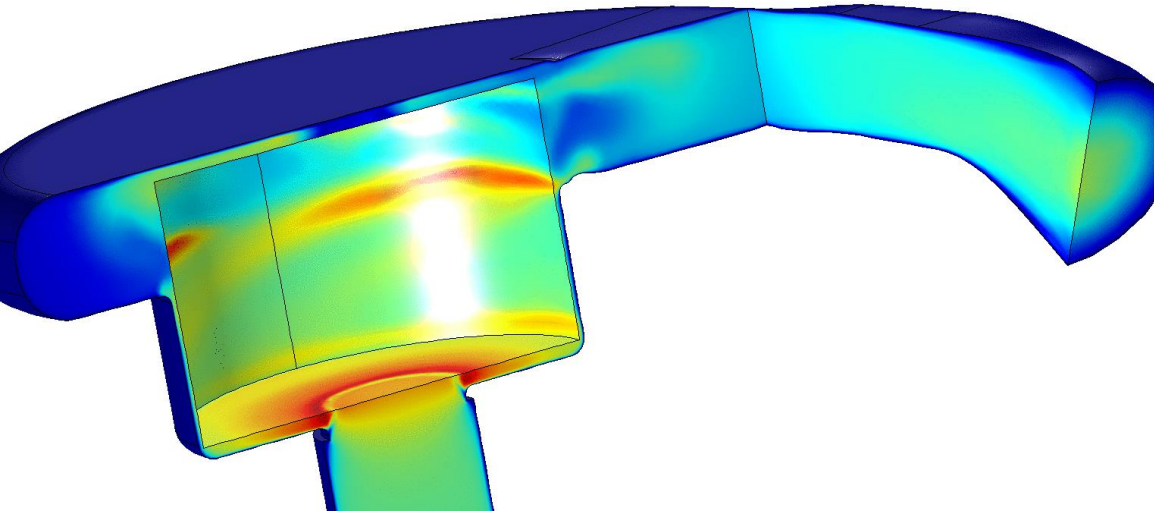


**Nusselt, Rayleigh, Grashof, and Prandtl:
Direct calculation of a user-defined
convective heat flux**

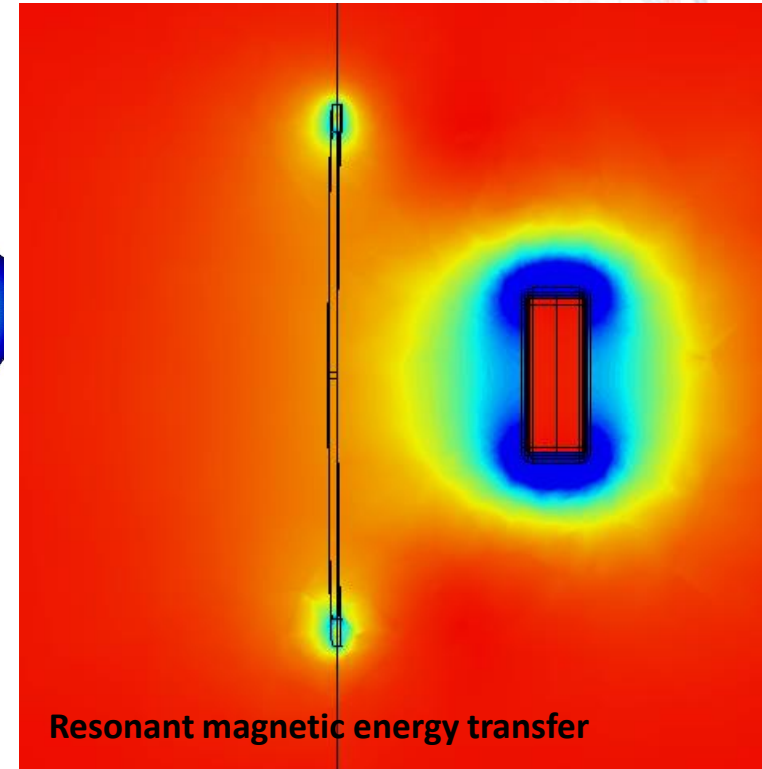
Freddy Hansen

We use COMSOL for a variety of simulations

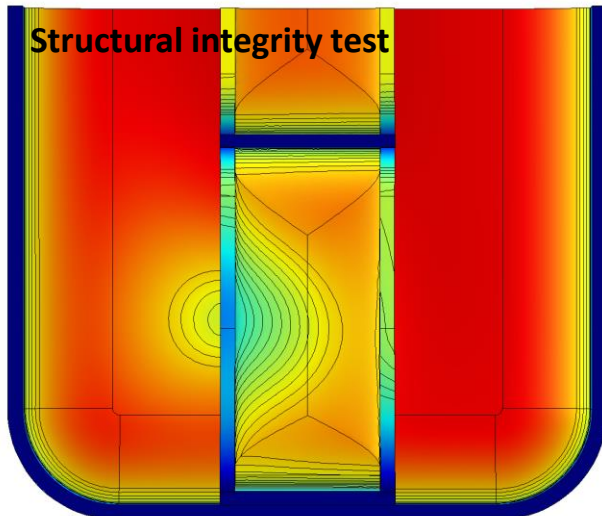
Just a few examples...



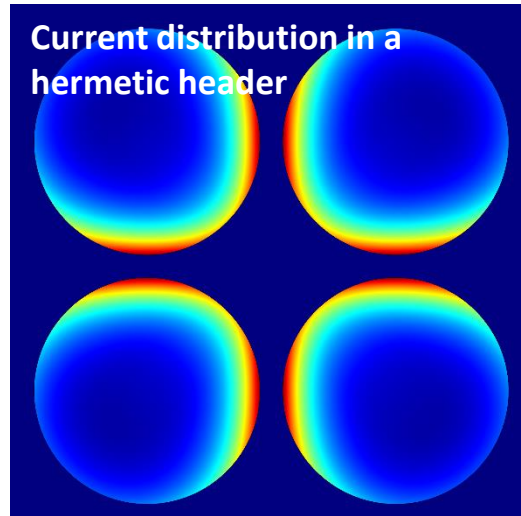
CFD simulation of a Ventricular Assist Device (VAD)



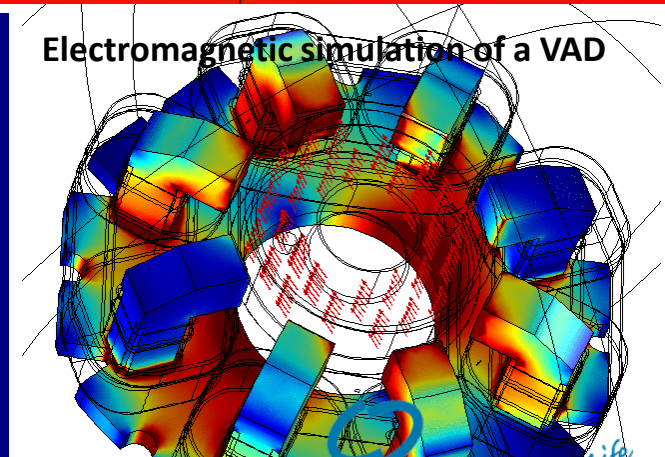
Resonant magnetic energy transfer



Structural integrity test



Current distribution in a hermetic header



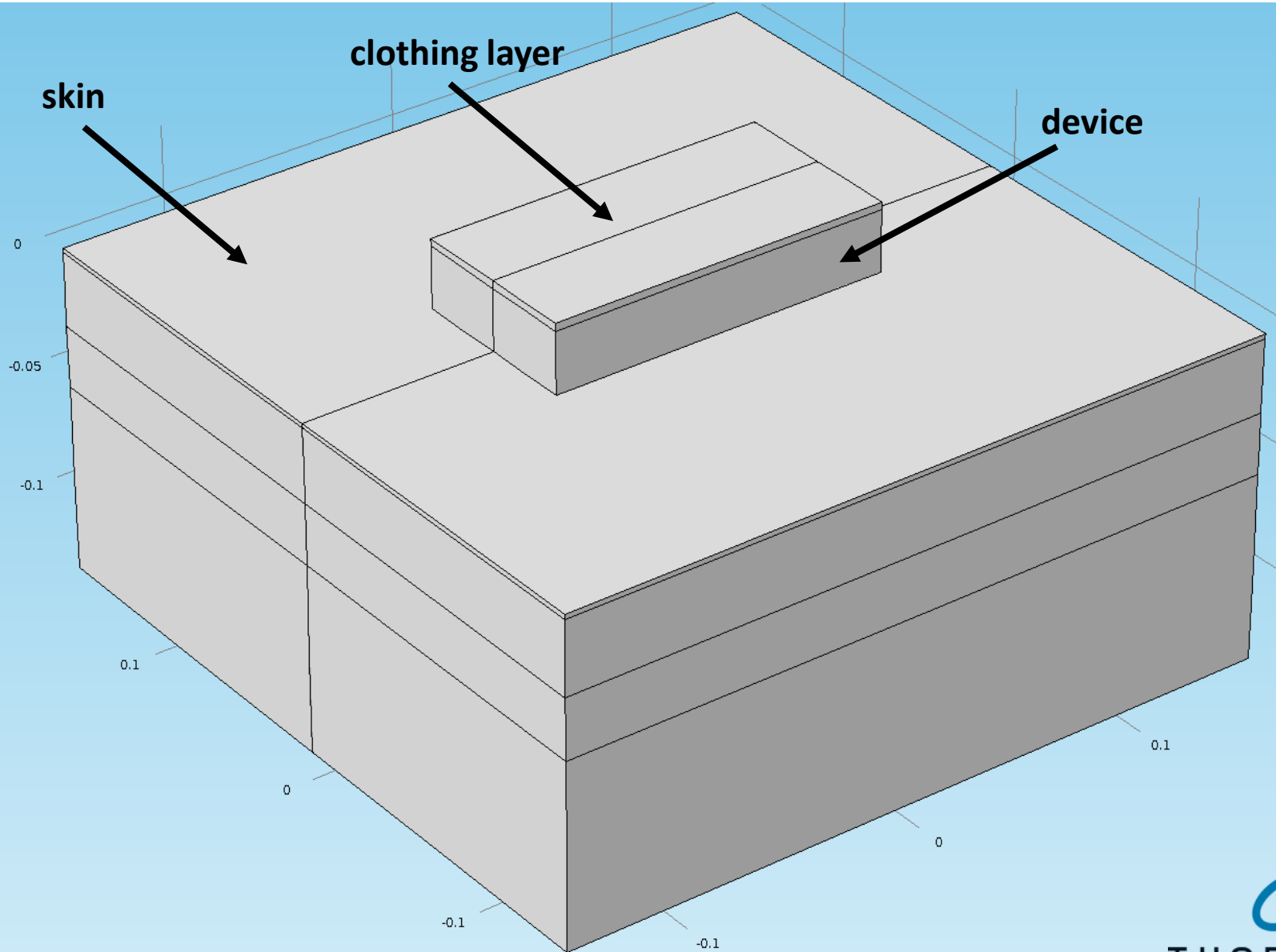
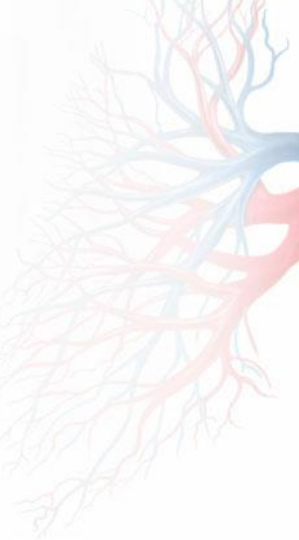
Electromagnetic simulation of a VAD

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)

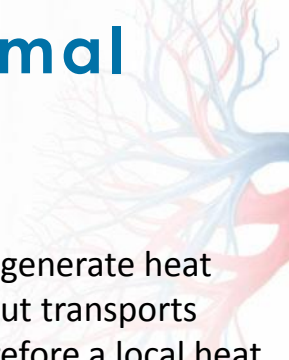
1. S. Hudack and P. D. McMaster, *J. Exp. Med.*, **55**, 431-439 (1932)
2. P. D. McMaster and S. Hudack, *J. Exp. Med.*, **56**, 239-253 (1932)
3. P. D. McMaster and S. Hudack, *J. Exp. Med.*, **60**, 479-501 (1934)
4. E. H. Leach, R. A. Peters, and R. J. Rossiter, *Q. J. Exp. Physiol.*, **32**, 67-86 (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



section of human body

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

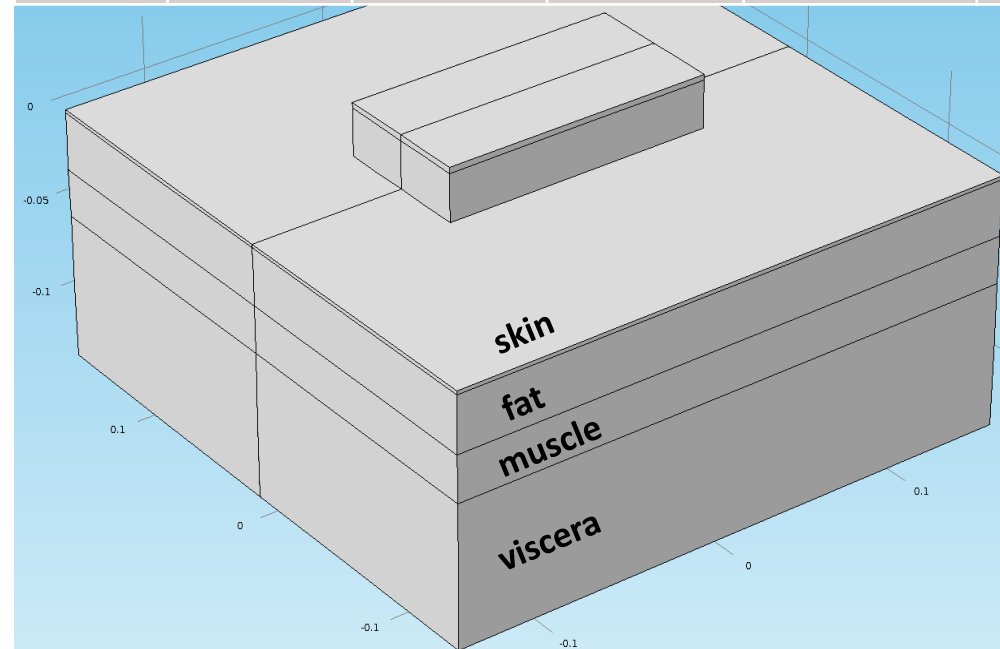


Blood does not generate heat metabolically, but transports heat and is therefore a local heat source or heat sink:

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

$$T_b = T_{core} = 36.7 \text{ }^\circ\text{C}$$

	thickness [mm]	metabolic rate [W/m ³]	perfusion ω [s ⁻¹]	thermal conductivity [W/m·K]	density [g/cm ³]	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	<i>net</i> ^[1]	<i>net</i> ^[2]	<i>average</i> ^[3]	0.53 ^[4]	1.0 ^[4]	3697 ^[4]
blood	n/a	Q_b	n/a	n/a	1.0 ^[5]	4200 ^[5]



References:

Values from “A Mathematical Model of the Human Thermal System,” E.D. Yildirim (2005)

except:

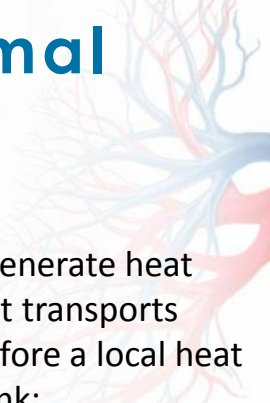
[1] viscera thickness to make torso width 267 mm total, based on 50-percentile male abdomen dimension in “The Measure of Men & Women,” A.R. Tilley, p. 12 (2002)

[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 Yildirim

[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)



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

	thickness [mm]	metabolic rate [W/m ³]	perfusion ω [s ⁻¹]	thermal conductivity [W/m·K]	density [g/cm ³]	heat capacity [J/kg·K]
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Blood does not generate heat metabolically, but transports heat and is therefore a local heat source or heat sink:

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$$T_b = T_{core} = 36.7 \text{ }^\circ\text{C}$$

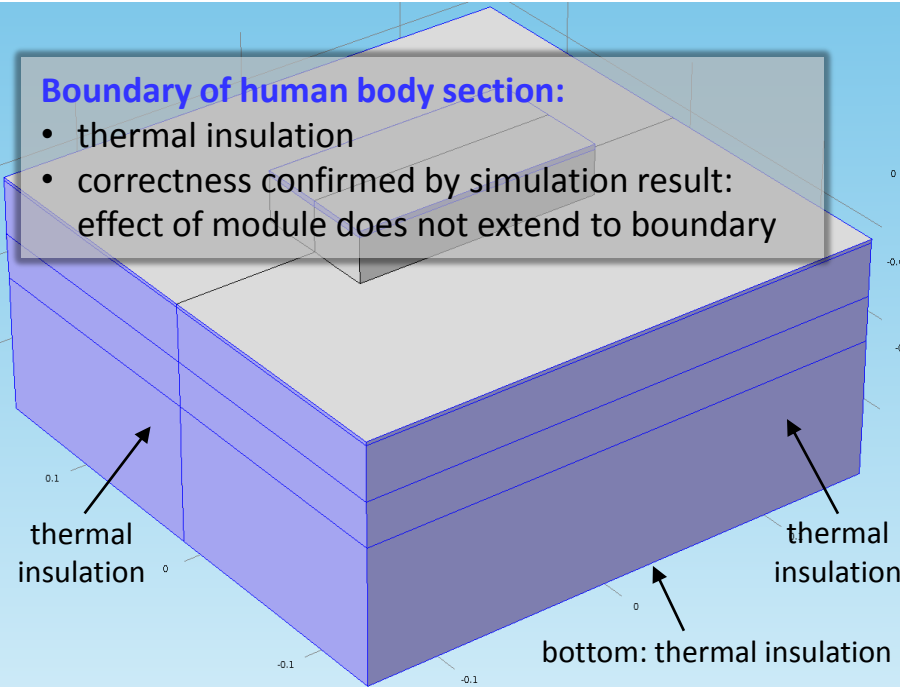
The screenshot shows the COMSOL Multiphysics interface. On the left is the Model Builder tree with 'heatv7.mph (root)' expanded to show 'Global Definitions', 'Parameters', 'Perfusion (perf)', 'Materials', and 'Component 1 (comp1)'. Under 'Component 1', 'Definitions' includes 'Variables 1', 'Average 1 (skinOp)', 'Average 2 (coreOp)', 'Average 3 (deviceSideOp)', 'Average 4 (deviceFaceOp)', 'Integration 1 (intop1)', 'Air (not modeled)', 'Heat flux skin', 'Skin', and 'Fat'. The 'Settings' window is open for 'Variables 1', showing 'Geometric entity level' set to 'Entire model' and 'Active' checked. A dropdown menu is open, listing heat sources: 'Heat flux Skin', 'Heat Skin', 'Heat Fat', 'Heat Muscle', 'Heat Viscera', 'Heat Blood', 'Heat Battery pack', 'Heat Circuit board', and 'Heat Electronic compone'. The 'Variables' table is also visible:

Name	Expression
qBlood	$\rho_{\text{Blood}} * C_{p,\text{Blood}} * \text{perf}(z) * (T_{\text{blood}} - T)$
Qblood	$\text{intop1}(q\text{Blood})$
DensSkin	$\text{mat7.def.rho}(p\text{Ambient}[1/\text{Pa}], T\text{skin}[1/\text{K}])(\text{kg}/\text{m}^3)$
Tside	$\text{deviceSideOp}(T)$

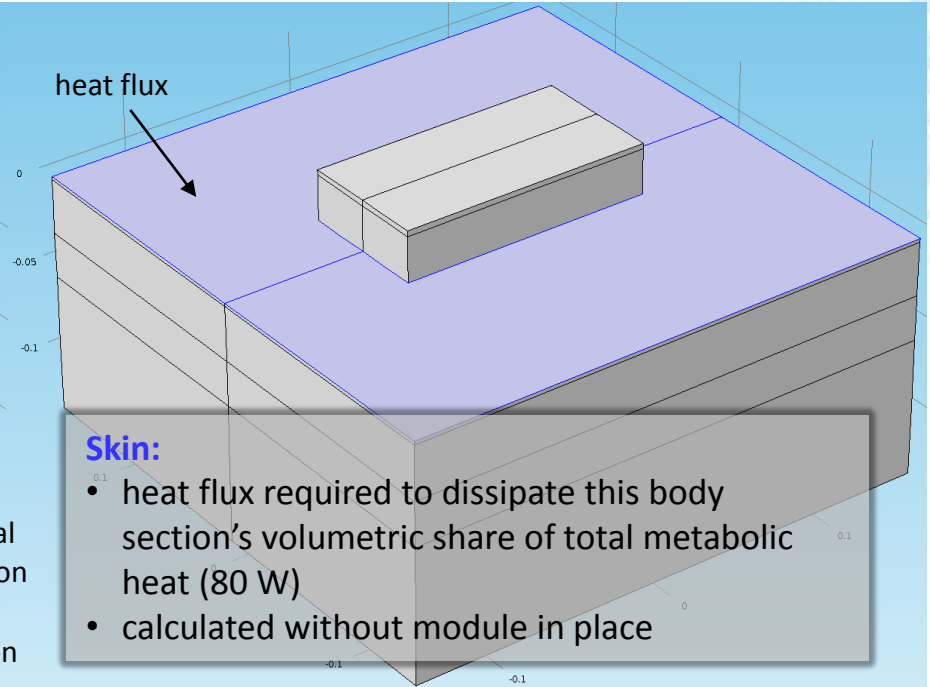
There are ≈ 6 different boundary conditions that must be correctly specified

Boundary of human body section:

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



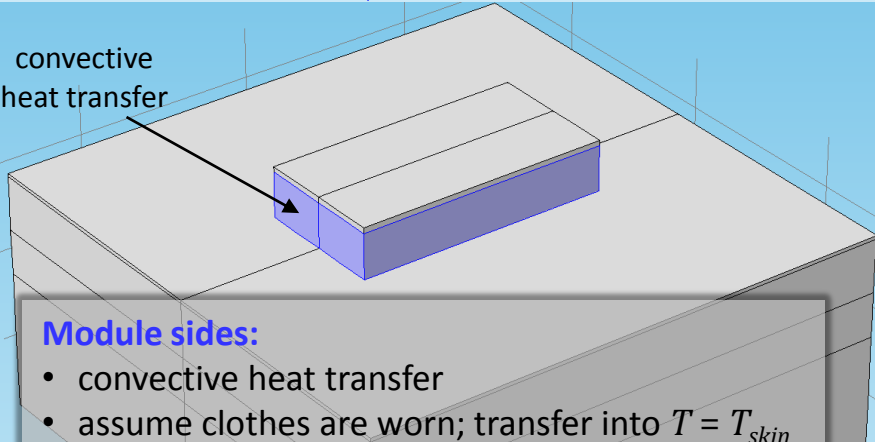
heat flux



Skin:

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

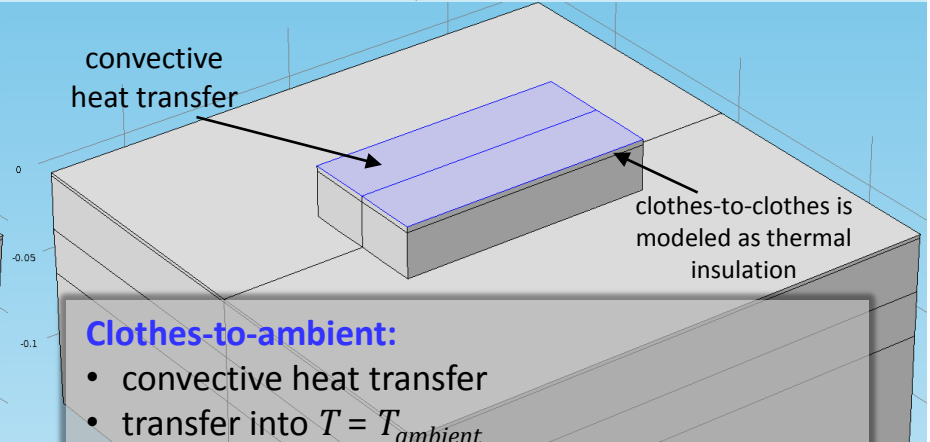
convective heat transfer



Module sides:

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

convective heat transfer



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

$$h_c = \frac{\text{Nu} \cdot k}{L}$$

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

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

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

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

where

$k = k(T_a)$ = heat conductivity of air

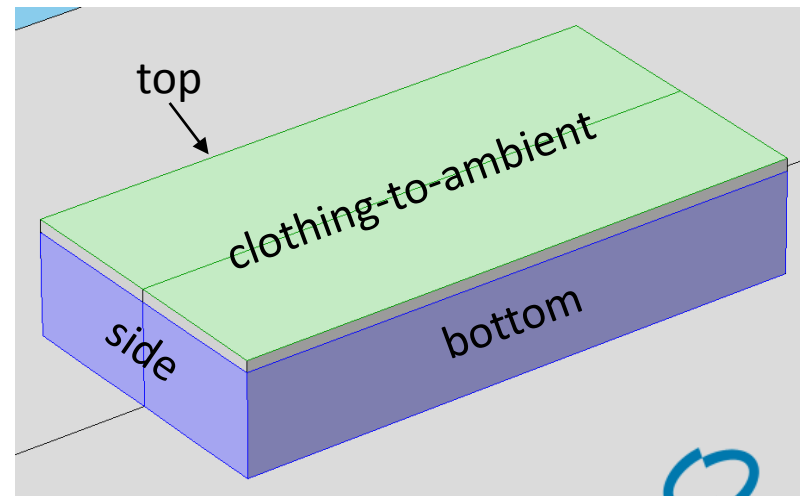
$\eta = \eta(T_a)$ = kinetic viscosity of air

$\mu = \mu(T_a)$ = dynamic viscosity of air

$C_p = C_p(T_a)$ = heat capacity of air

g = acceleration of gravity 9.81 m/s²

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



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

Model Builder Selection List Settings

Variables

Label: Variables 1

Geometric Entity Selection

Geometric entity level: Entire model

Active

Name	Expression	Unit	Description
qBlood	$\rho_{\text{Blood}} \cdot C_p \text{Blood} \cdot \text{perf}(z) \cdot (T_{\text{Blood}} - T)$	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	$g_{\text{const}} \cdot L_{\text{side}}^3 \cdot \max(T_{\text{side}} - T_{\text{skin}}, 0) / T_{\text{ski}}$		Grashof number under cl...
RaSkin	PrSkin * GrSkin		Rayleigh number under cl...
NuSkin	$0.59 \cdot \text{RaSkin}^{0.25}$		Nusselt number vertical si...
hcSkinCalc	$\text{NuSkin} \cdot \text{mat7.def.k}(T_{\text{skin}}[1/K]) [W / (m^2 \cdot K)] \dots$	W/(m ² ·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	$g_{\text{const}} \cdot L_{\text{face}}^3 \cdot \max(T_{\text{face}} - T_{\text{ambient}}, 0) \dots$		Grashof number ambient...
RaAmb	PrAmb * GrAmb		Rayleigh number ambient...
NuAmb	$0.59 \cdot \text{RaAmb}^{0.25}$		Nusselt number large face
hcAmbCalc	$\text{NuAmb} \cdot \text{mat7.def.k}(T_{\text{ambient}}[1/K]) [W / (...]$	W/(m ² ·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)



The screenshot shows the COMSOL Multiphysics interface. On the left is the Model Builder tree, where 'Heat Flux clothes to ambient' is selected under 'Heat Transfer in Solids (ht)'. The main window displays the 'Settings' for this boundary condition. The label is 'Heat Flux clothes to ambient'. The 'Boundary Selection' is set to 'Manual' with a list of active boundaries (37, 44). The 'Equation' section shows the equation
$$-\mathbf{n} \cdot (-k \nabla T) = h_c \cdot (T_{\text{ext}} - T)$$
 and the 'Heat Flux' type is set to 'Convective heat flux'. The 'Heat transfer coefficient' is set to 'User defined' with the variable name 'hcAmb' entered in the input field.

...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...

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

Model Builder Selection List

heat.mph (root)

- Global
- Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Heat Transfer in Solids (ht)
 - Global ODEs and DAEs (ge)
 - Global Equations 1**
 - Equation View
 - Mesh 1
- Study 1
- Results

Settings

Global Equations

Label: Global Equations 1

Global Equations

$f(u, u_t, u_{tt}, t) = 0, u(t_0) = u_0, u_t(t_0) = u_{t0}$

Name	f(u, u_t, u_{tt}, t) (W/(m^2*K))	Initial value
hcSkin	hcSkinCalc-hcSkin	5
hcAmb	hcAmbCalc-hcAmb	5
		0

Name:

f(u, u_t, u_{tt}, t) (W/(m^2*K)):

Initial value (u_0) (W/(m^2*K)):

Initial value (u_t0) (kg/(s^4*K)):

Description:

Units

- Dependent variable quantity
- Heat transfer coefficient (W/(m^2*K))
- Source term quantity
- Heat transfer coefficient (W/(m^2*K))

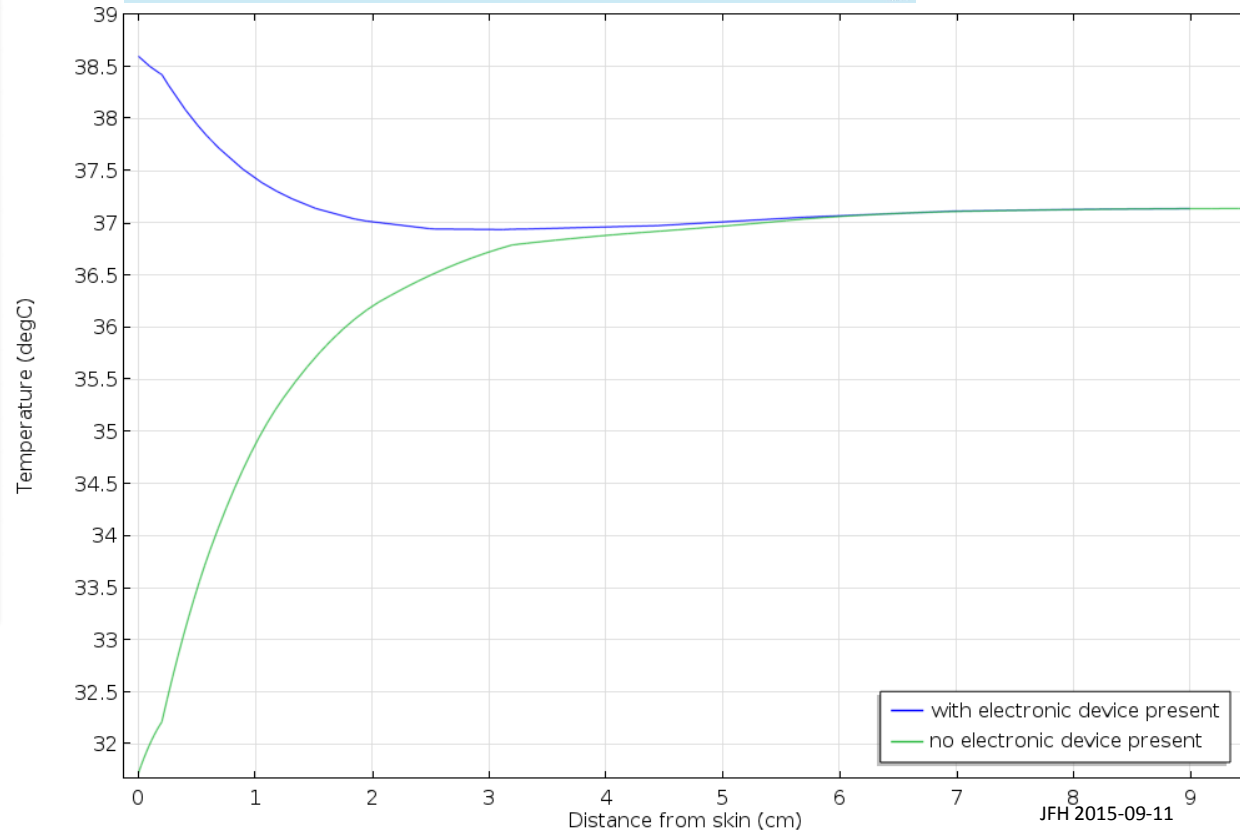
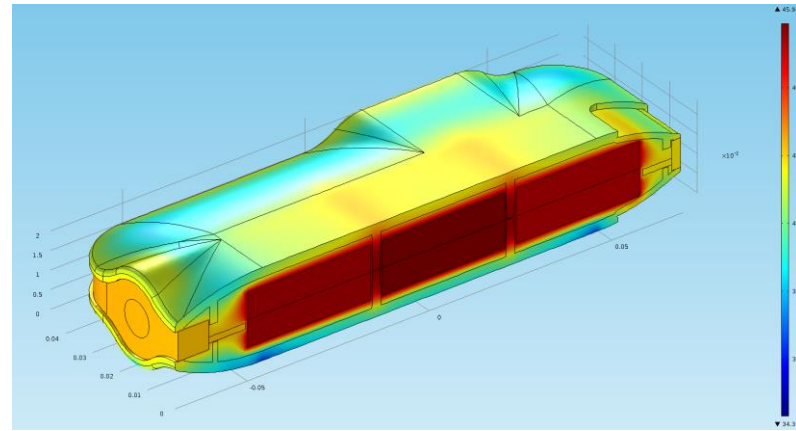
...so we have to add another physics node, a global ODE, that makes the input h_c and the output h_c the same.

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

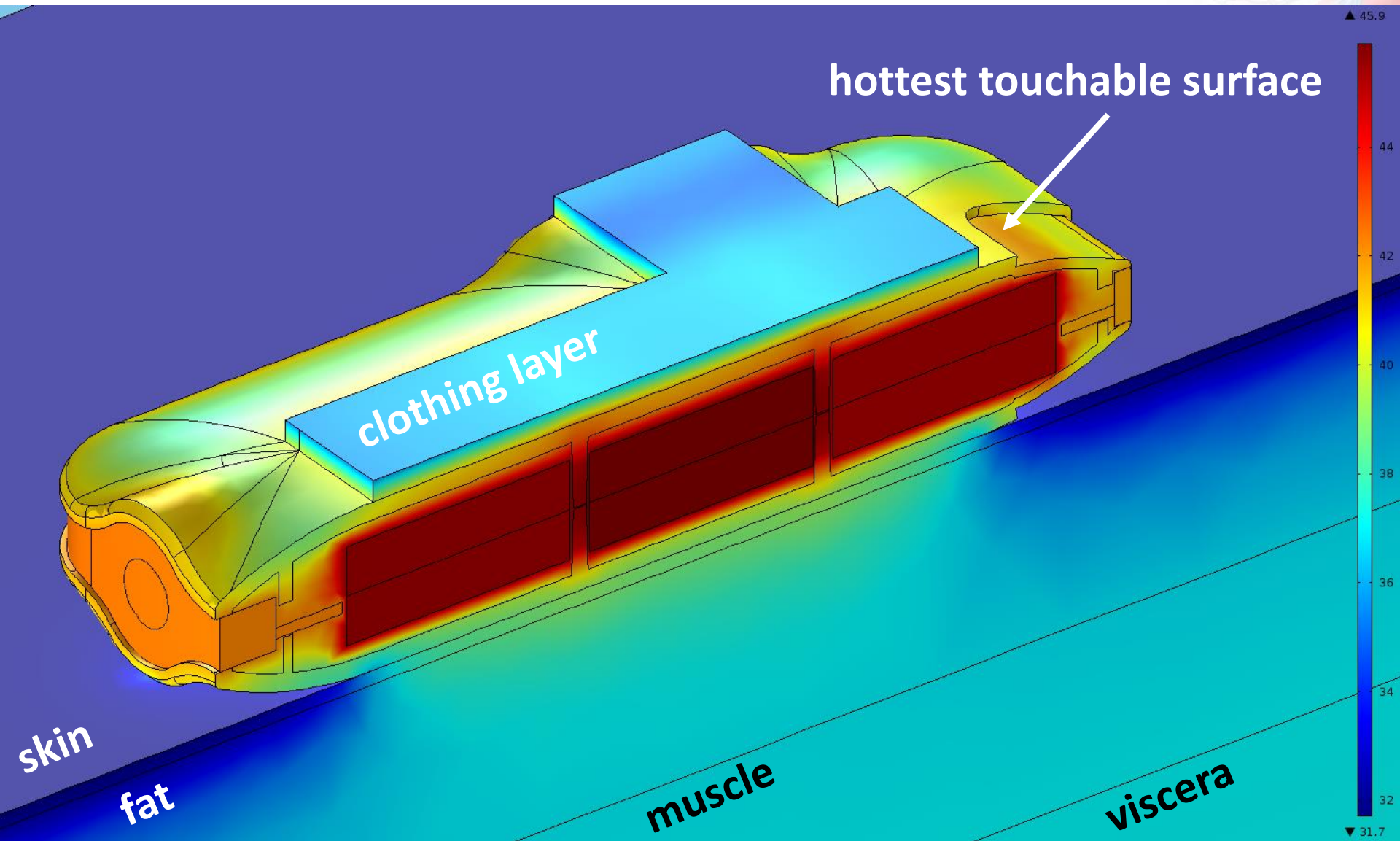


Electronics heat [W]	0.75
out of which:	
Boost converters [%]	60
Circuit board [%]	40
Ambient temperature [°C]	26.0
Patient exertion level	At rest
%VO ₂ max	13
Patient core temperature [°C]	36.7
Patient skin temperature [°C]	31.8
Clothing thickness [mm]	3.0
Clothing fit	Tight

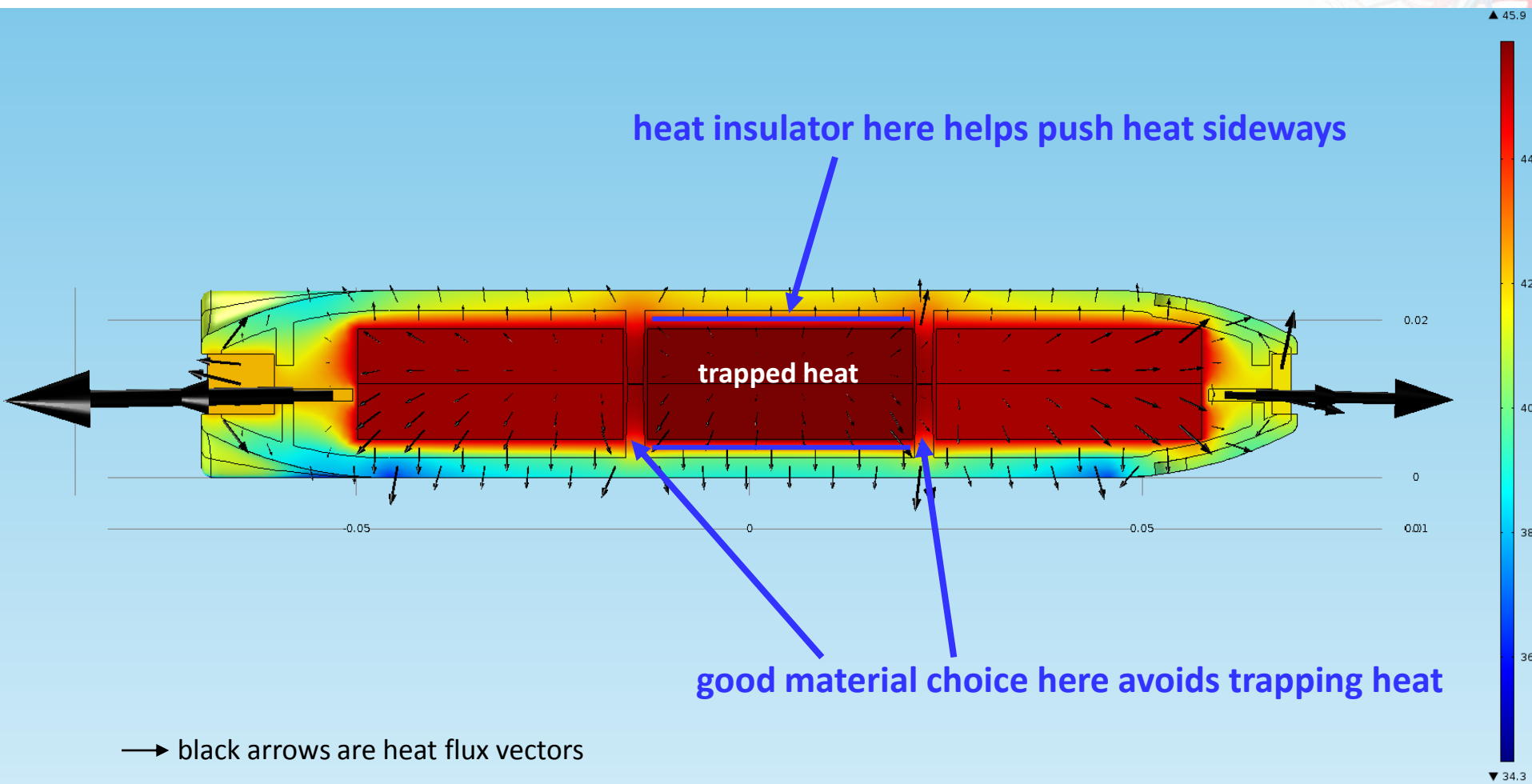
Battery heat [W]	Max temperatures [°C]	
	Human skin	Module surface
0.0	36.6	39.7
0.5	37.9	41.4
1.0	39.4	43.0
1.5	40.8	45.8
2.0	42.2	49.5
2.5	43.7	53.0
3.0	45.0	56.5
Max allowed 60601-1	43	damage integral



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



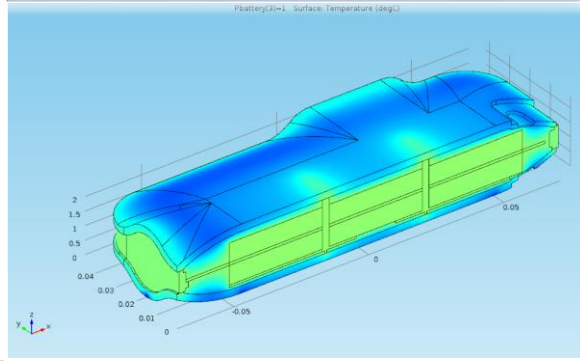
Choice of internal materials can help in distributing heat to a larger area



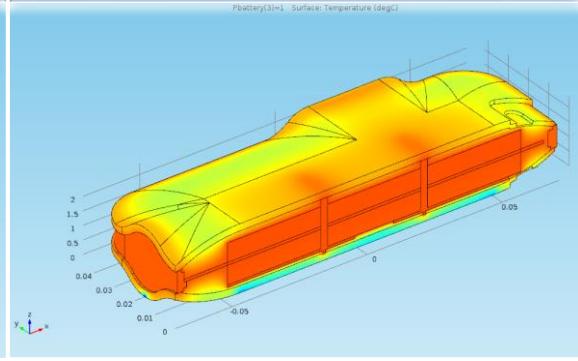
Performance in different ambient conditions can also be explored



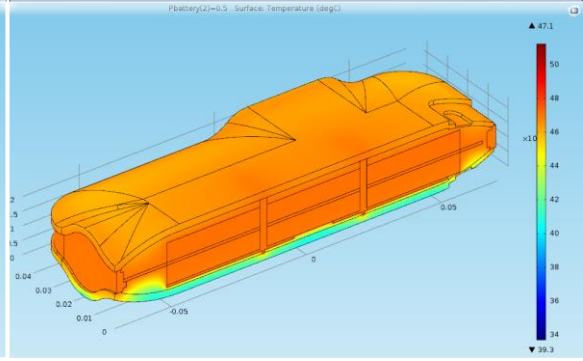
26°C ambient



40°C ambient



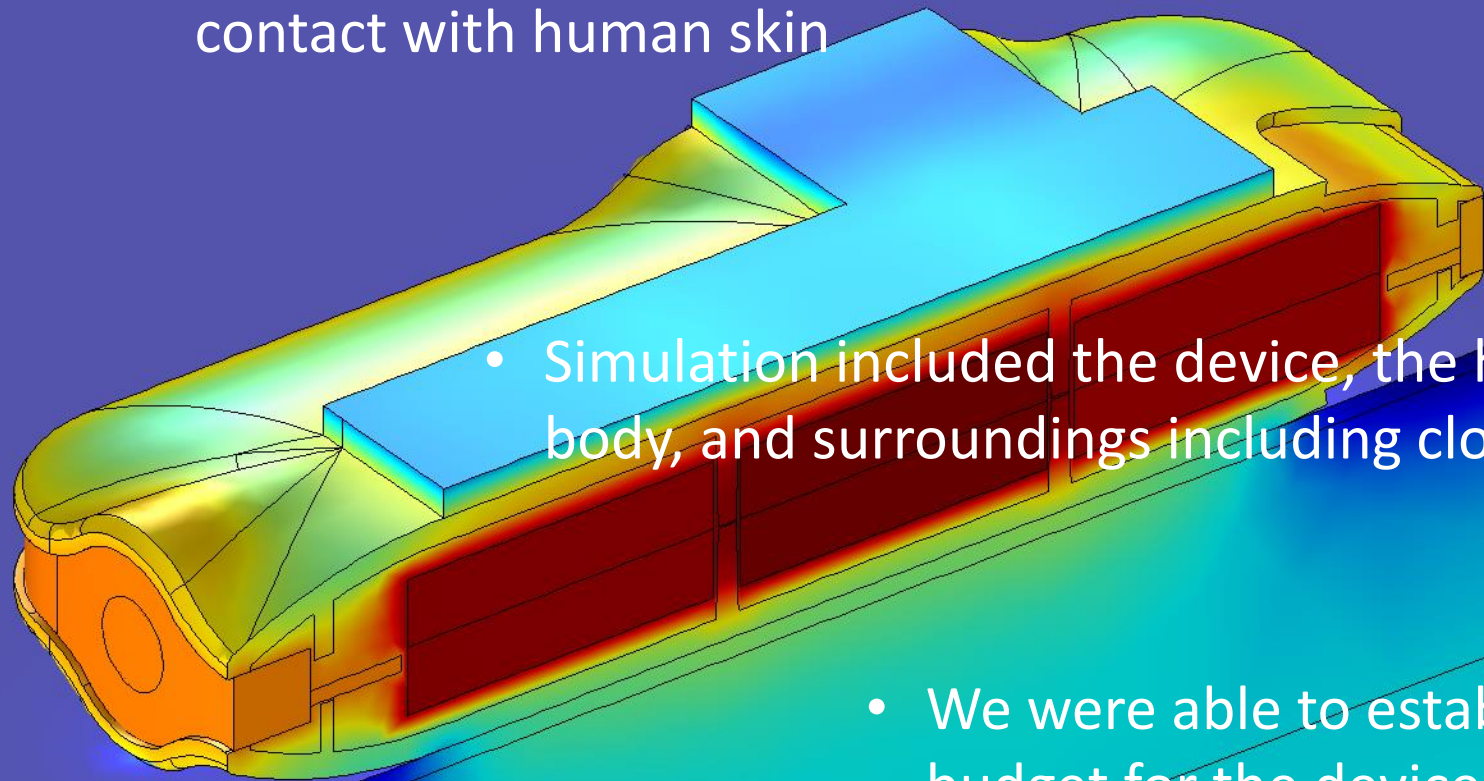
device between human body and mattress



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