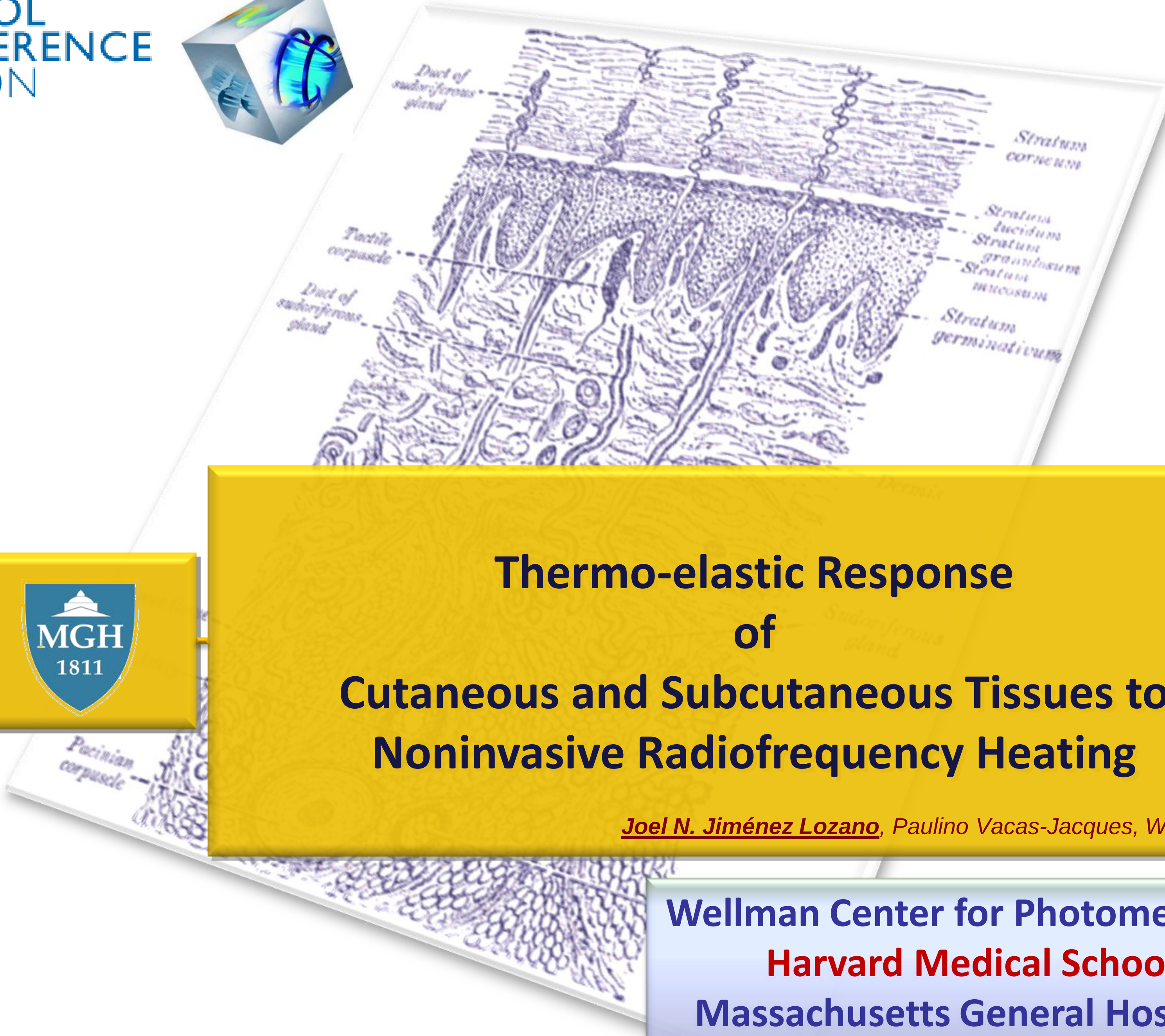
COMSOL CONFERENCE
BOSTON
2012



Thermo-elastic Response of Cutaneous and Subcutaneous Tissues to Noninvasive Radiofrequency Heating

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Outline

1. **Introduction**
2. **Problem definition**
3. **Mathematical modeling and solution**
4. **Results**
5. **Significance**
6. **Conclusions**

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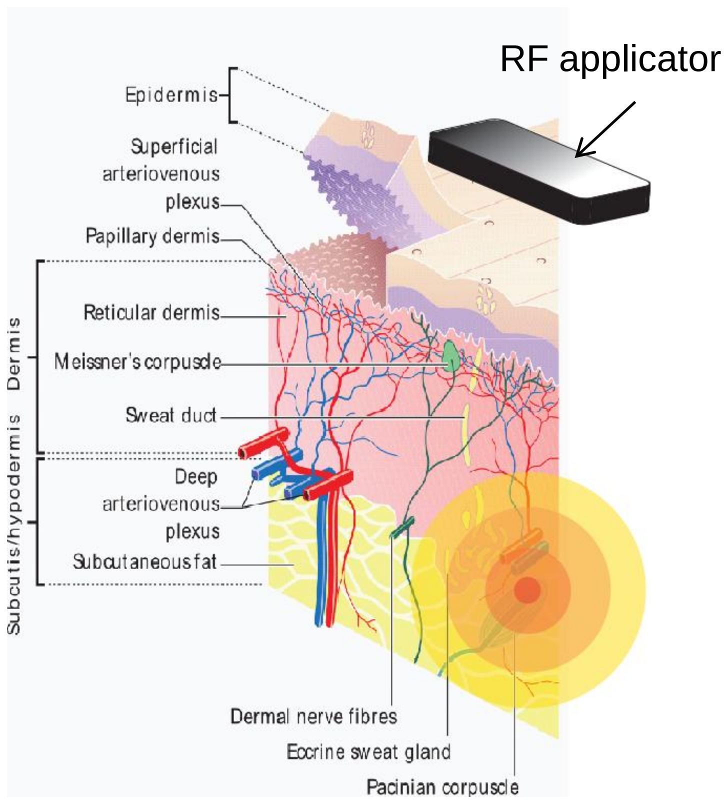
1 Introduction

Radiofrequency (RF) heating uses frequencies in the range of 30kHz – 1GHz. RF energy is used for generating heat, which can be used to cut, or induce metabolic processes in the body target tissue.

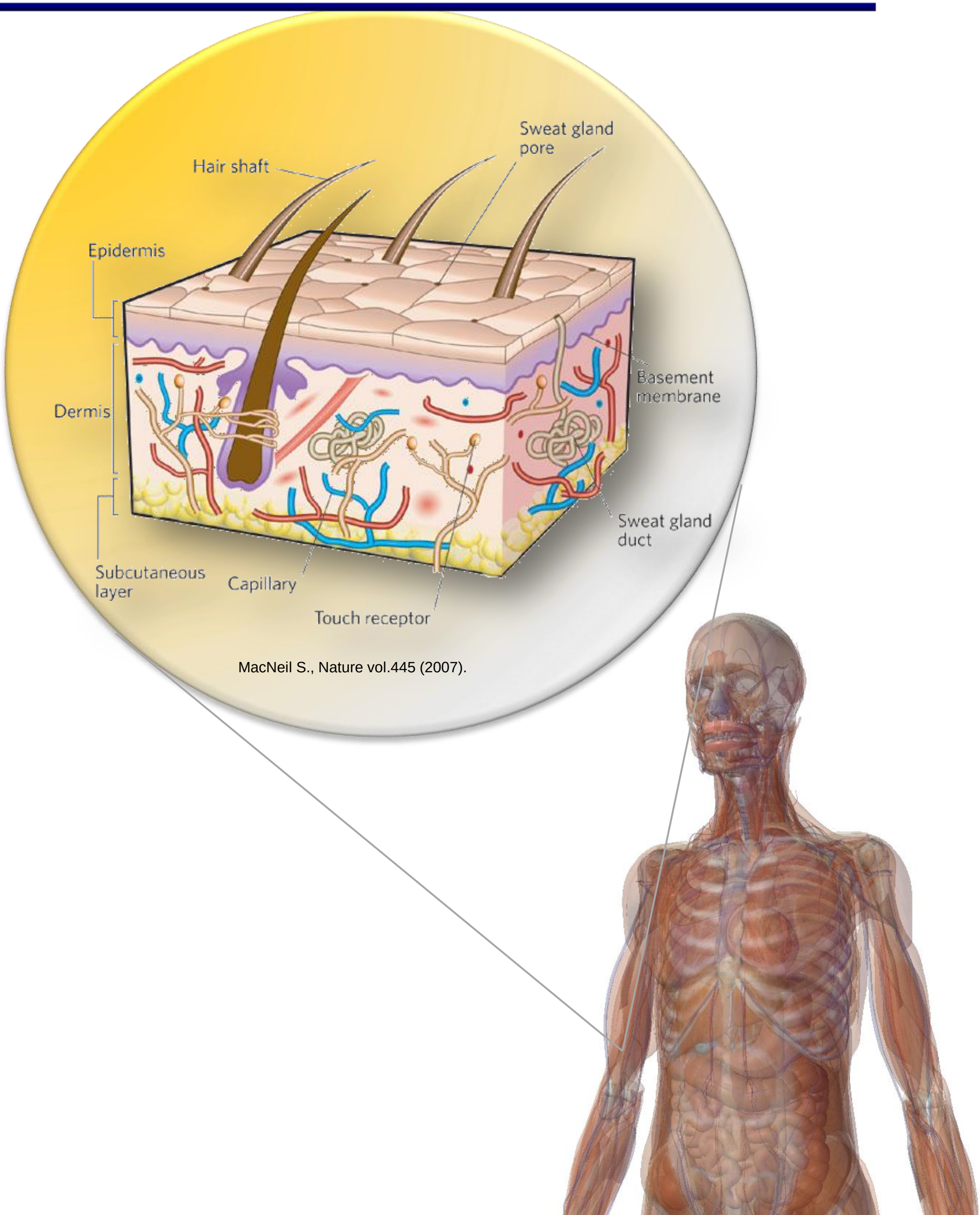
RF technology offers unique advantages for *non-invasive* selective heating of relatively large volumes of tissue.



1 Introduction

The skin-fat structure:

- An outer cellular layer, the **epidermis**. (~0.1 mm)
- A dense connective tissue layer perfused with micro-vessels, the **dermis**. (~1 mm)
- A thick fatty layer, the **hypodermis** or subcutaneous tissue. (1 cm to 10 cm)

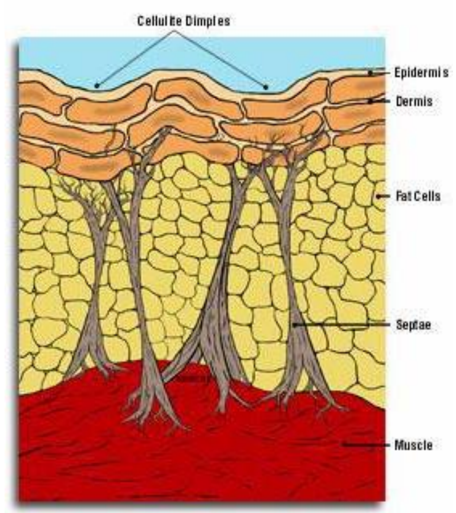


MacNeil S., Nature vol.445 (2007).

Anatomy: Subcutaneous tissue

Subcutaneous structure: clusters of adipocytes interlaced by a fine collagen fiber mesh (fiber septa).

Micro-MRI clearly shows thickness and structural alterations of connective tissues that correlate with abnormalities of skin.



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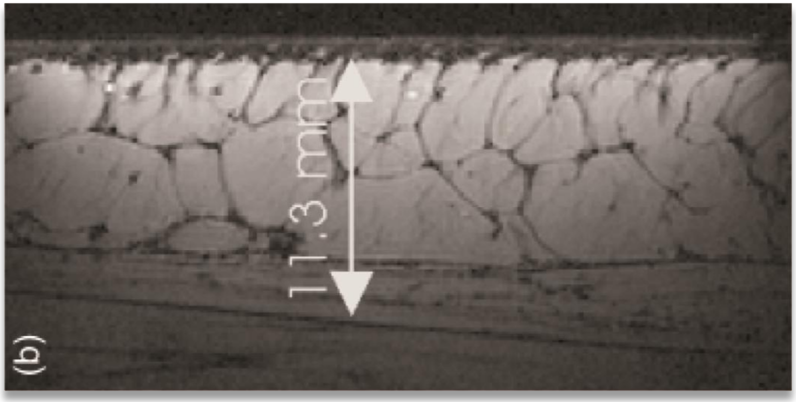

High-resolution *in vivo* MRI of the skin of a female. Dark filaments correspond to fiber septa within the subcutaneous fat. *Mirrashed, F., et al., Skin Research and Technology,* ***10*** *(2004).*

Objectives:

i. Present a mathematical model for selective, non-invasive, non-ablative RF heating of cutaneous and subcutaneous tissue including their thermo-elastic responses;

ii. Investigate the effect of fiber septa networks interlaced between fat clusters in the RF energy deposition;

iii. Illustrate the electric, thermal and elastic response of tissues.

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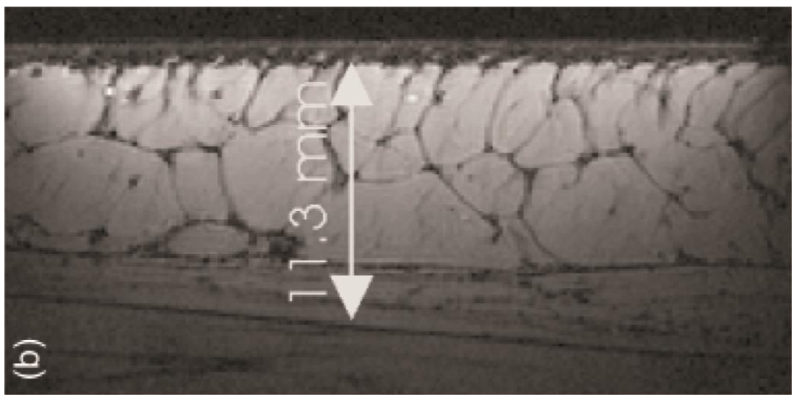
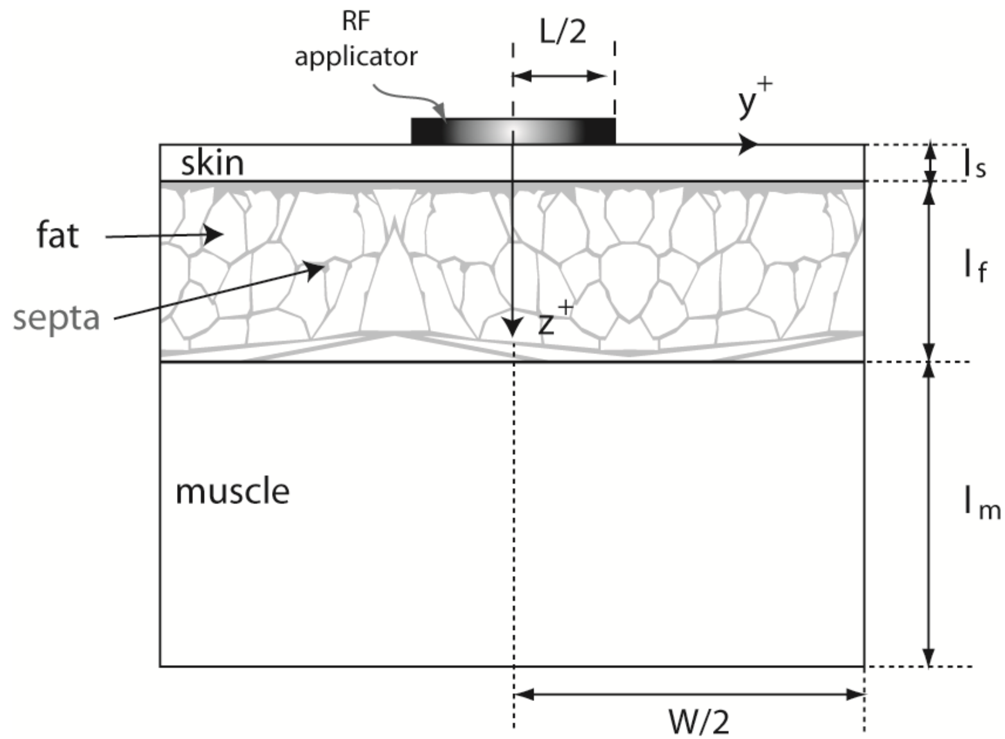
Domain Geometry

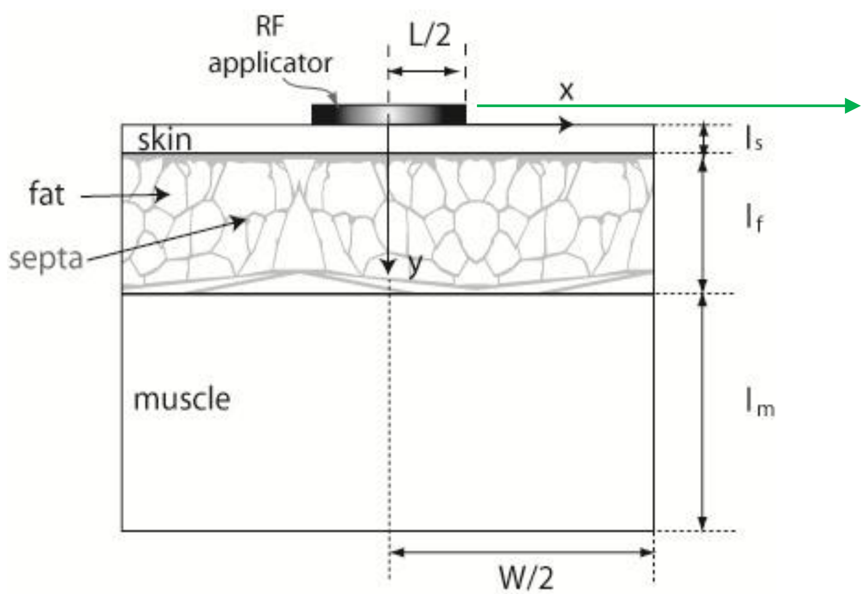


High-resolution *in vivo* MRI of the skin of a female. Dark filaments correspond to fiber septa within the subcutaneous fat.

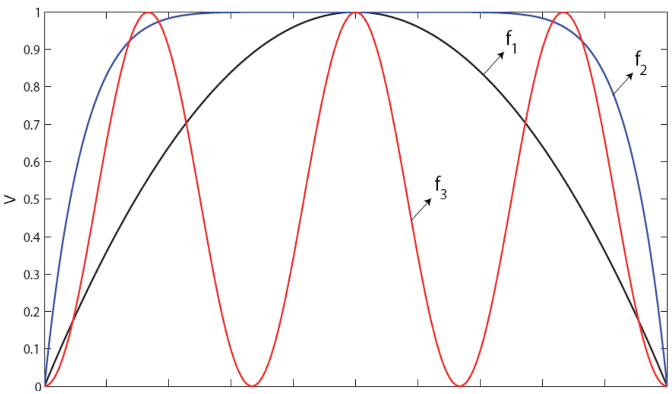


Problem definition

RF applicator in contact to the skin surface



Electric B.C. at the surface defined from Voltage measurements.



Tissue physical parameters:

- Electric conductivity, σ, (ability to transport electric current)
- Relative permittivity, ε, (ability to concentrate electric flux)
- Thermal conductivity, k, (ability to conduct heat)
- Blood perfusion, ω, (ability to dissipate heat)
- Elastic modulus, E, (ability to be deformed)
- Thermal expansion coefficient, α, (ability to expand by increasing temperature).

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Governing Equations (i = skin, hypodermis, muscle, septa)

$$\nabla \cdot (\sigma_i \nabla V_i) = 0, \quad \text{(1)}$$

$$\rho_i c_i \frac{\partial T_i}{\partial t} + \alpha_i T_0 \frac{\partial (\overline{\sigma}_{kk})_i}{\partial t} = \nabla \cdot (k_i \nabla T_i) + c_b \omega_i (T_b - T_i) + Q_i, \quad \text{(2)}$$

(i) (ii) (iii) (iv) (v)

$$\rho_i \frac{\partial^2 \boldsymbol{u}_i}{\partial t^2} - \overline{\overline{\nabla}} \cdot \overline{\sigma}_i = \overline{F}_i. \quad \text{(3)}$$

(I) (II) (III)

1. Electric Potential
2. Heat Transfer
   - i. change in heat storage,
   - ii. thermo-elastic coupling,
   - iii. heat conduction,
   - iv. blood perfusion,
   - v. electric power absorption, $Q_i = \frac{1}{2}\sigma_i \|E_i(y,z)\|^2$
3. Solid Mechanics
   - I. rate increase momentum,
   - II. divergence of stress,
   - III. external forces.

Main physical assumptions:

- Tissues are homogeneous and have isotropic electric and thermal properties
- Electromagnetic propagation is very fast compared to heat diffusion
- Distribution of blood vessels is isotropic
- Blood flow enters at arterial temperature but reaches local tissue temperature before leaving
- Fourier conduction
- Linear elasticity

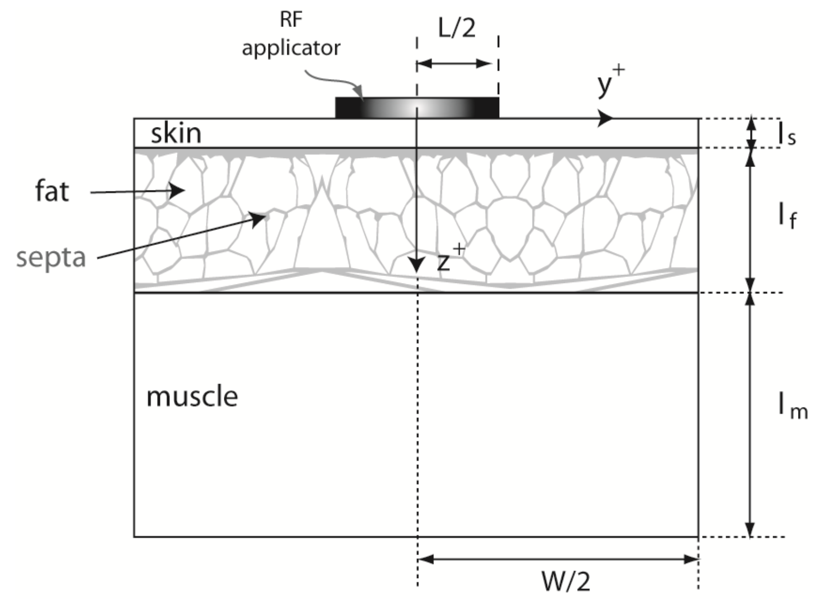
Boundary conditions

(a) Electric:

i. a *voltage source distribution* at the skin surface,
ii. a *zero voltage* condition at the muscle bottom,
iii. *no electric flux* at the lateral boundaries;

(b) Thermal:

i. a *cooling plate* below the applicator,
ii. *air convection* at the top of skin,
iii. a *core temperature* at the muscle bottom,
iv. *no thermal flux* at the lateral boundaries,



(c) Elastic:

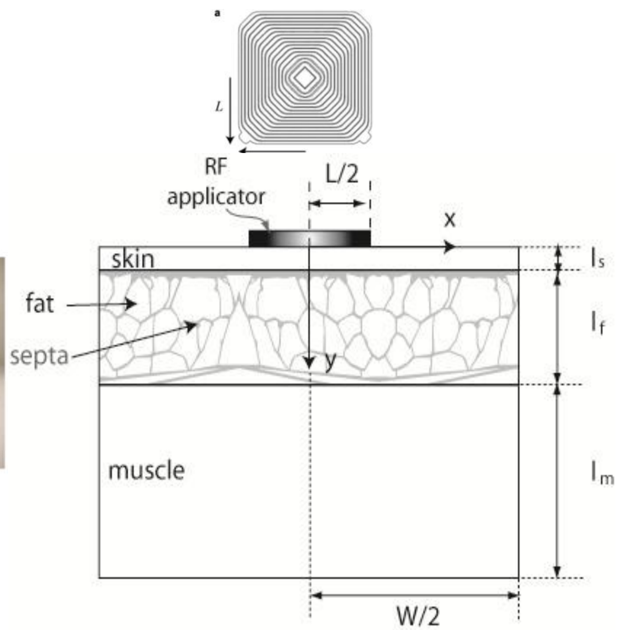
i. *fixed* at the skin upper surface and muscle bottom,
ii. lateral boundaries are assumed to *move freely*.

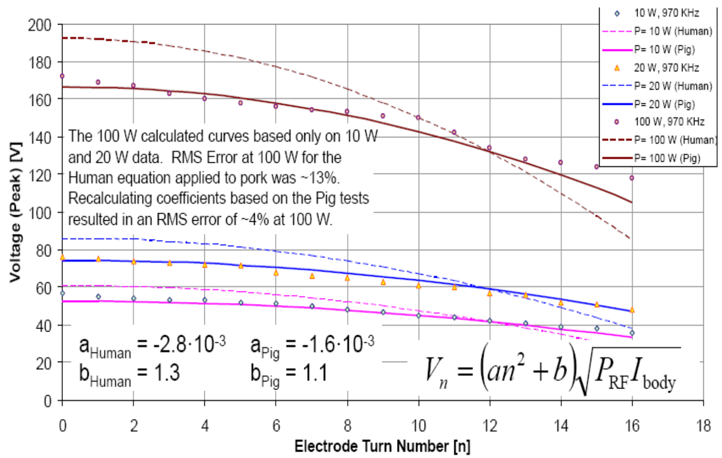
As initial conditions at t=0 s, we assume V=0, T_0=310 K and no initial strain.

RF Monopolar applicator (*Franco, W. et al. LSM 42, 2010*)

The RF applicator consists of a multidimensional series of tightly spaced concentric rings that are energized at variable operational frequencies.

Upper view





Voltage B.C.

$$V_s(-L \le y \le L, 0) = \left(a\left(l\frac{y}{L} \right)^2 + b \right)\sqrt{PI}$$

Parameters

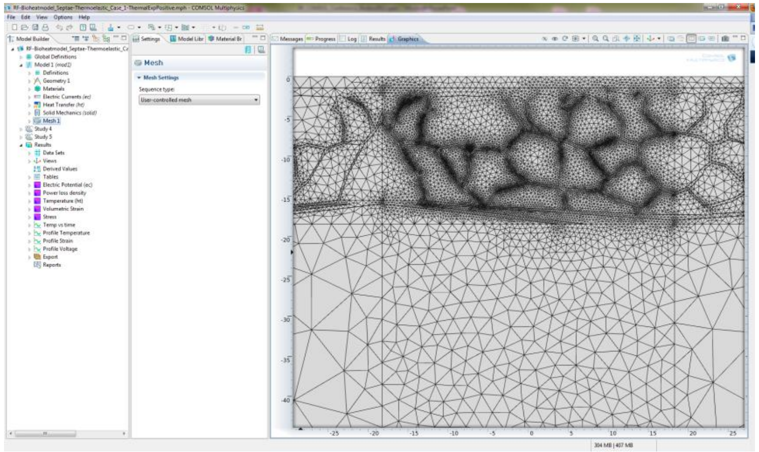
Parameter	Value	Reference
Geometrical Dimensions [mm]		
l_s	1.5	[6]
l_f	17	[6]
l_m	38	[6]
L	18.5	[6]
W	54.5	[6]
Permittivity		
ε_s	1832.8	[6]
ε_f	27.22	[6]
ε_m	1836.4	[6]
ε_{sp}	1832.8	Assumption
Electric conductivity [S/m]		
σ_s	0.22	[6]
σ_f	0.025	[6]
σ_m	0.5	[6]
σ_s	0.22	Assumption
Density [kg/m³]		
ρ_s	1200	[6]
ρ_f	850	[6]
ρ_m	1270	[6]
ρ_{sp}	1200	Assumption
ρ_b	1000	[6]
Thermal conductivity [W/m/K]		
k_s	0.53	[6]
k_f	0.16	[6]
k_m	0.53	[6]
k_{sp}	0.53	Assumption

Parameter	Value	Reference
Perfusion [kg/m³/s]		
ω_s	2	[6]
ω_f	0.6	[6]
ω_m	0.5	[6]
Young's Modulus [kPa]		
E_s	35	[9]
E_f	2	[9]
E_m	80	[9]
E_{sp}	0.009	[10]
Thermal expansion coefficient [1/°C]		
α_s	6E-5	[11]
α_f	2.76E-5	[12]
α_m	4.14E-5	[12]
α_{sp}	6E-5	Assumption
Fixed constants		
h	10 [W/m²/K]	
T_∞	298 [K]	
T_b	310 [K]	
T_{core}	310[K]	
T_{plate}	303[K]	

COMSOL Solution

The model was implemented using the *electric currents, heat transfer and solid mechanics* modules.

- Simulations were run in a Intel Core i5 at 3.1 GHz PC computer with 4 GB RAM memory.
- Model has 355,772 dof.
- Processing required about 134 min real time.
- The model mesh has 44380 elements. Skin, fat, muscle and septa central domains had a higher mesh density.



- The time dependent solution was set from 0-1200 seconds with a time-step of 0.1 seconds.
- We used COMSOL MUMPS direct solver.

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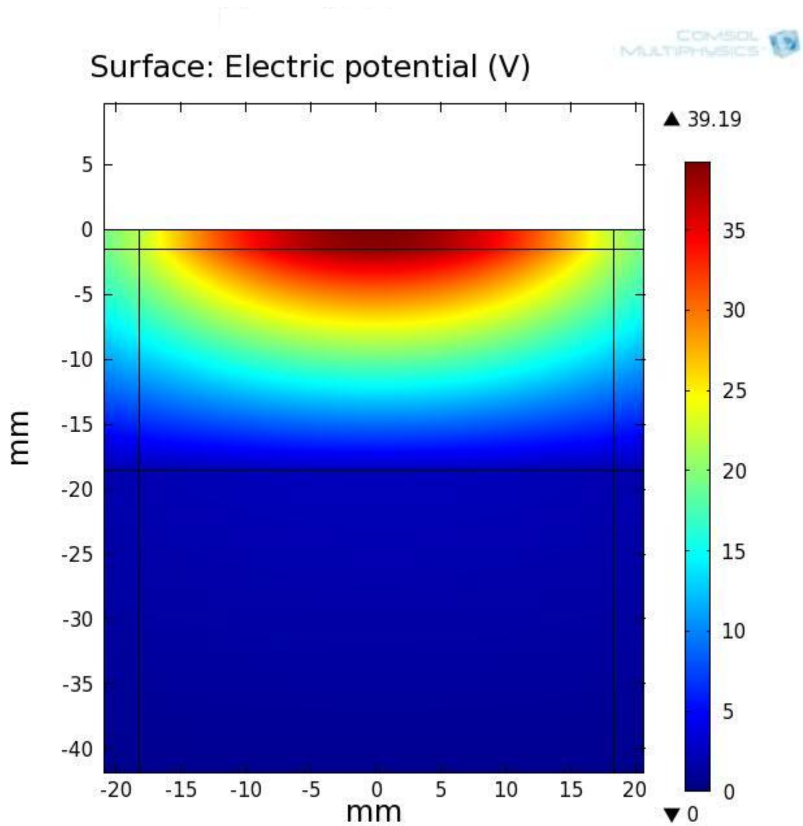
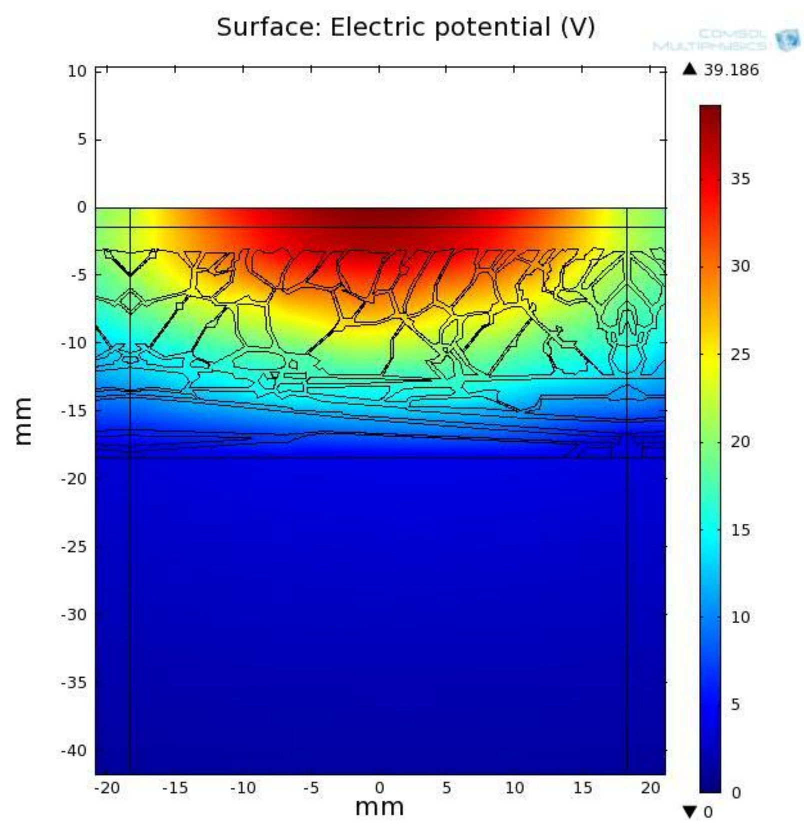
Voltage distribution

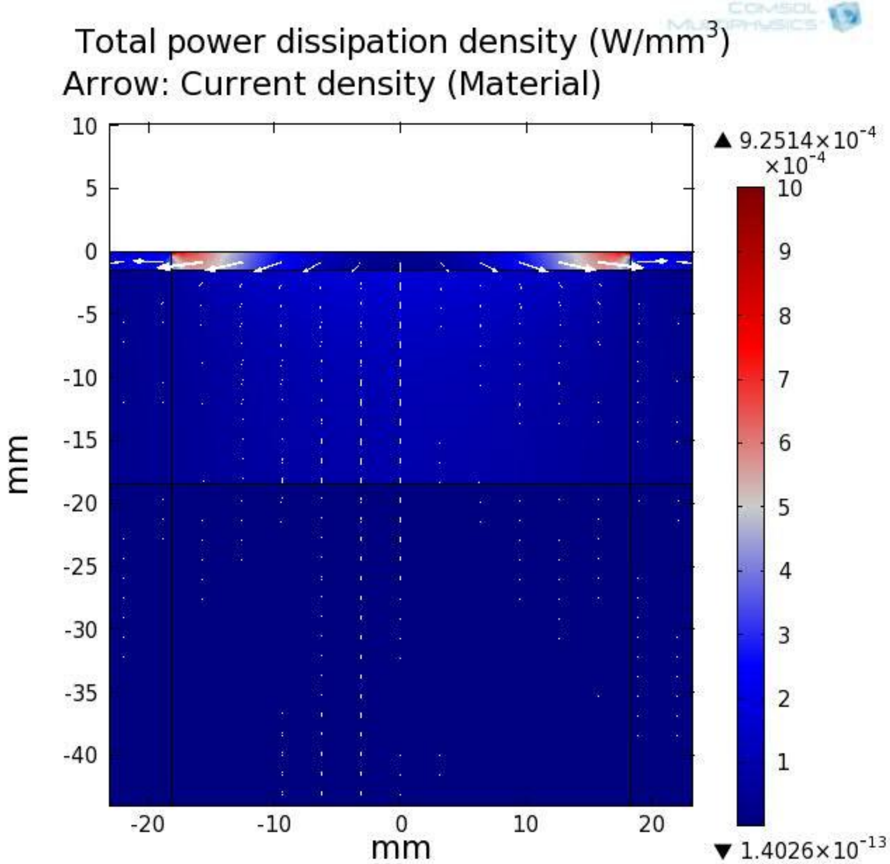


Voltage distribution within tissue, homogeneous fat tissue (no fiber septa).

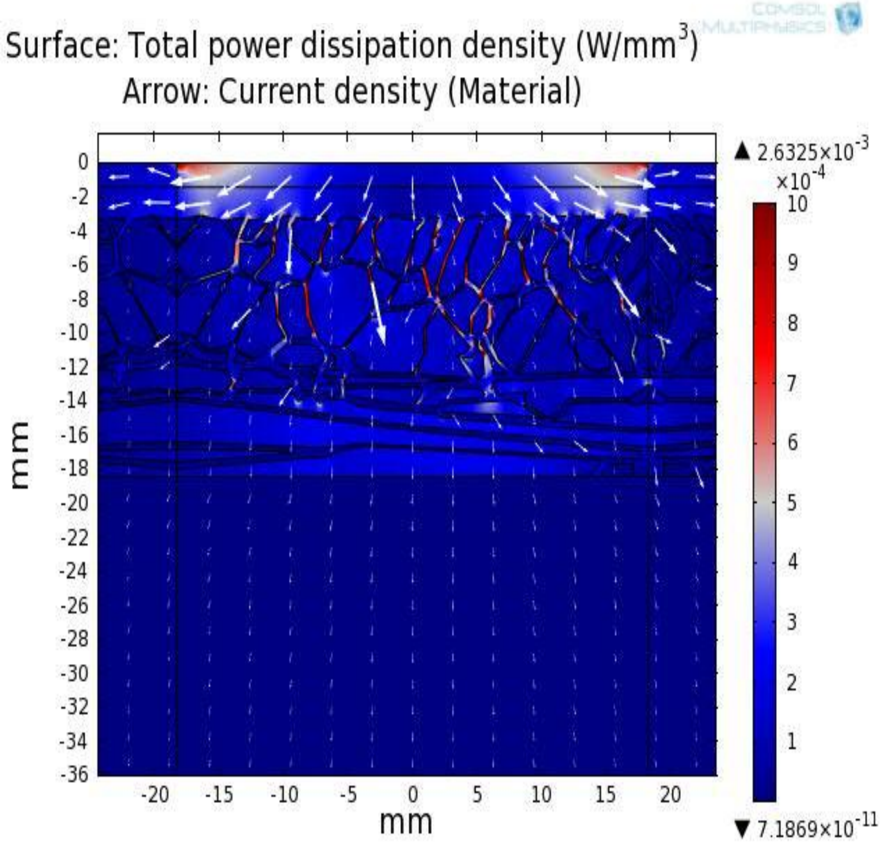


Voltage distribution within tissue, fat tissue with fiber septa.

Total electric power absorption (Q) and Electric field (arrows)

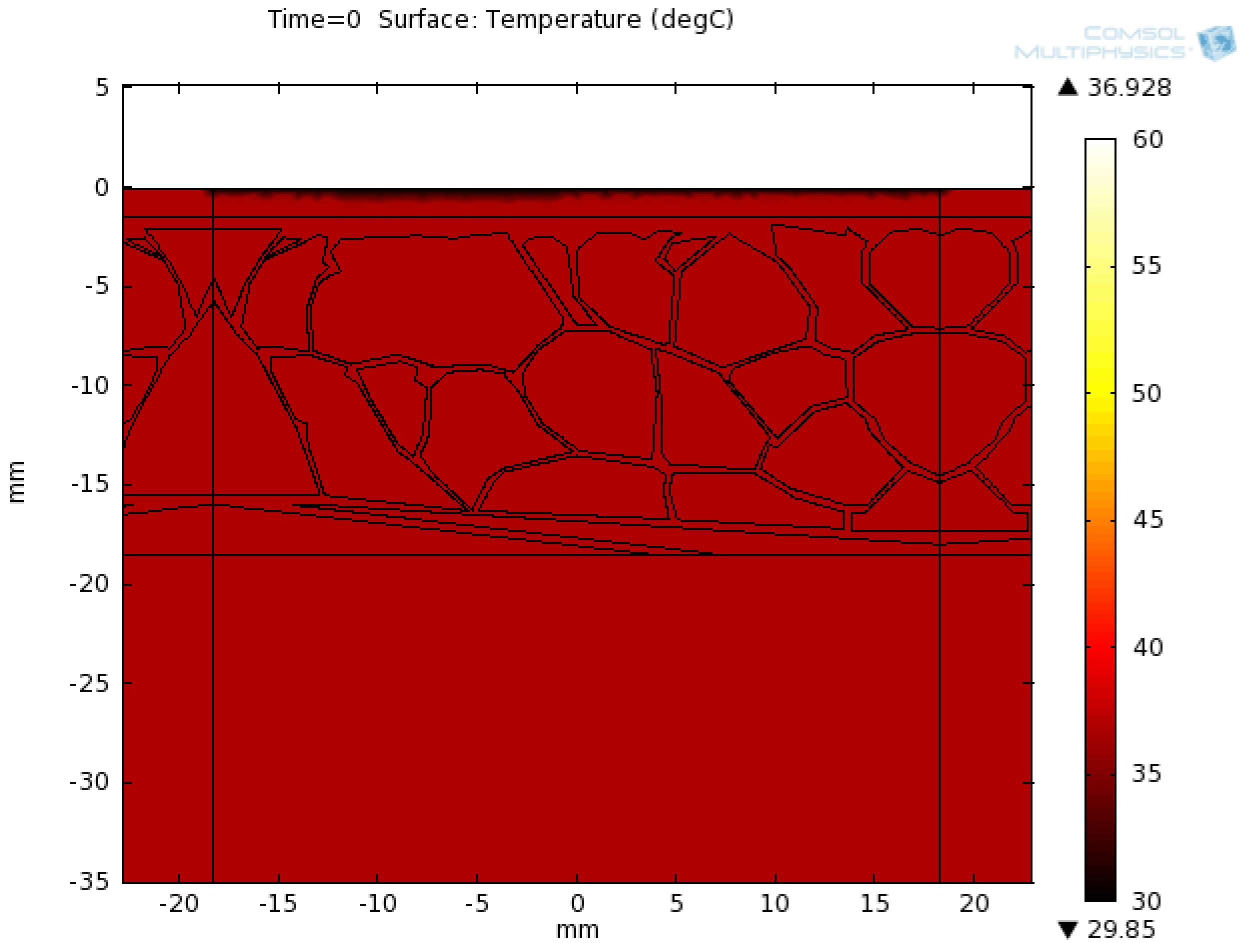


Electric power absorption and Electric field within tissue for homogeneous fat tissue.



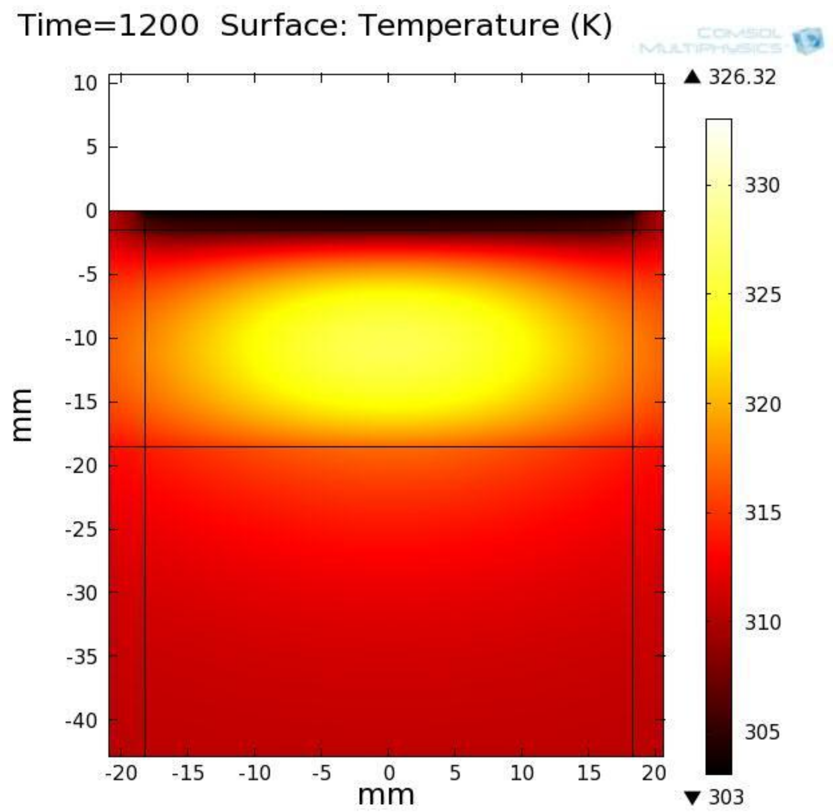
Electric power absorption and Electric field within tissue for fat with fiber septa.

Temperature distribution

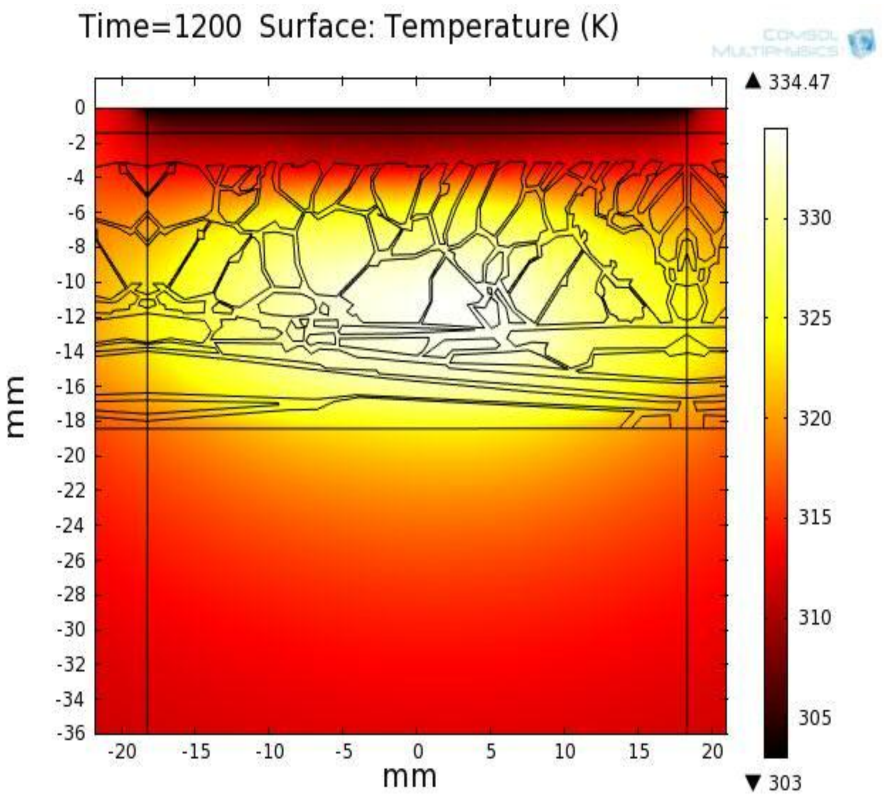


Time to reach steady-state ~1200s

Temperature distribution



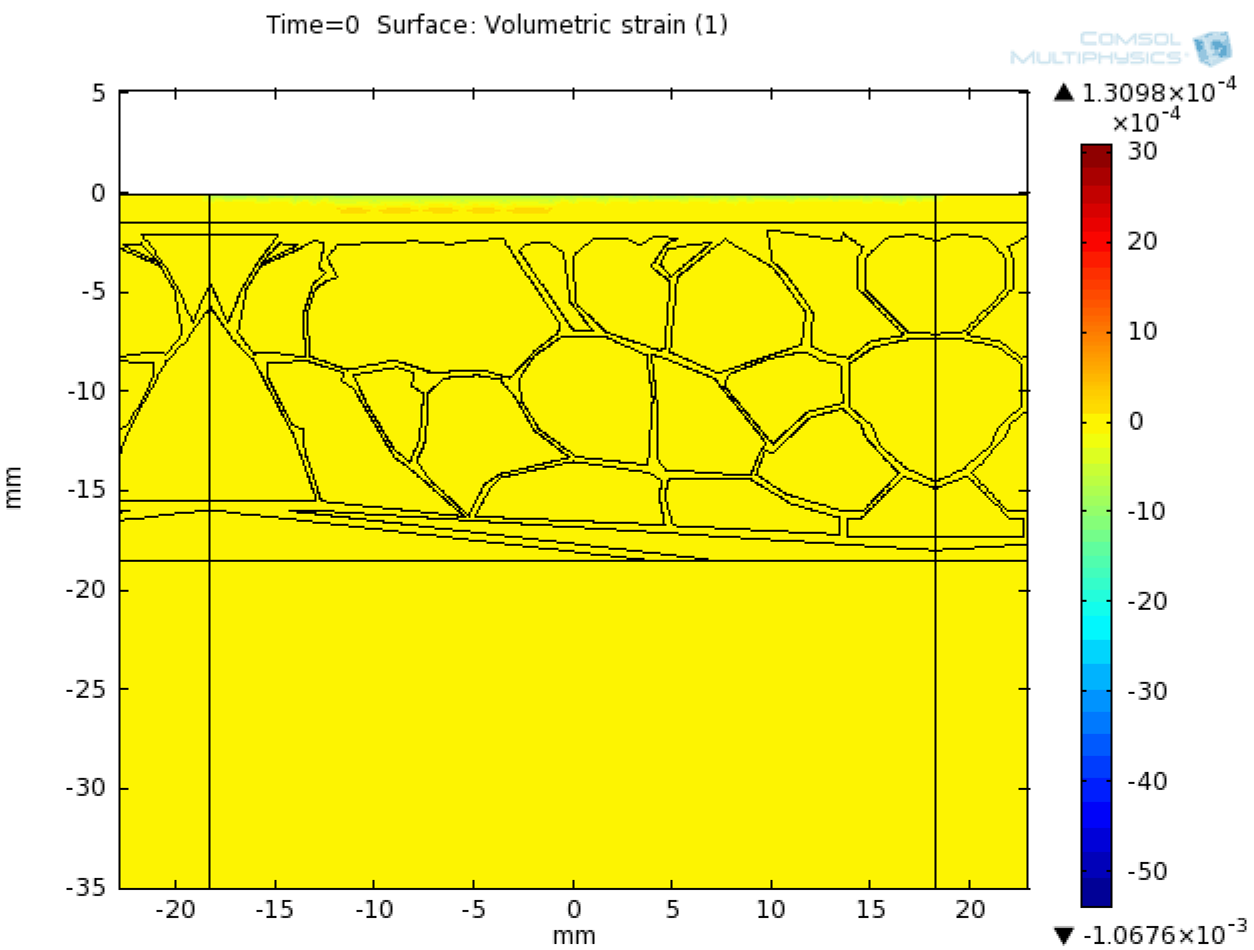
Temperature map at 1200 seconds (steady-state) for homogeneous fat tissue.



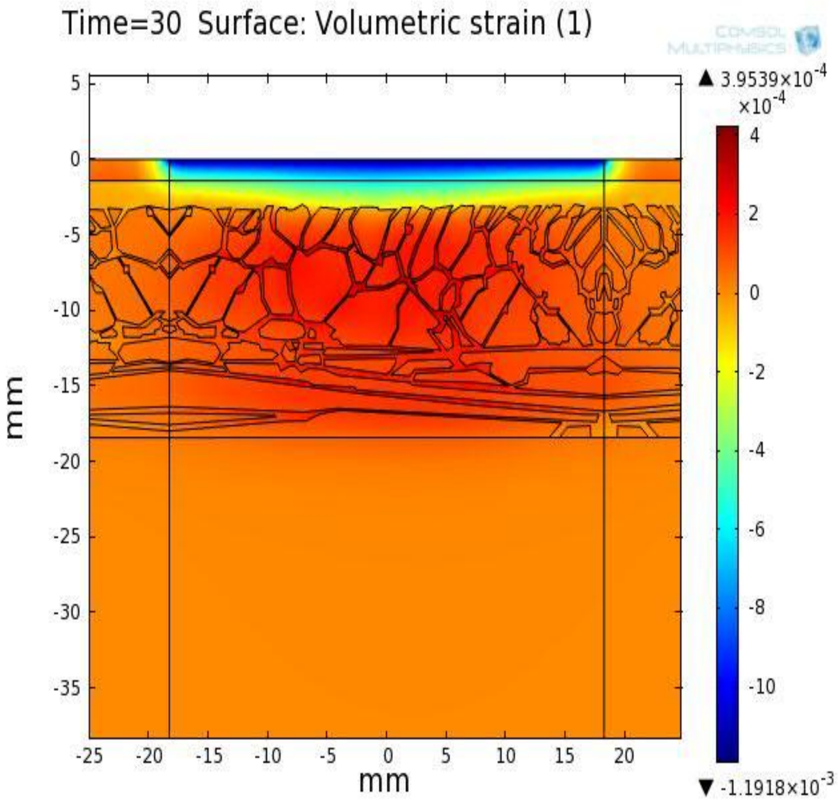
Temperature map at 1200 seconds (steady-state) for fat tissue with fiber septa.

Difference in maximum temperature ~8 ^{o}C.

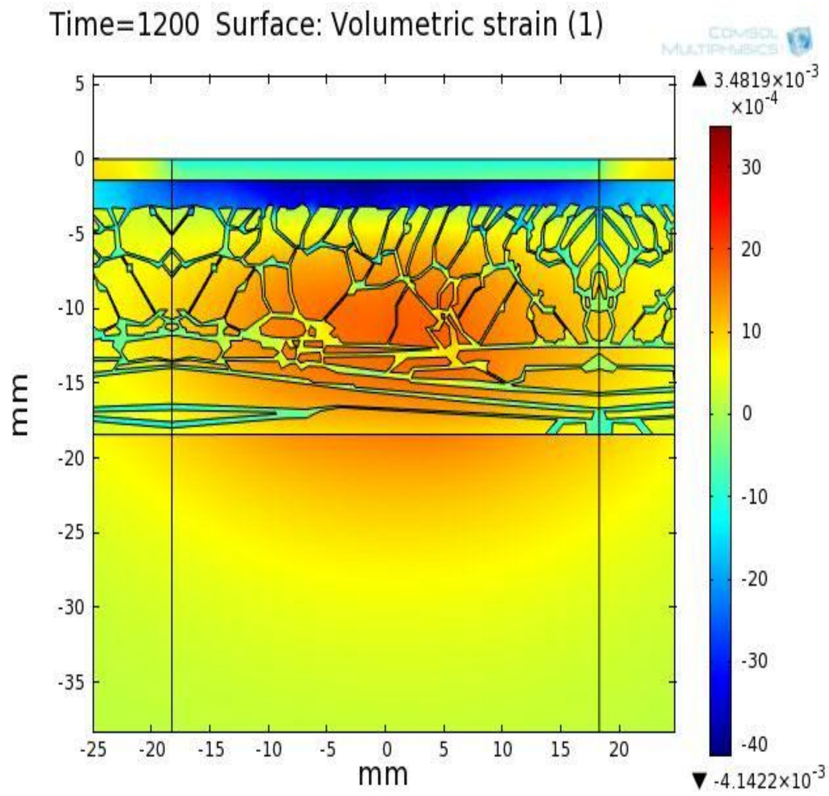
Volumetric strain



Volumetric strain



Volumetric strain at 30 seconds.



Volumetric strain at steady-state.

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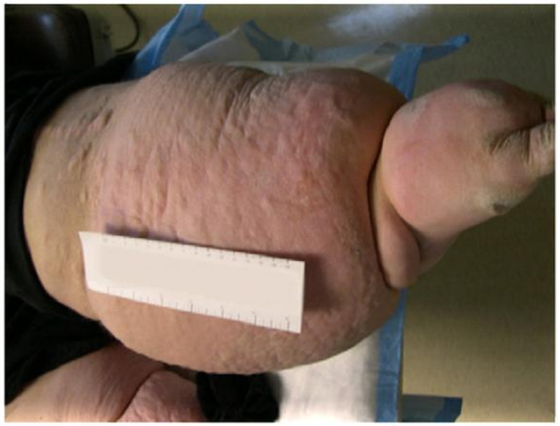
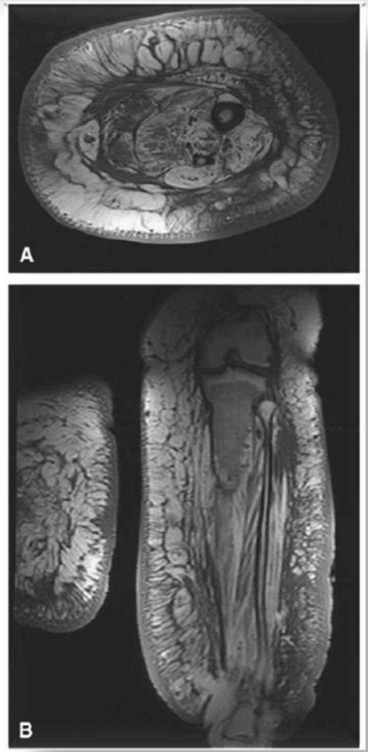
5 Significance

- A specific clinical application of our analysis is hyperthermic injury to adipocyte cells.

- Model developed for
  - planning the clinical treatment of subcutaneous fat related disorders; such as, *lipomatosis, Madelung's disease, or lipedema*,*
  - studying the tissue response as a function of structure; such as, density of fibers, *cellulite*.





* MRIs of lipedema show massive circumferential enlargement of the subcutaneous tissue occupied by fat lobules and a highly dense fibrous septa structure.

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Conclusions

- Fiber septa structures in the subcutaneous fat tissue concentrate electric power and contribute to increase the bulk temperature.
- Subcutaneous tissue with septa reaches a higher maximum temperature when compared to homogenous tissue.
- Dermis and fat exhibit a volumetric expansion whereas fiber septa contracts.
- Accurate assessment of tissue thermal responses will benefit the design of thermal therapies in the field of clinical hyperthermia (38-45 ^{o}C).

Thank you.
Questions?