimizing Performance of Equipment for Thermostimulation of Muscle Tissue using COMSOL Multiphysics*., Biophysics & Bioeng. Letters Vol 4, No 2 , pp 9-33

COMSOL CONFERENCE EUROPE 2012