



# Nonhomogeneous heat transfer simulation using a female human model

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**COMSOL**  
**CONFERENCE**  
2018 BOSTON

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# Disclaimer

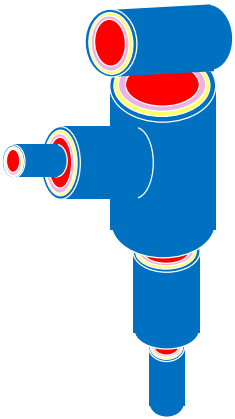


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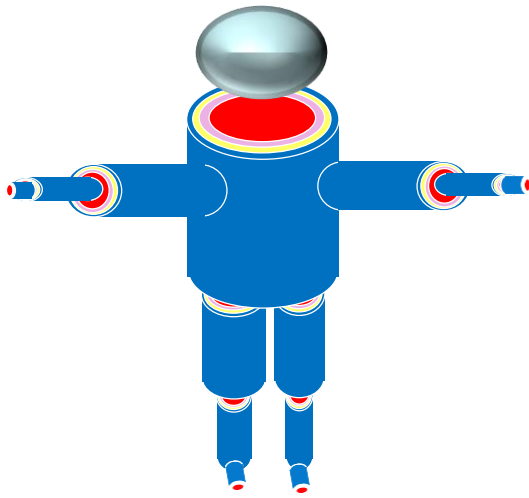


# Introduction

- Human thermoregulatory models have been developed and applied since early 1960s
- Most human body models have been constructed from cylinders and ellipses using CAD software
- Medical images can be used to create a more accurate representation of the human body
- Purpose of the study is to use a geometrically and anatomically accurate mesh to perform heat transfer analysis and create temperature profiles in the human body



Multiple cylinders or elliptical-cylinder





# Mesh

Average American Female

Height: 1.62 m (~5' 4")

Weight: 66 kg (~145 lbs.)

Body Fat: 36.1%

Age: 36 year

Volume: 0.0445 m<sup>3</sup>

Surface Area: 0.777m<sup>2</sup>

Vertices: 566,830

Tetrahedra: 2,985,530

Triangles: 802,750

Edge elements: 13,020

(Segars et al Med Phys 2010, Simpleware Inc)

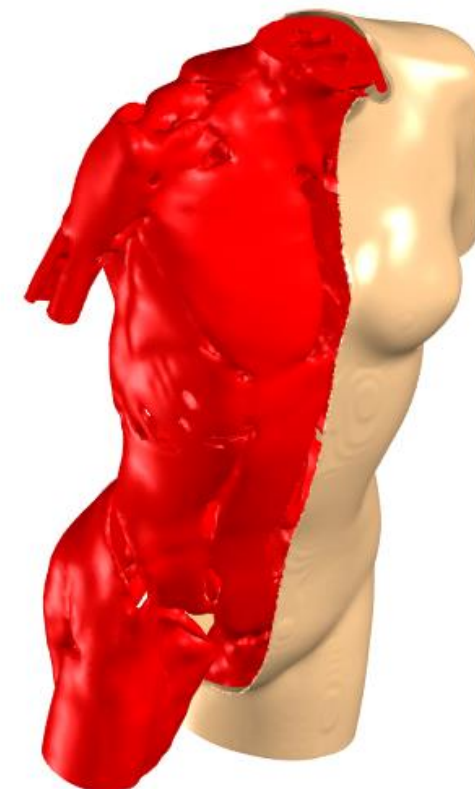




# Organs

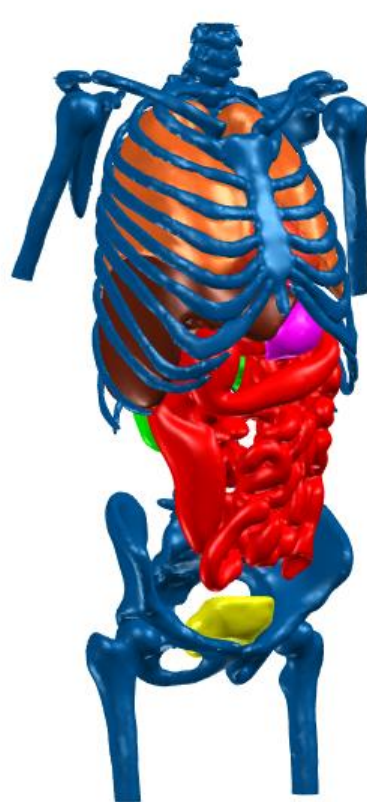
Skin

Muscle





# Bones and Internal Organs





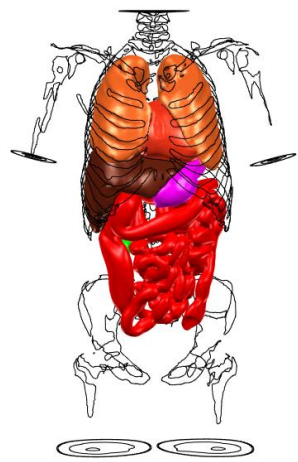
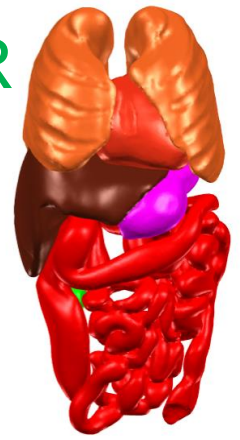


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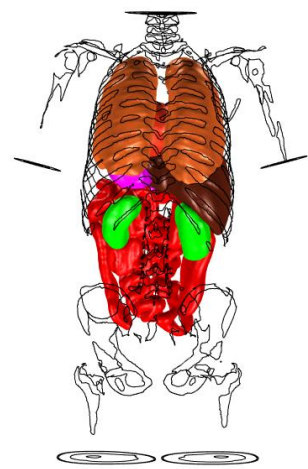
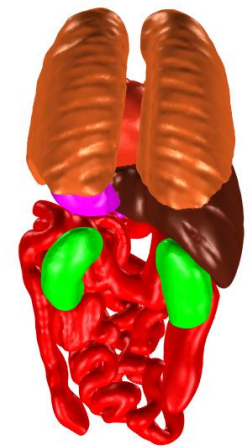
# Internal Organs



ANTERIOR



POSTERIOR



Unclassified



# Biophysical Heat Transfer

BIOLOGICAL HEAT TRANSFER WITHIN THE BODY:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T + Q + \omega_b \rho_b c_b (T_b - T)$$

HEAT FLUX AT THE SURFACE:

$$q = (h_c + h_r) \cdot (T - T_a) + E$$





# Comsol Implementation

Model Builder

- Female50 Heat Transfer test.mph (root)
  - Global Definitions
    - Parameters
  - Materials
    - Model 1 (mod1)
      - Definitions
      - Geometry 1
      - Materials
        - Part Material: SKIN (mat1)
        - Part Material: FAT (mat2)
        - Part Material: MUSCLE (mat3)
        - Part Material: BLADDER (mat4)
        - Part Material: INTENSTINES (mat5)
        - Part Material: STOMACH (mat6)
        - Part Material: KIDNEYS (mat7)
        - Part Material: LUNGS (mat8)
        - Part Material: LIVER (mat9)
        - Part Material: HEART (mat10)
        - Part Material: BONES (mat11)
    - Bioheat Transfer (ht)
      - Biological Tissue 1
      - Initial Values 1
        - Thermal Insulation 1
        - Heat Flux 1
        - Heat Flux 2 convection
      - Global Equations 1
  - Mesh 1
  - Study 1
    - Step 1: Stationary
    - Solver Configurations
  - Study 2
  - Study 3
  - Results
    - Data Sets
      - Study 1/Solution 1 (sol1)
        - Cut Plane 1
        - Cut Plane 2
        - Cut Plane 3
      - Study 2/Solution 2 (sol2)
        - Cut Plane 4
        - Cut Plane 5
        - Cut Plane 6
      - Study 3/Solution 3 (sol3)
        - Cut Plane 7
        - Cut Plane 8
        - Cut Plane 9
        - Cut Plane 10
    - Views
    - Derived Values

Settings Properties

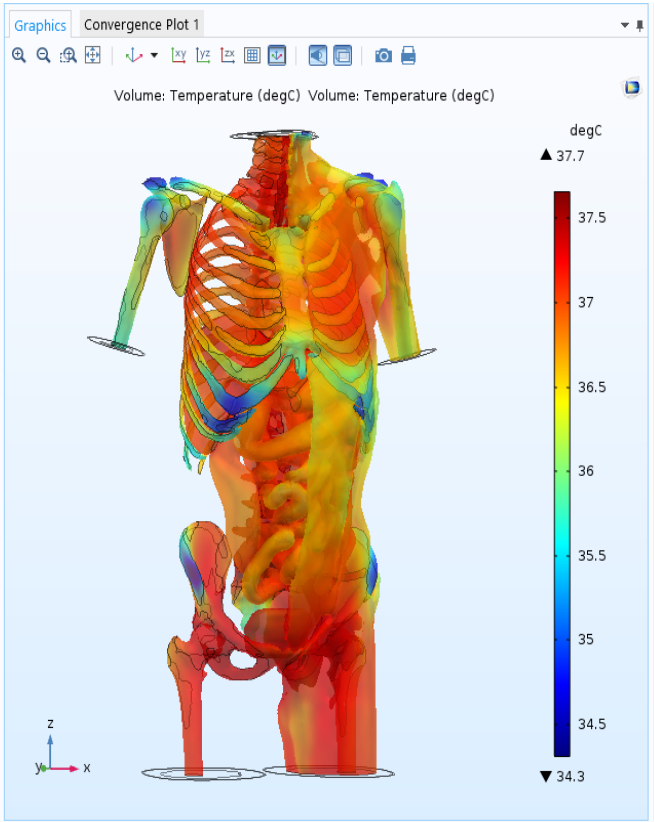
Parameters

Name	Expression	Value	Description
Q_skin_0	368.12[W/m^3]	368.12 W/m <sup>3</sup>	
Q_fat_0	368.36[W/m^3]	368.36 W/m <sup>3</sup>	
Q_muscle_0	684.18[W/m^3]	684.18 W/m <sup>3</sup>	
Q_bladder_0	370.37[W/m^3]	370.37 W/m <sup>3</sup>	
Q_intestine_0	368.339[W/m^3]	368.34 W/m <sup>3</sup>	
Q_kidney_0	23889[W/m^3]	23889 W/m <sup>3</sup>	
Q_liver_0	14413.6[W/m^3]	14414 W/m <sup>3</sup>	
Q_lung_0	365.49[W/m^3]	365.49 W/m <sup>3</sup>	
Q_heart_0	24000 [W/m^3]	24000 W/m <sup>3</sup>	
omega_skin_0	0.000361[1/s]	3.61E-4 1/s	
omega_fat_0	0.000077[1/s]	7.7E-5 1/s	
omega_muscle_0	0.000542[1/s]	5.42E-4 1/s	
omega_bladder_0	0.0001543[1/s]	1.543E-4 1/s	
omega_intestine_0	0.0064002[1/s]	0.0064002 1/s	
omega_kidney_0	0.07208[1/s]	0.07208 1/s	
omega_lung_0	0.04893[1/s]	0.04893 1/s	
omega_liver_0	0.018008[1/s]	0.018008 1/s	
omega_heart_0	0.0144072*1.0[1/s]	0.014407 1/s	
T_blood	37 [degC]	310.15 K	
Ta	28 [degC]	301.15 K	
Cp_blood	3850 [J/kg/K]	3850 J/(kg·K)	
rho_blood	1059 [kg/m^3]	1059 kg/m <sup>3</sup>	

Name:

Expression:

Description:



Add Physics Add Study

+

Add Study

— Studies

- Presets Studies
  - Eigenfrequency
  - Eigenvalue
  - Stationary
  - Thermal Perturbation, Eigenfrequency
  - Thermal Perturbation, Frequency Domain
  - Time Dependent
- Custom Studies
- Empty Study

— Physics interfaces in study

Physics	Solve
Bioheat Transfer (ht)	<input checked="" type="checkbox"/>

— Multiphysics couplings in study

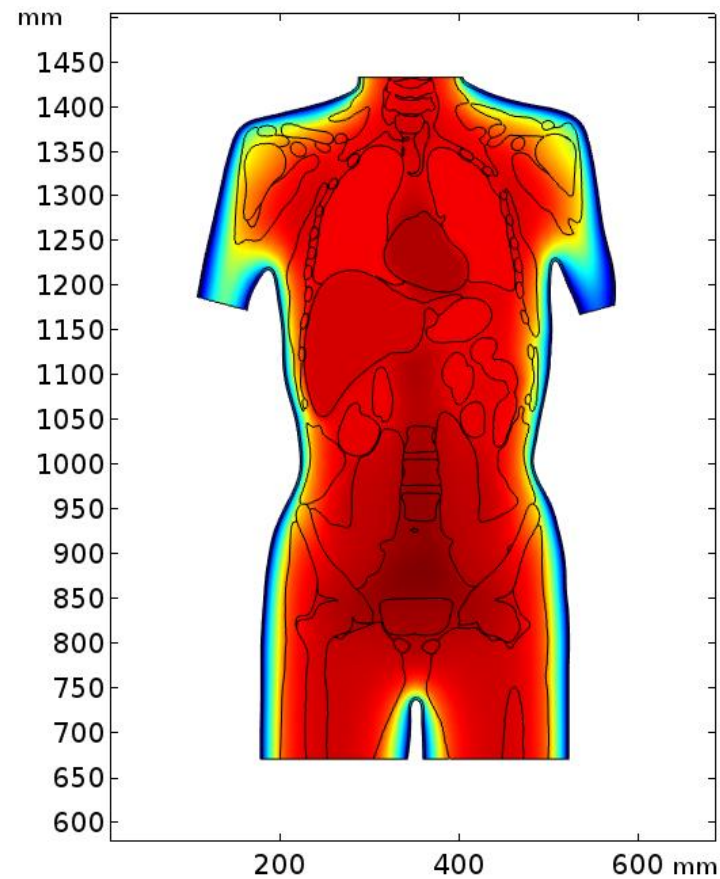
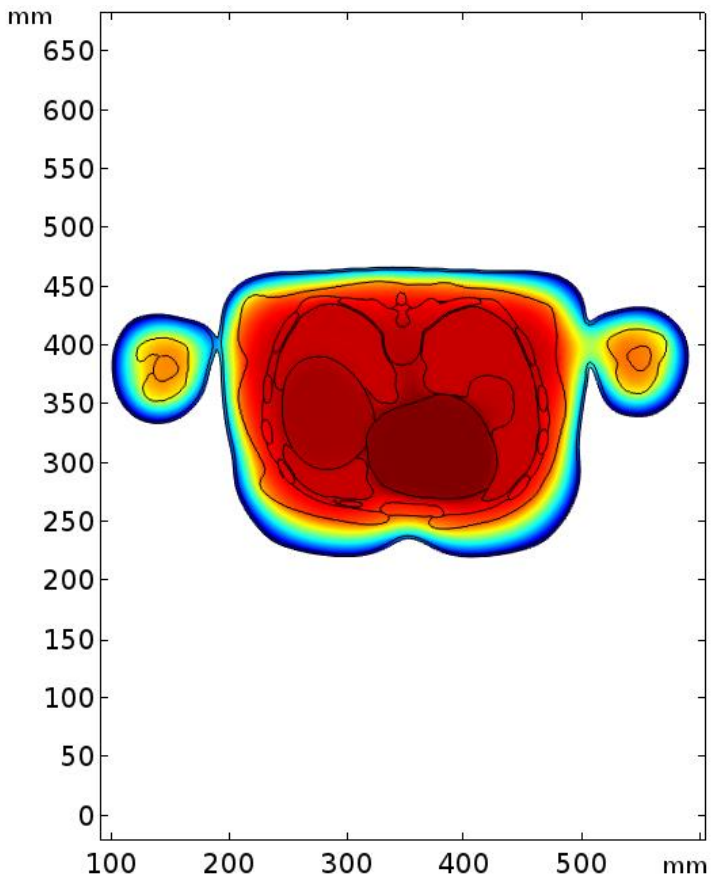
Multiphysics couplings	Solve
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Messages Progress Log Maximum and minimum values

Solution time (Study 1): 81 s. (1 minute, 21 seconds)  
 Number of degrees of freedom solved for: 566830 (plus 727104 internal DOFs).  
 Solution time (Study 1): 70 s. (1 minute, 10 seconds)  
 Number of degrees of freedom solved for: 566830 (plus 727104 internal DOFs).  
 Solution time (Study 3): 99 s. (1 minute, 39 seconds)  
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 Number of degrees of freedom solved for: 566830 (plus 727104 internal DOFs).  
 Solution time (Study 3): 104 s. (1 minute, 44 seconds)  
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# Results

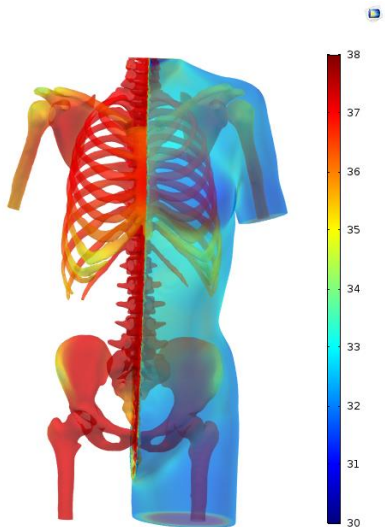




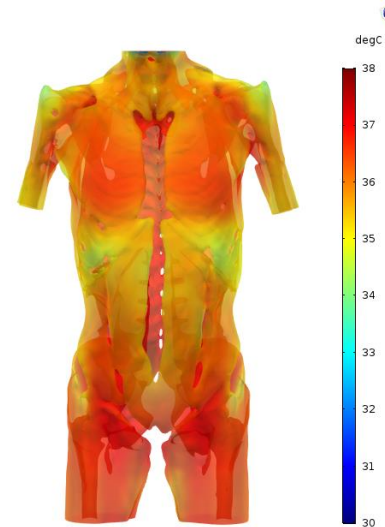
# Results



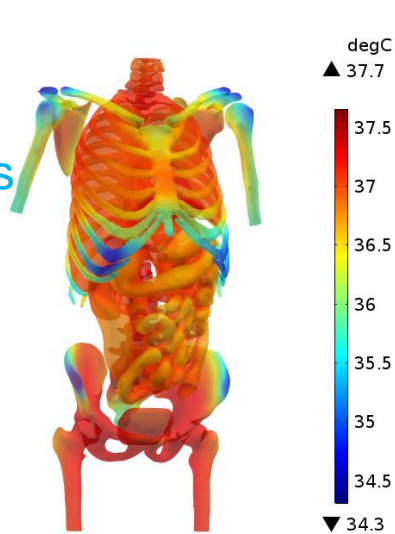
Skin & Bones



Muscle



Bones & Internal Organs



Skin

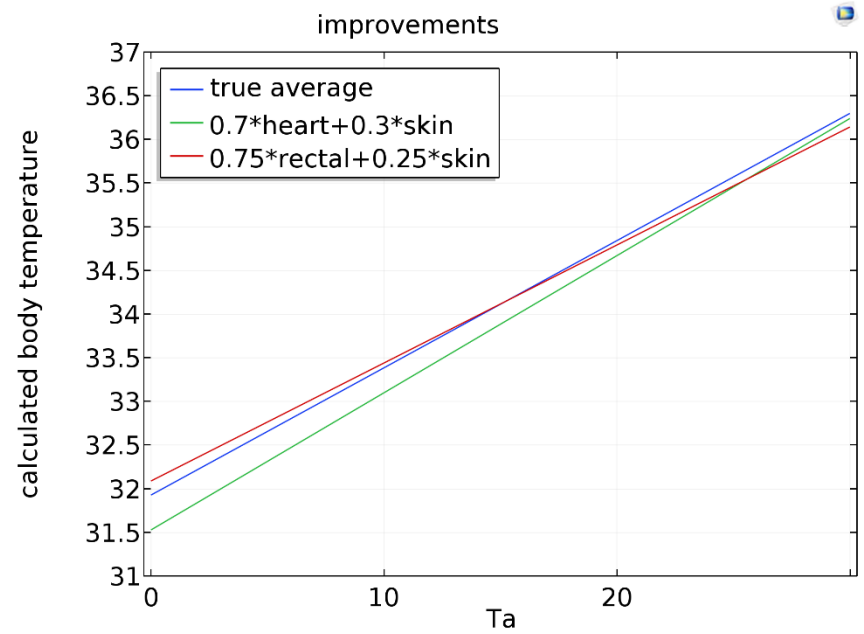
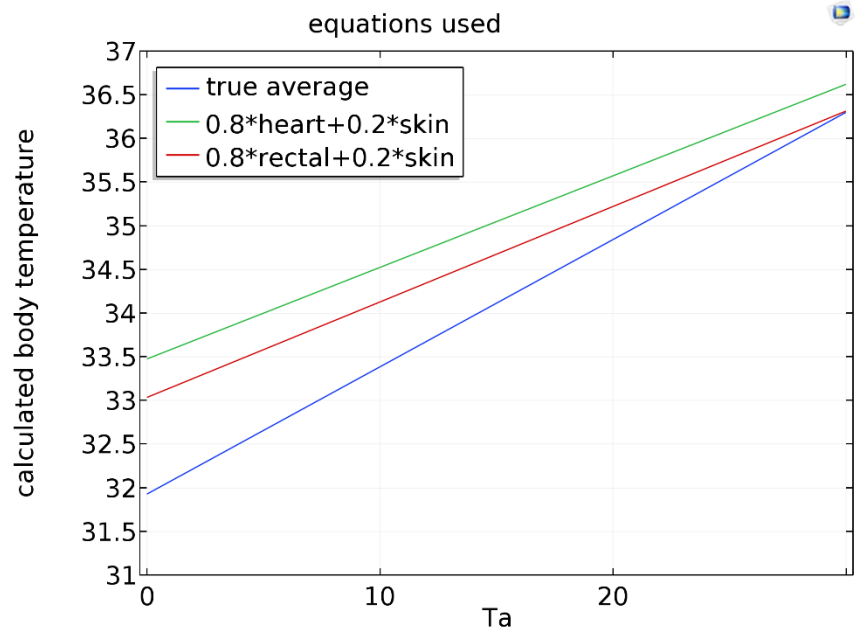




# Calculating Average Body Temperature Application Example 1



$$\text{average temperature} = \frac{\int TdV}{\int dV}$$

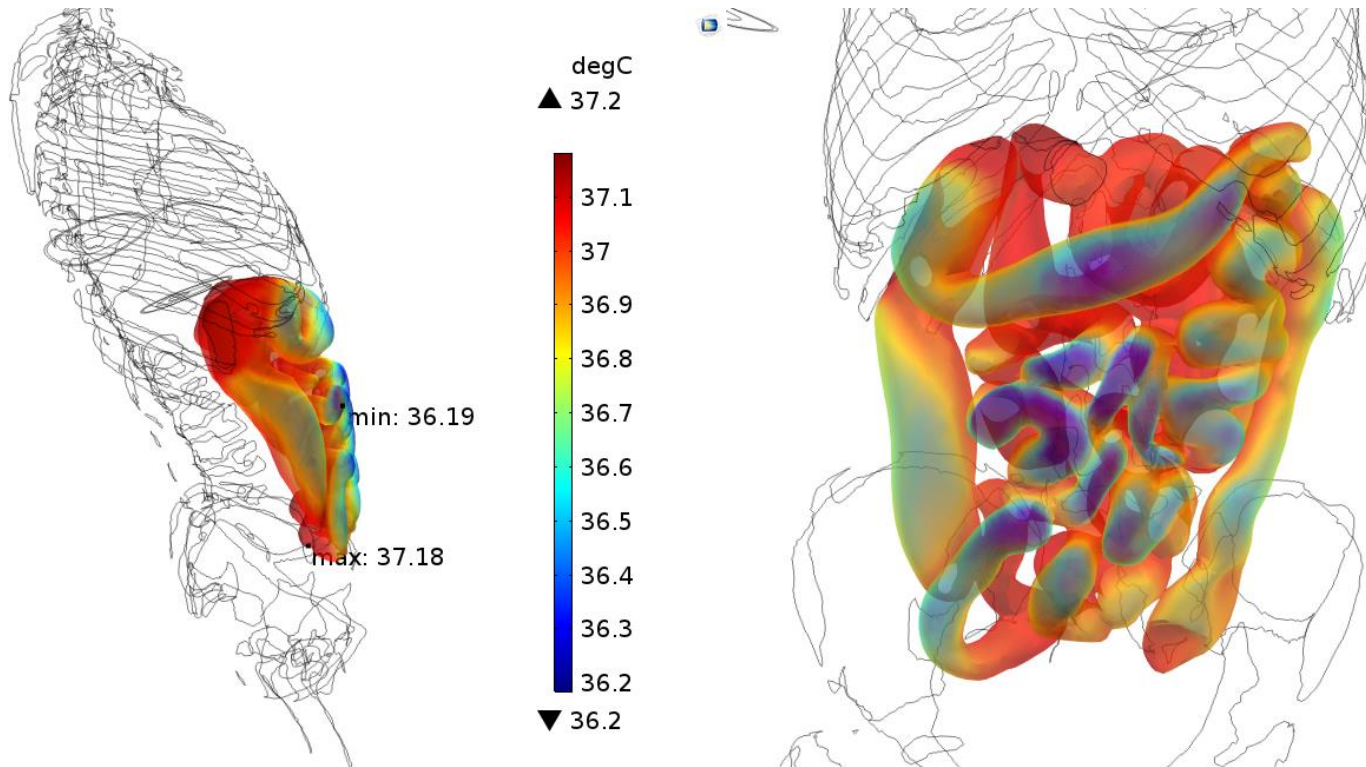


(Burton, Human Calorimetry, 1935)





# What does a temperature pill measure? Application Example 2



Consistent with the finding from Goodman et al. Influence of Sensor Ingestion Timing on Consistency of Temperature Measures (Med. Sci. Sports Exerc, Vol. 41, No. 3, pp. 597–602, 2009)



# CONCLUSION

- The simulations provide an accurate assessment of the human body temperature with respect to the inhomogeneity
- Detailed data can be obtained from the simulations, which would be difficult to obtain during human studies, and can aid in study design and result analysis
- Finite element methods (e.g., COMSOL Multiphysics™) and geometries of nonhomogeneous human bodies can be used to create a new approach in modeling physiology