COMSOL CONFERENCE 2015 GRENOBLE

Nusselt, Rayleigh, Grashof, and Prandtl: Direct calculation of a user-defined convective heat flux

Freddy Hansen

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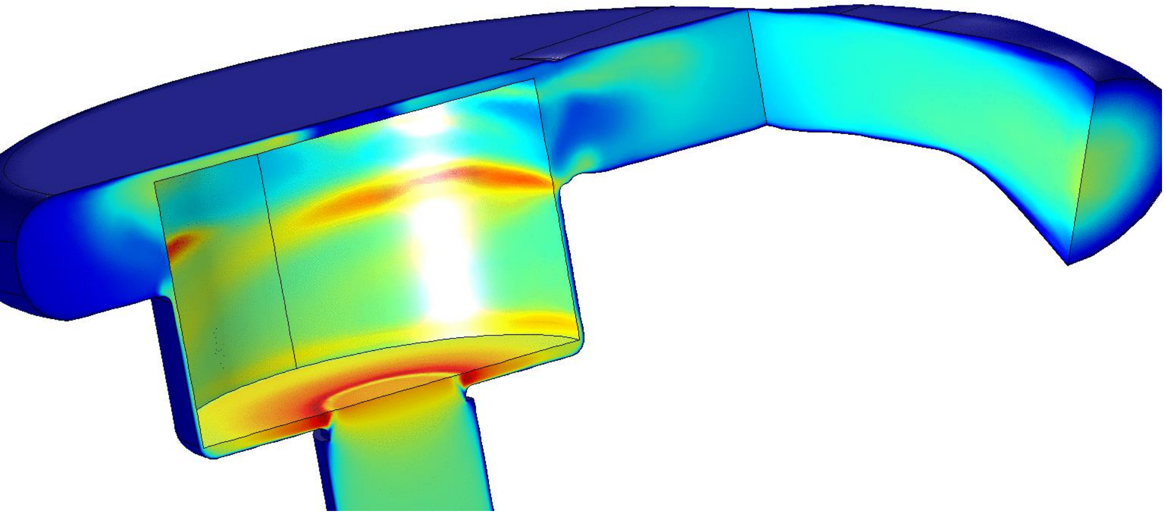
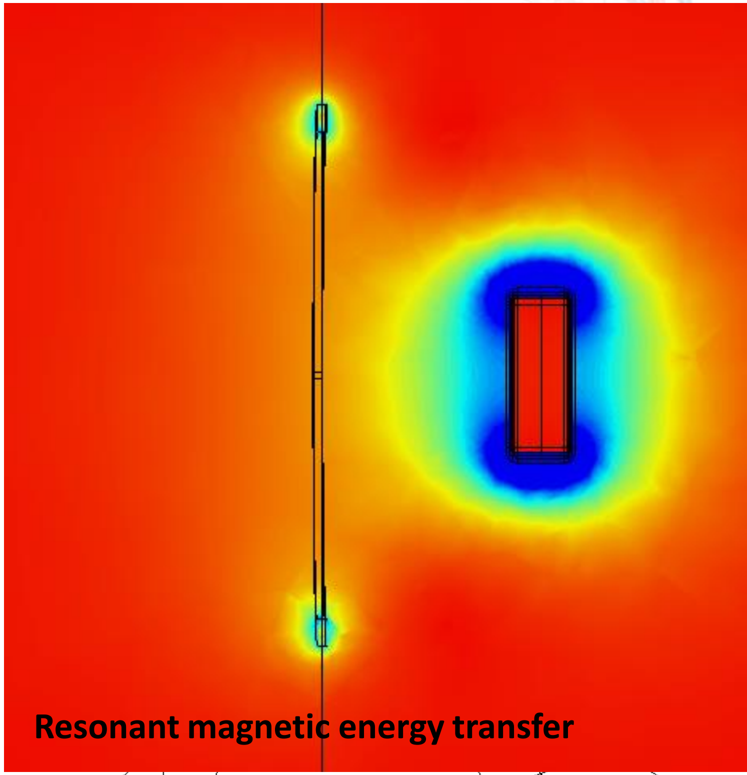
We use COMSOL for a variety of simulations

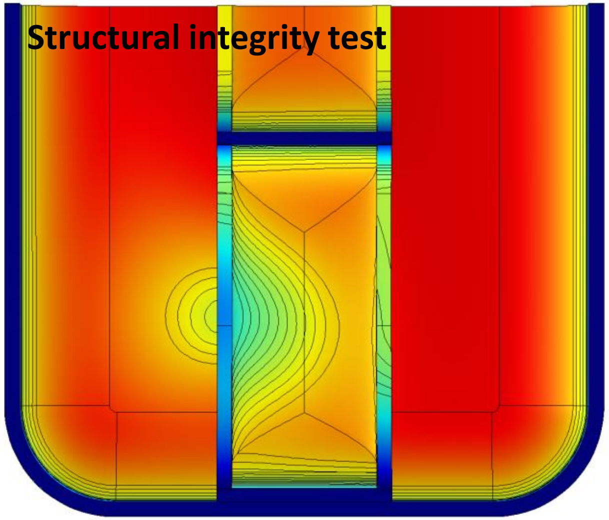
Just a few examples…



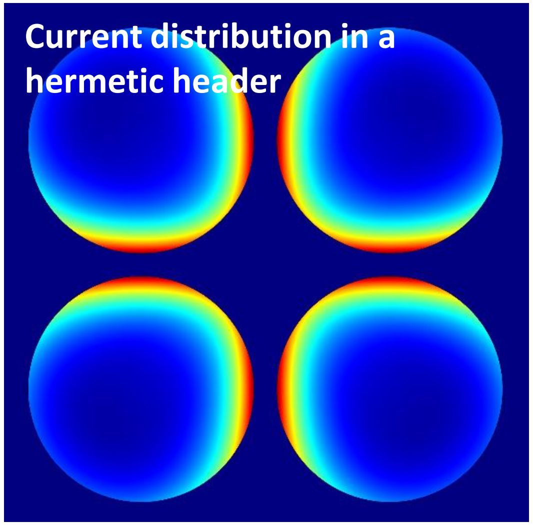
CFD simulation of a Ventricular Assist Device (VAD)



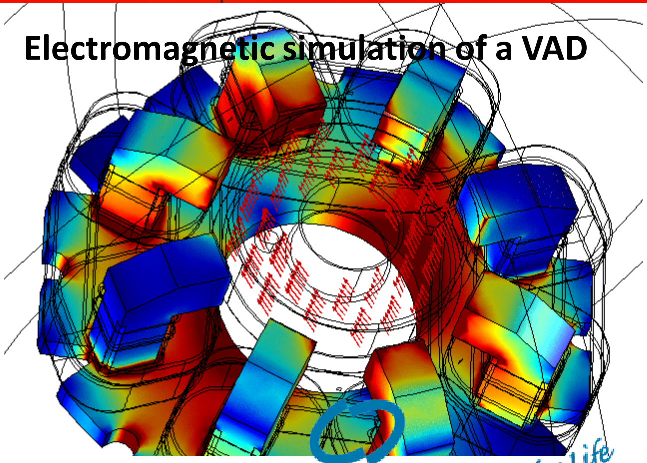
Resonant magnetic energy transfer



Structural integrity test



Current distribution in a hermetic header



Electromagnetic simulation of a VAD

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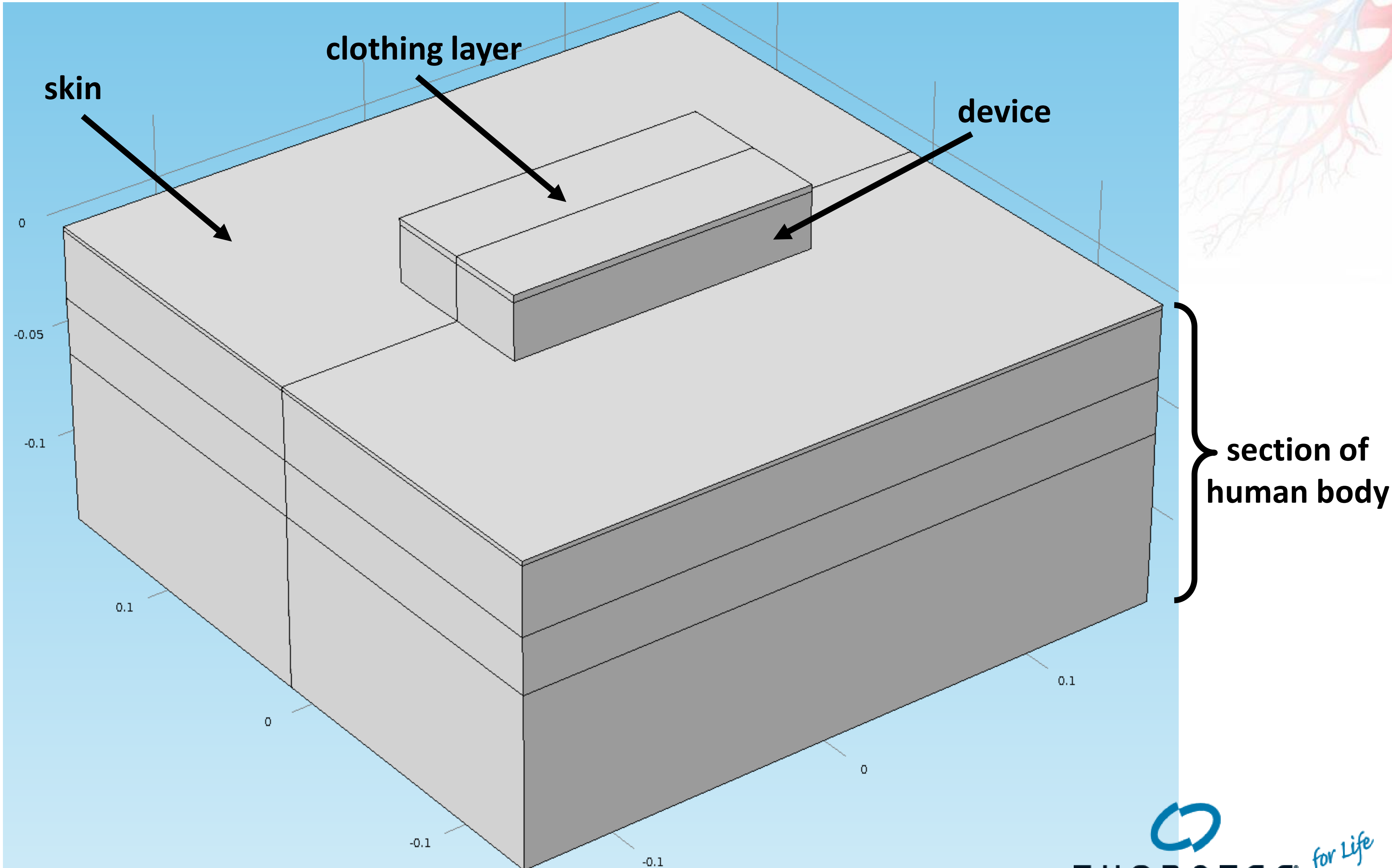
In today's presentation we'll look at an electronic device in direct contact with the human body

- Electronics generate heat, which can damage human tissue, e.g., the skin
- Damage occurs at 44°C and higher temperatures [1-5]
- Higher temperatures lead to damage faster
  - at 48°C damage occurs in 15 minutes
  - time until damage roughly halved with every 1°C rise
- Regulatory limits and standards may apply, e.g., IEC 60601-1
- In the presentation we will look at long durations
  - goal is to design a device that does not exceed IEC 60601-1 limit (43°C)
  - thermal simulation in COMSOL (steady state study)

1. S. Hudack and P. D. McMaster, *J. Exp. Med.*, **55**, 431-439 (1932)
2. P. D. McMaster and S. Hudack, *J. Exp. Med.*, **56**, 239-253 (1932)
3. P. D. McMaster and S. Hudack, *J. Exp. Med.*, **60**, 479-501 (1934)
4. E. H. Leach, R. A. Peters, and R. J. Rossiter, *Q. J. Exp. Physiol.*, **32**, 67-86 (1943-44)
5. F. C. Henriques, A. R. Moritz, *Am. J. Pathol.*, **23**, 530-549 (1947)

The simulation must model the device, the human body, and boundary conditions



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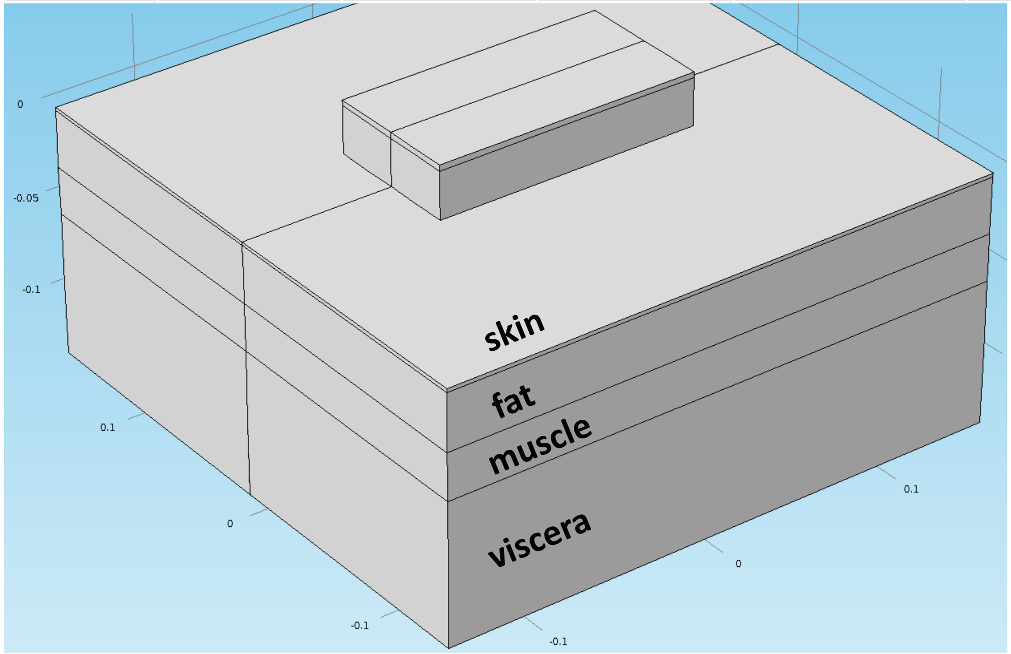
The human body is simulated using both thermal conduction and a blood perfusion model

	thickness [mm]	metabolic rate [W/m³]	perfusion ω [s⁻¹]	thermal conductivity [W/m·K]	density [g/cm³]	heat capacity [J/kg·K]
skin	2	1300	0.0018	0.47	1.085	3680
fat	30	250	0.00043	0.16	0.85	2300
muscle	25	500	0.0005	0.42	1.085	3768
viscera	*net*[1]	*net*[2]	*average*[3]	0.53[4]	1.0[4]	3697[4]
blood	n/a	Q_b	n/a	n/a	1.0[5]	4200[5]

Blood does not generate heat metabolically, but transports heat and is therefore a local heat source or heat sink:

$$Q_b = \rho_b C_{p,b} \omega (T_b - T)$$

$$T_b = T_{core} = 36.7\ °\mathrm{C}$$



References:

Values from "*A Mathematical Model of the Human Thermal System*," E.D. Yildrim (2005)

except:

[1] viscera thickness to make torso width 267 mm total, based on 50-percentile male abdomen dimension in "*The Measure of Men & Women*," A.R. Tilley, p. 12 (2002)

[2] viscera metabolic rate to make body metabolism 80 W total, based on Fig. 21-8 in "*New Human Physiology*," G. Zubieta-Calleja and P.-E. Paulev (2004)

[3] average of skin/fat/muscle values

[4] organ viscera values from Yildrim

[5] "*Simulation and Calculation of Magnetic and Thermal Fields of Human using Numerical Method and Robust Soft wares*," K.M. Takami and H. Hekmat (2008)

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The human body is simulated using both thermal conduction and a blood perfusion model

	thickness [mm]	metabolic rate [W/m³]	perfusion ω [s⁻¹]	thermal conductivity [W/m·K]	density [g/cm³]	heat capacity [J/kg·K]
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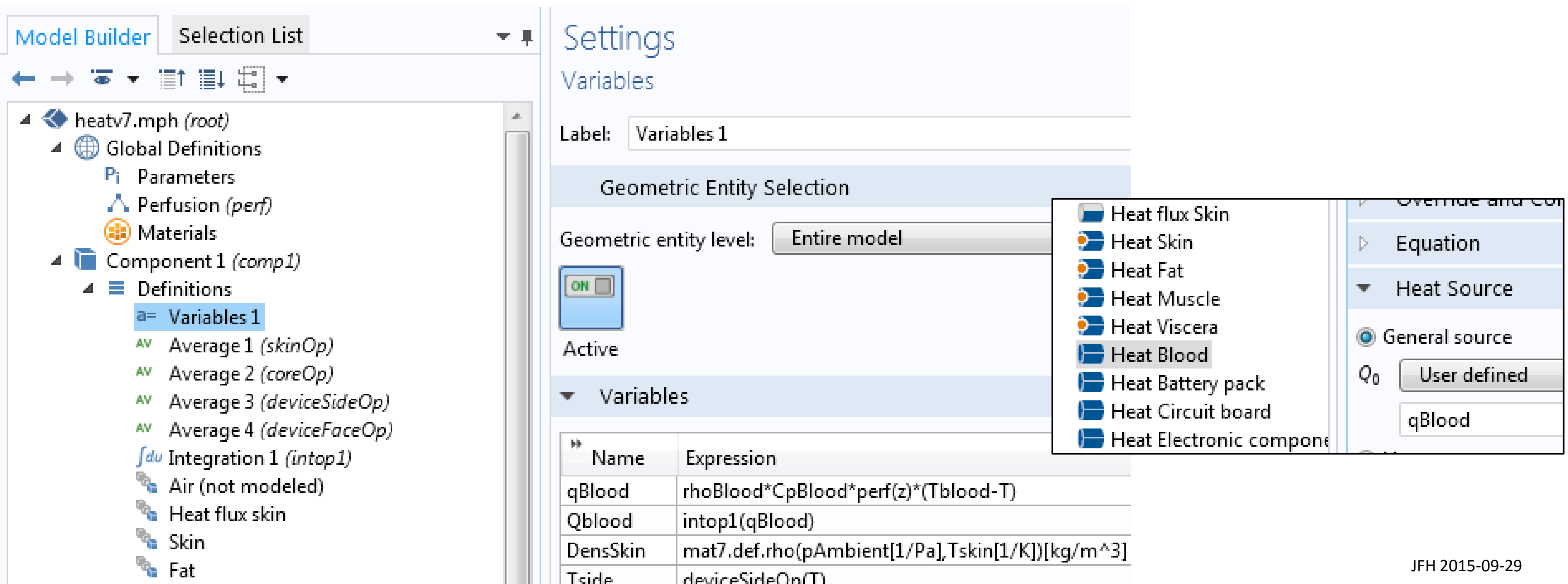
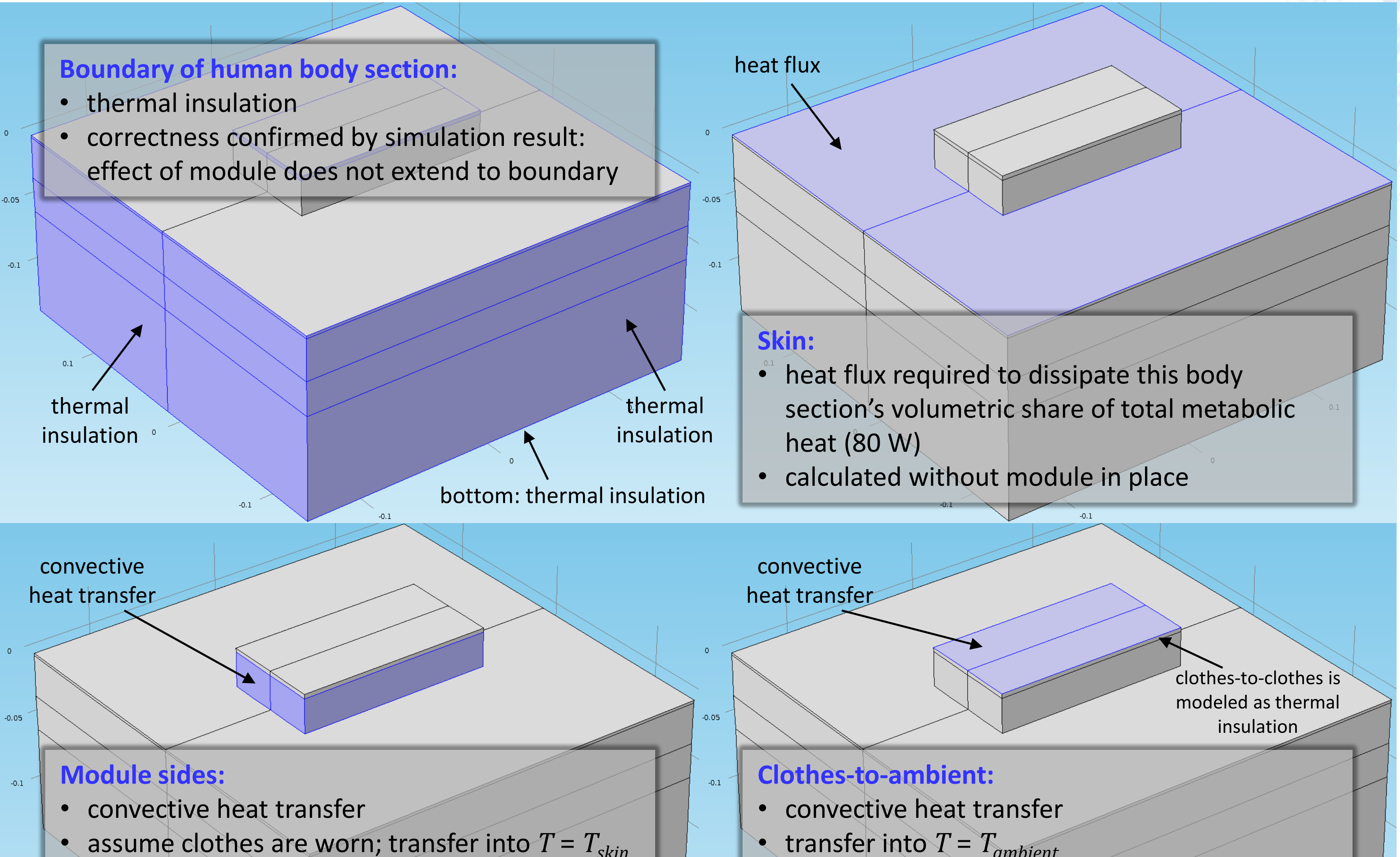


There are ≈6 different boundary conditions that must be correctly specified



Boundary of human body section:
- thermal insulation
- correctness confirmed by simulation result: effect of module does not extend to boundary

Skin:
- heat flux required to dissipate this body section's volumetric share of total metabolic heat (80 W)
- calculated without module in place

Module sides:
- convective heat transfer
- assume clothes are worn; transfer into $T = T_{skin}$
- heat transfer coefficient is calculated(!), not prescribed

Clothes-to-ambient:
- convective heat transfer
- transfer into $T = T_{ambient}$
- heat transfer coefficient is calculated(!), not prescribed, assuming no wind

The heat transfer coefficient can be calculated from a series of dimensionless numbers

$$h_C = \frac{\mathrm{Nu} \cdot k}{L}$$

$$\mathrm{Nu} = C \cdot \mathrm{Ra}^n$$

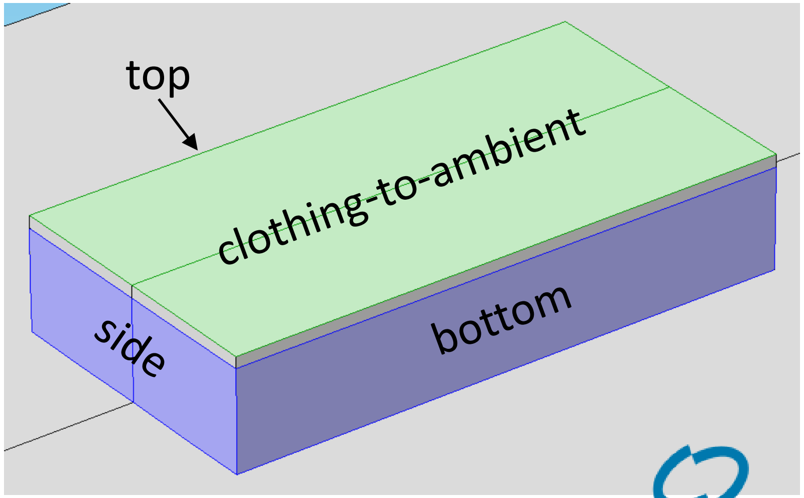
$$\mathrm{Ra} = \mathrm{Gr} \cdot \mathrm{Pr}$$

$$\mathrm{Gr} = \frac{gL^3}{\eta^2}\left(\frac{T_p}{T_a} - 1\right)$$

$$\mathrm{Pr} = \frac{\mu C_p}{k}$$

where
$k = k(T_a)$ = heat conductivity of air
$\eta = \eta(T_a)$ = kinetic viscosity of air
$\mu = \mu(T_a)$ = dynamic viscosity of air
$C_p = C_p(T_a)$ = heat capacity of air
g = acceleration of gravity 9.81 m/s^2

	L	C	n	T_p	T_a	valid for
module sides	y_m	0.59	0.25	$\overline{T_{side}}$	T_{skin}	$10^4<\mathrm{Ra}<10^9$
module top	$x_m/2$	0.54	0.25	$\overline{T_{top}}$	T_{skin}	$10^4<\mathrm{Ra}<10^7$
module bottom	$x_m/2$	0.27	0.25	$\overline{T_{bottom}}$	T_{skin}	$10^5<\mathrm{Ra}<10^{11}$
clothing-to-ambient	y_m	0.59	0.25	$\overline{T_{face}}$	$T_{ambient}$	$10^4<\mathrm{Ra}<10^9$



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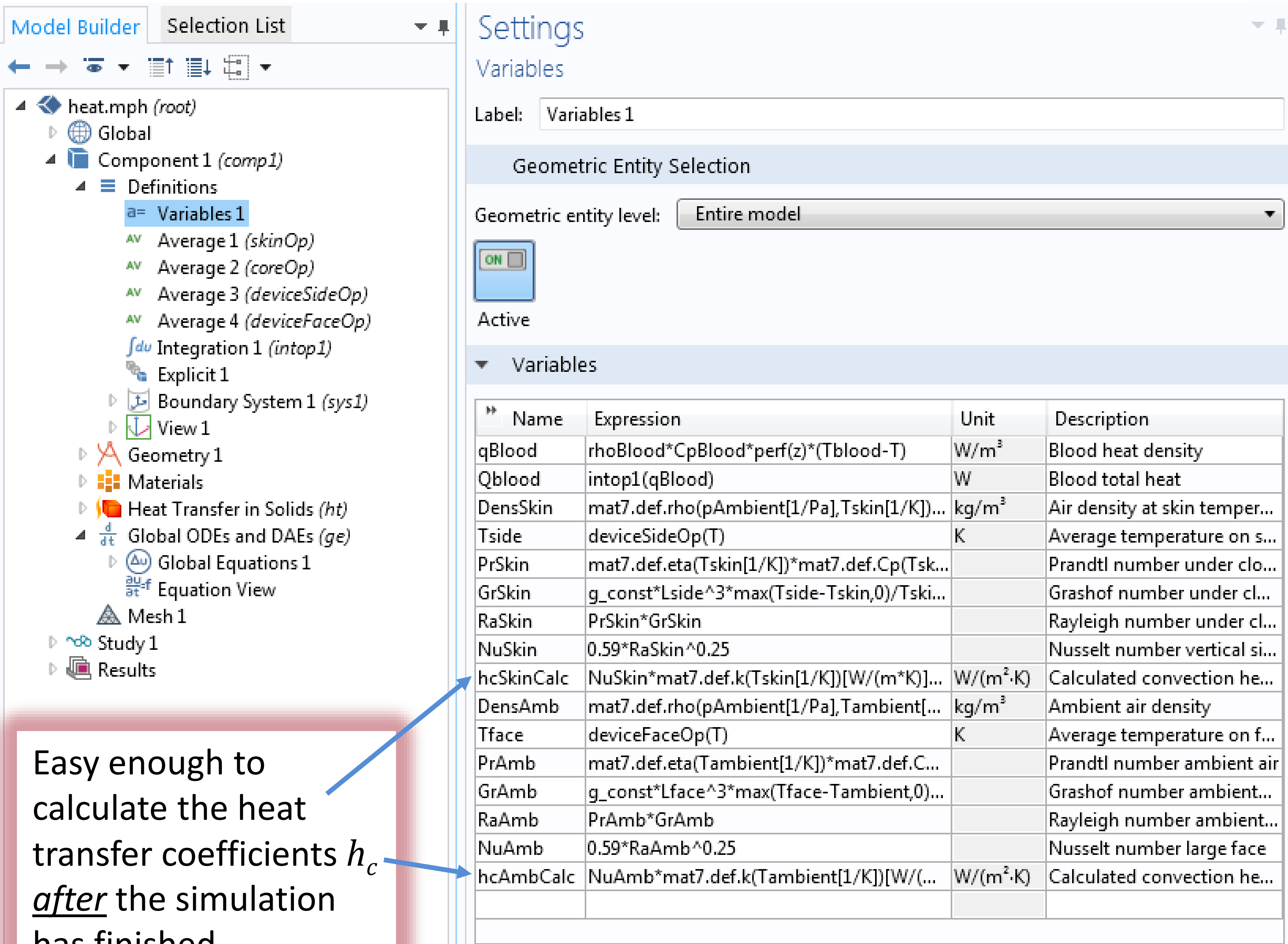
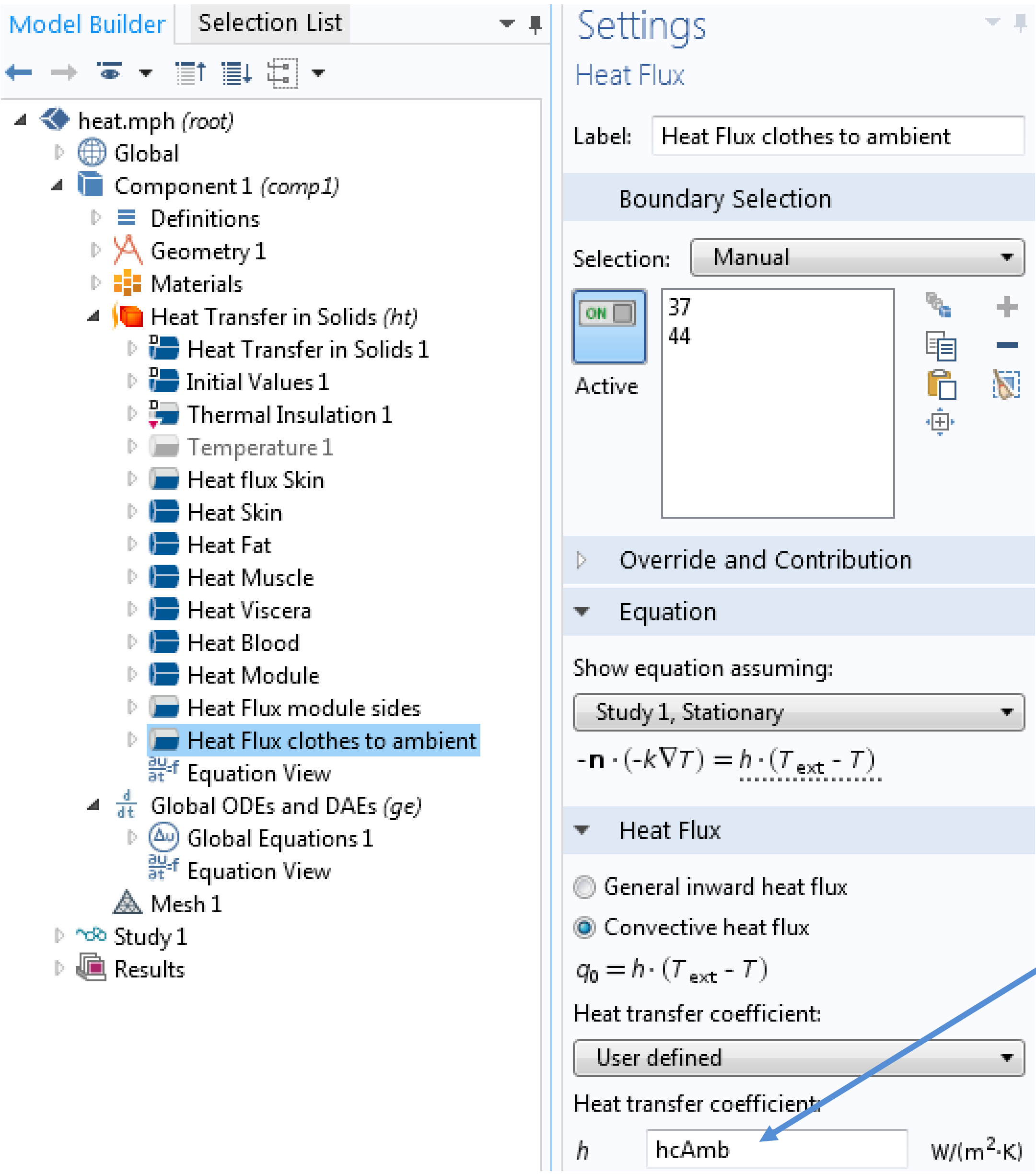
Direct calculation of the heat transfer coefficient can be done in COMSOL (step 1)



Name	Expression	Unit	Description
qBlood	rhoBlood*CpBlood*perf(z)*(Tblood-T)	W/m^3	Blood heat density
Qblood	intop1(qBlood)	W	Blood total heat
DensSkin	mat7.def.rho(pAmbient[1/Pa],Tskin[1/K])...	kg/m^3	Air density at skin temper...
Tside	deviceSideOp(T)	K	Average temperature on s...
PrSkin	mat7.def.eta(Tskin[1/K])*mat7.def.Cp(Tsk...		Prandtl number under clo...
GrSkin	g_const*Lside^3*max(Tside-Tskin,0)/Tski...		Grashof number under cl...
RaSkin	PrSkin*GrSkin		Rayleigh number under cl...
NuSkin	0.59*RaSkin^0.25		Nusselt number vertical si...
hcSkinCalc	NuSkin*mat7.def.k(Tskin[1/K])[W/(m*K)]...	$W/(m^2 \cdot K)$	Calculated convection he...
DensAmb	mat7.def.rho(pAmbient[1/Pa],Tambient[...	kg/m^3	Ambient air density
Tface	deviceFaceOp(T)	K	Average temperature on f...
PrAmb	mat7.def.eta(Tambient[1/K])*mat7.def.C...		Prandtl number ambient air
GrAmb	g_const*Lface^3*max(Tface-Tambient,0)...		Grashof number ambient...
RaAmb	PrAmb*GrAmb		Rayleigh number ambient...
NuAmb	0.59*RaAmb^0.25		Nusselt number large face
hcAmbCalc	NuAmb*mat7.def.k(Tambient[1/K])[W/(...	$W/(m^2 \cdot K)$	Calculated convection he...

Easy enough to calculate the heat transfer coefficients h_c *after* the simulation has finished…

Direct calculation of the heat transfer coefficient can be done in COMSOL (step 2)



...but if we entered the h_c variable name (hcAmbCalc) here, we would get an error message, because we need a value here to calculate hcAmbCalc in the first place...

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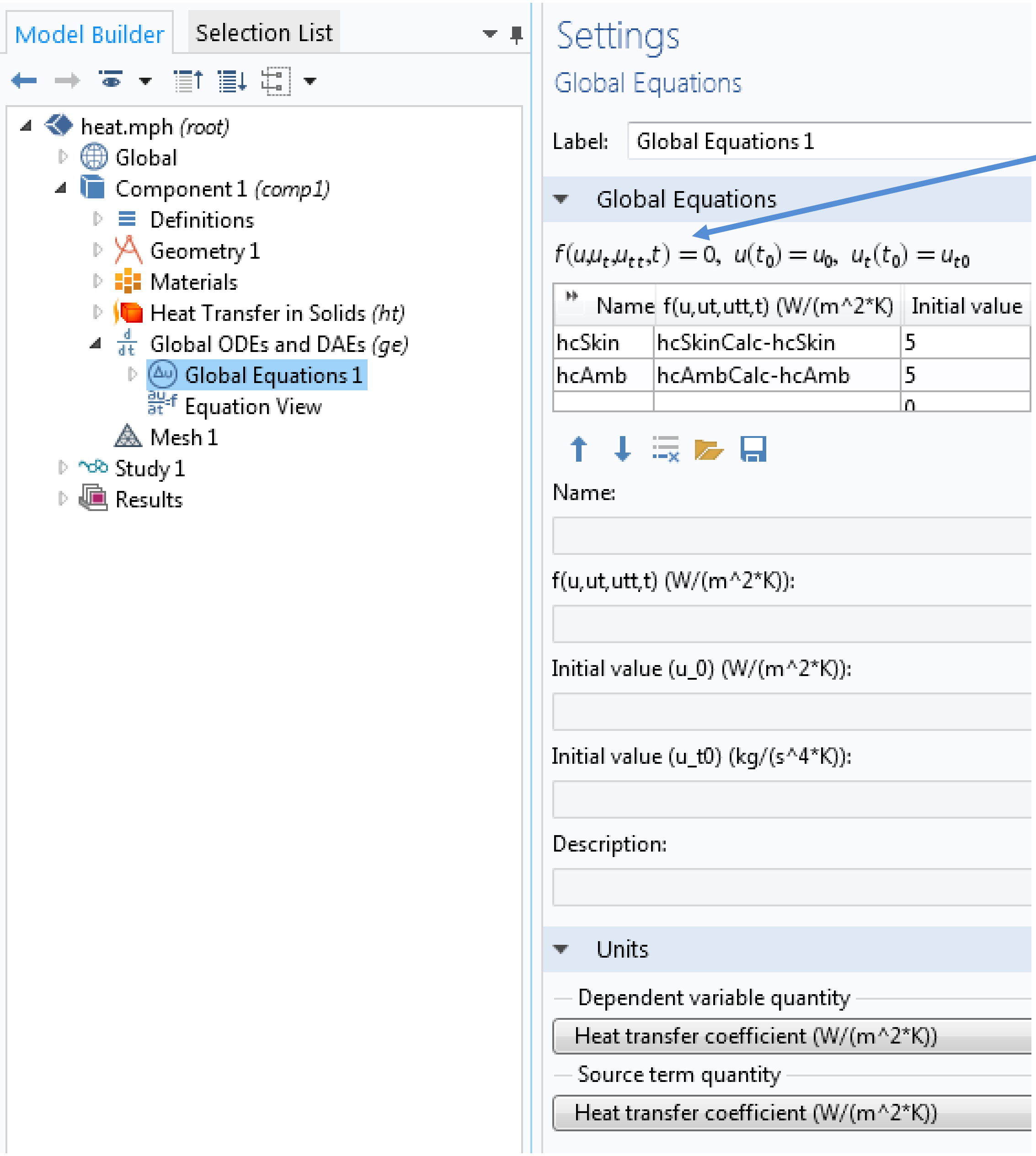
Direct calculation of the heat transfer coefficient can be done in COMSOL (step 3)



…so we have to add another physics node, a global ODE, that makes the input h_c and the output h_c the same.

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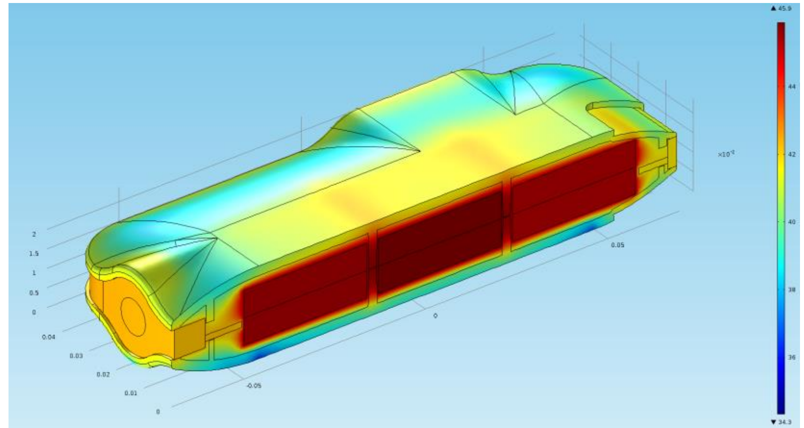
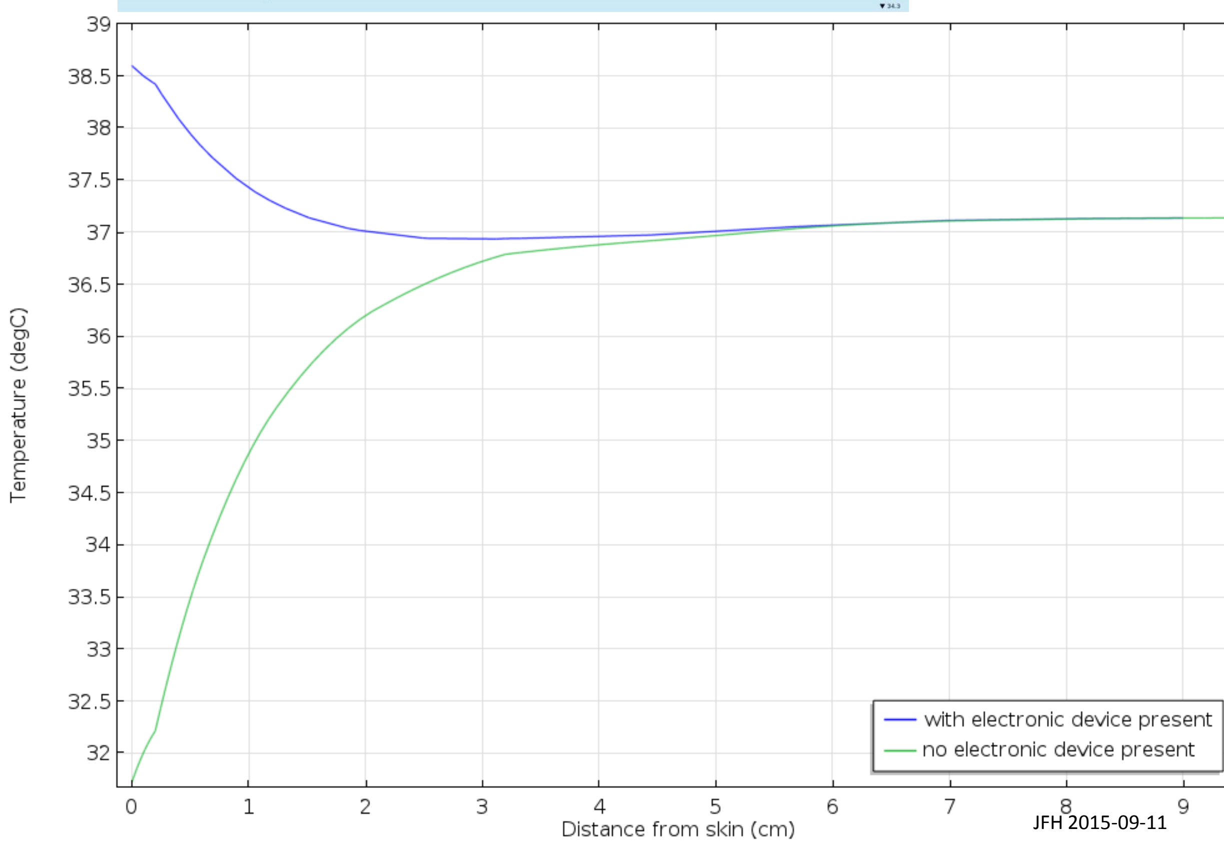
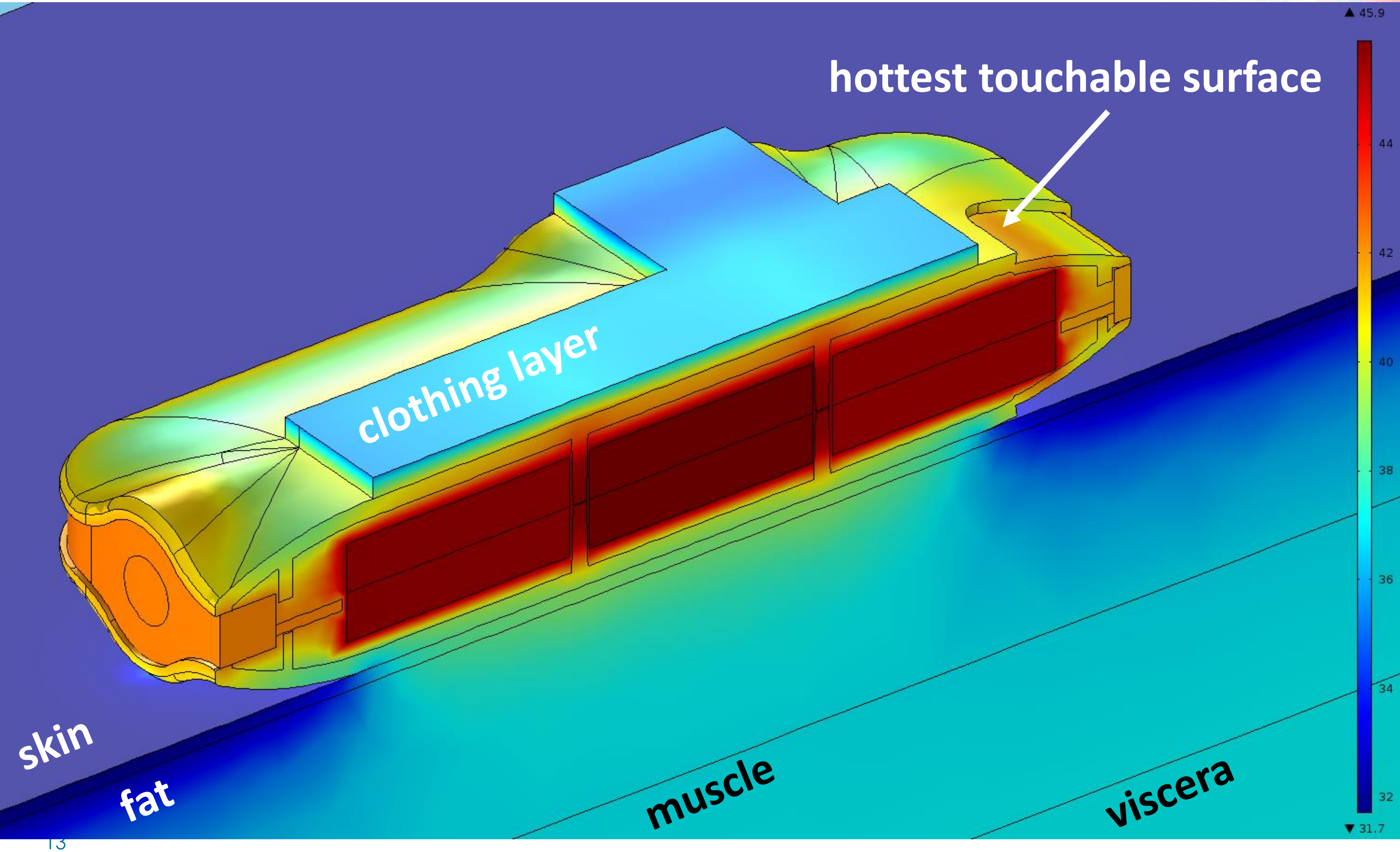
We find that one possible design allows ≈1.75 W of heat

Electronics heat [W]		0.75
out of which:		
Boost converters [%]		60
Circuit board [%]		40
Ambient temperature [°C]		26.0
Patient exertion level		At rest
%VO_2 max		13
Patient core temperature [°C]		36.7
Patient skin temperature [°C]		31.8
Clothing thickness [mm]		3.0
Clothing fit		Tight
Battery heat	Max temperatures [°C]	
[W]	Human skin	Module surface
0.0	36.6	39.7
0.5	37.9	41.4
1.0	39.4	43.0
1.5	40.8	45.8
2.0	42.2	49.5
2.5	43.7	53.0
3.0	45.0	56.5
Max allowed 60601-1	43	damage integral

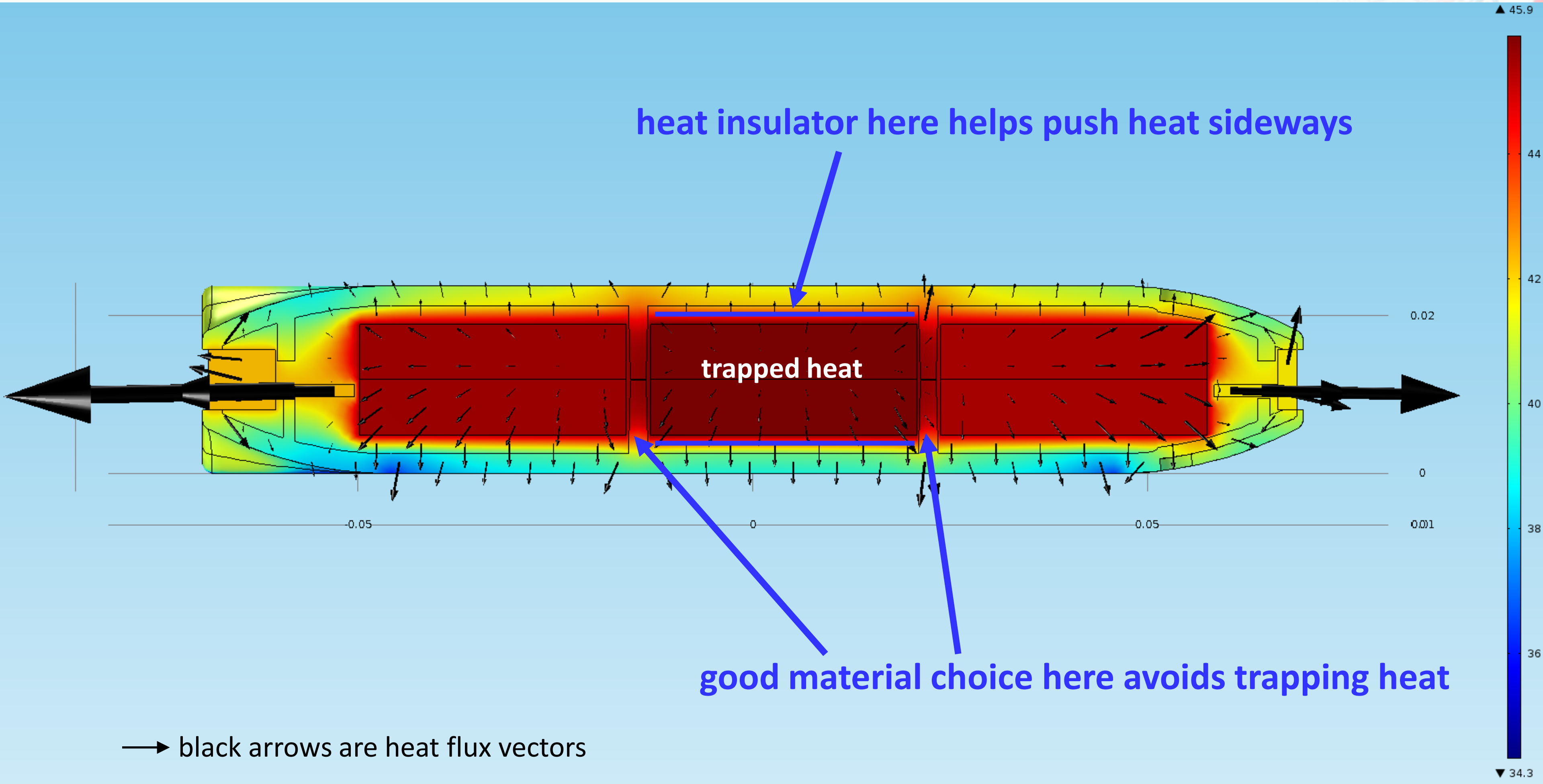




Simulation can be used to identify the hottest surface (IEC 60601-1 limit)



Choice of internal materials can help in distributing heat to a larger area



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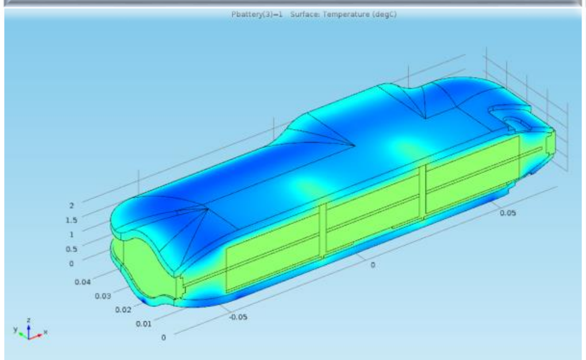
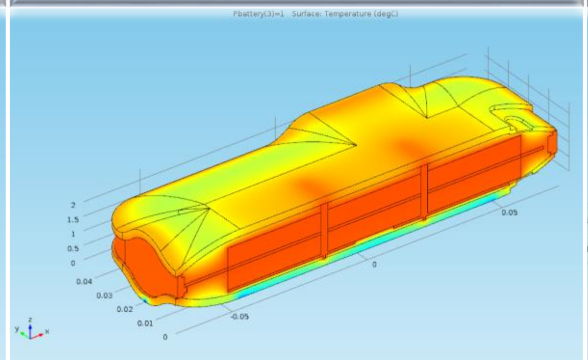
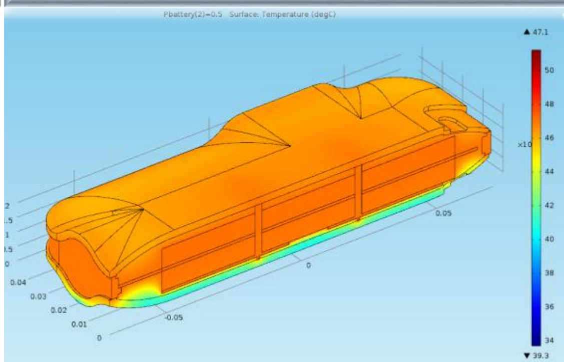
Performance in different ambient conditions can also be explored

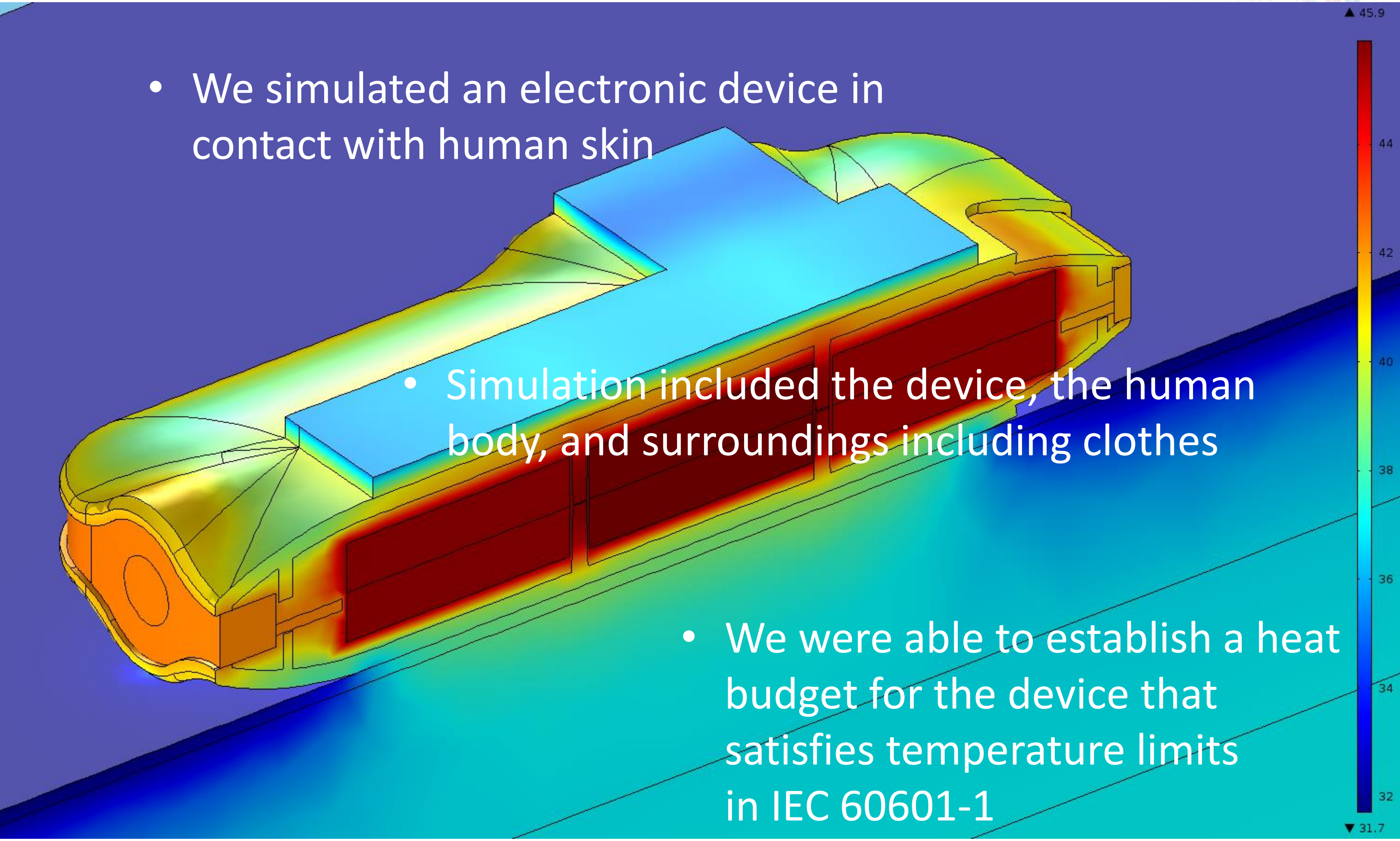






	26°C ambient			40°C ambient			device between human body and mattress		
Q_{batt} [W]	Skin [°C]	Module surface [°C]	Battery [°C]	Skin [°C]	Module surface [°C]	Battery [°C]	Skin [°C]	Module surface [°C]	Battery [°C]
0.0	37.0	37.4	37.5	39.5	42.5	42.5	39.8	43.0	43.0
0.5	38.4	40.1	40.2	40.8	45.1	45.1	41.8	47.1	47.1
1.0	39.6	42.8	42.8	42.0	47.6	47.7	43.8	51.2	51.2
1.5	40.9	45.3	45.3	43.2	50.1	50.2	45.8	55.3	55.4
2.0	42.1	47.8	47.8	44.4	52.6	52.6	47.8	59.4	59.4
2.5	43.3	50.3	50.3	45.6	55.0	55.0	49.8	63.4	63.5
3.0	44.5	52.7	52.7	46.8	57.3	57.4	51.8	67.4	67.5

Conclusions



- We simulated an electronic device in contact with human skin
- Simulation included the device, the human body, and surroundings including clothes
- We were able to establish a heat budget for the device that satisfies temperature limits in IEC 60601-1