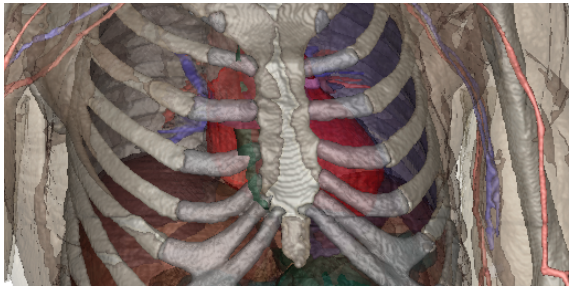
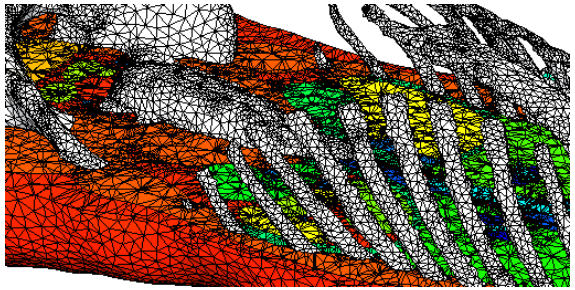
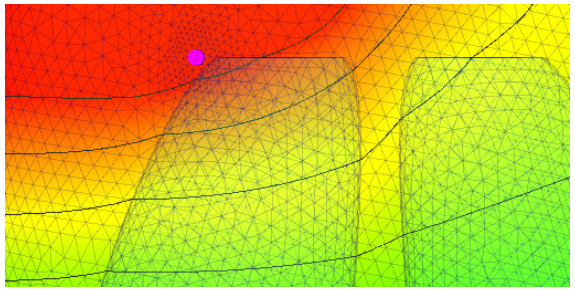
High resolution human body computational models

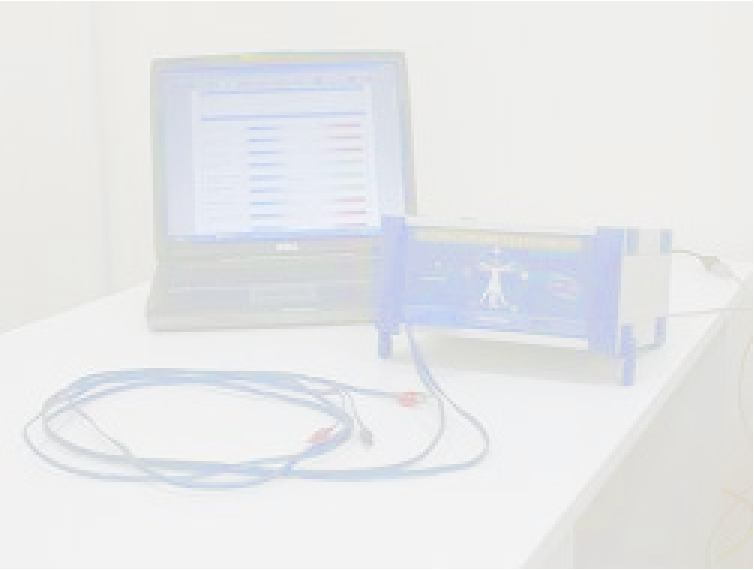
Alexander Danilov

Institute of Numerical Mathematics, Russian Academy of Sciences
Moscow, Russia

Mathematical and Computational Modelling in Cardiovascular Problems

Bioimpedance measurements



- Impedance is measured
- Several electric frequencies
- Local and segmental electrode schemes
- Hydration estimation, fat-free mass, muscle mass, etc.

Noninvasive, efficient, portable, simple and convenient

Research project at INM RAS, Moscow, Russia
2010 – present

Alexander Danilov, INM RAS
Victoria Salamatova, MIPT
Yuri Vassilevski, INM RAS

Bioimpedance measurements

- Impedance is measured
- Several electric frequencies
- Local and segmental electrode schemes
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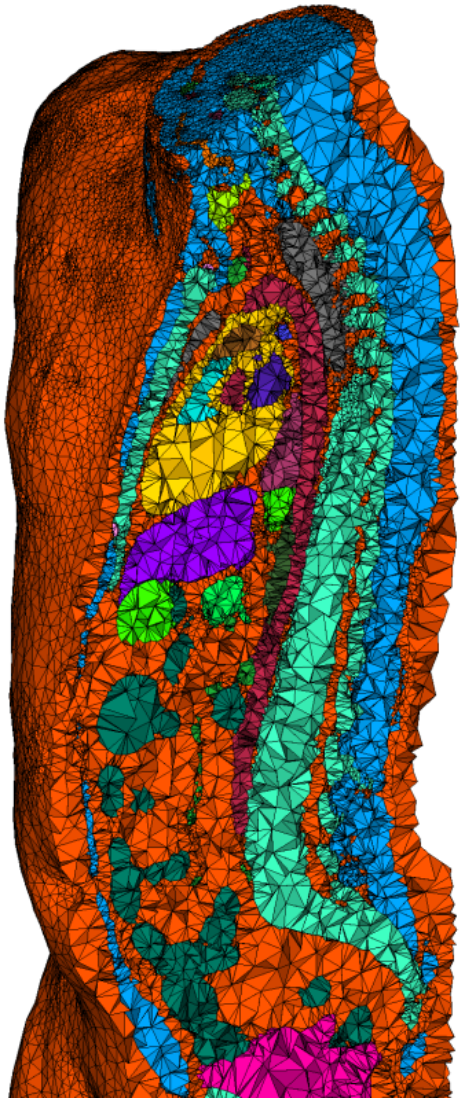
Noninvasive, efficient, portable, simple and convenient

- Finite element method and adaptive tetrahedral grids for bioimpedance measurements modelling
- High-resolution multimaterial 3D models based on real human anatomy
- Sensitivity analysis for tetrapolar electrode schemes

S.Grimnes, O.G.Martinsen. Bioimpedance and Bioelectricity Basics. Elsevier, Amsterdam, 2008.

Mathematical model



$$
\begin{aligned}
\operatorname{div}(\mathbf{C}\nabla U) = 0 \quad & \text{in} \quad \Omega \\
\mathbf{J}_n = \pm I_0 / S_\pm \quad & \text{on} \quad \Gamma_\pm \\
\mathbf{J}_n = 0 \quad & \text{on} \quad \partial\Omega \setminus \Gamma_\pm
\end{aligned}
$$

U – potential field
$\mathbf{C}$ – conductivity tensor
$\mathbf{E} = \nabla U$ – intensity field
$\mathbf{J} = \mathbf{C}\ \mathbf{E}$ – current density field
I_0 – current injection
$S_\pm$ – contact surface of electrodes

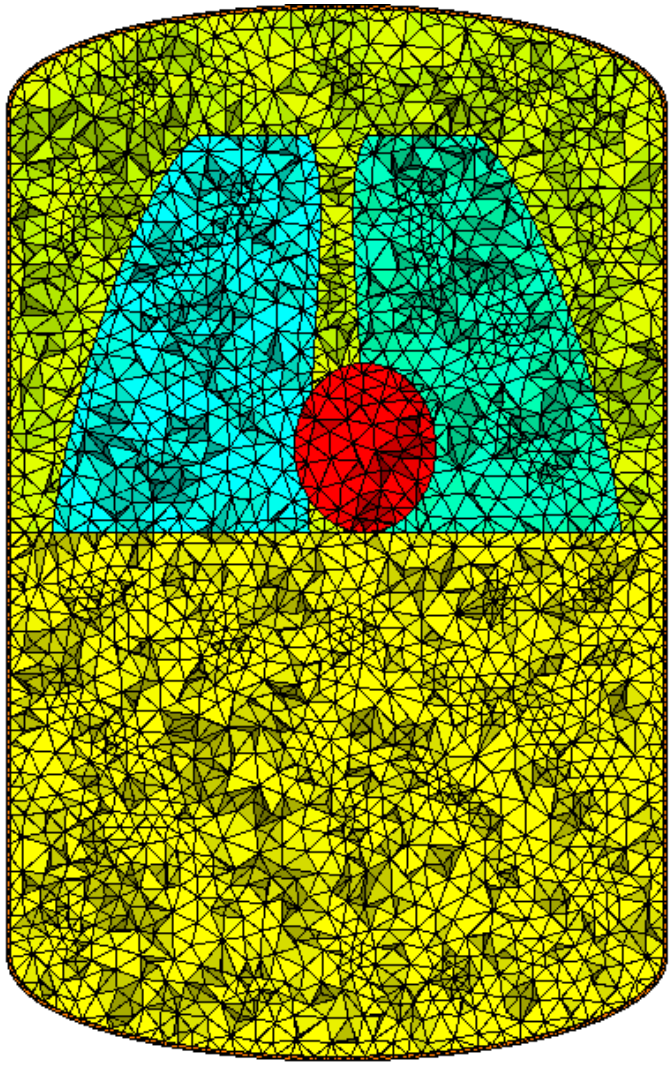
Bioelectrical conductivity

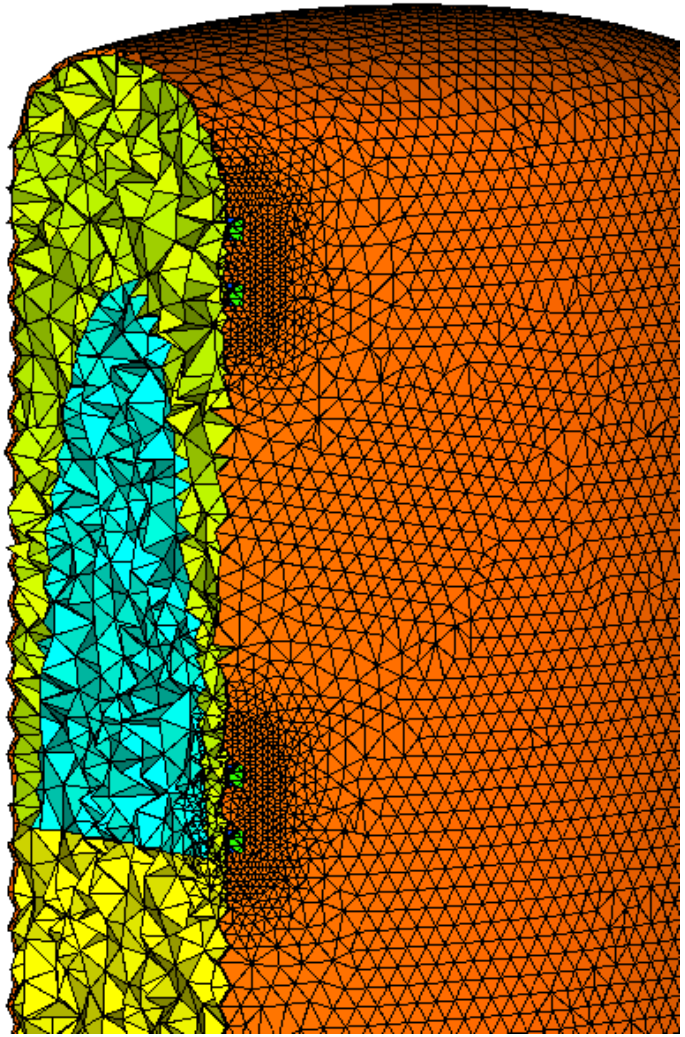
Typical conductivity parameters @ 50kHz (S/m)

Blood	0.7	+	$0.02 \cdot j$
Muscles	0.36	+	$0.035 \cdot j$
Fat	0.0435	+	$0.001 \cdot j$
Bones	0.021	+	$0.001 \cdot j$
Skin	0.03	+	$0.06 \cdot j$
Heart	0.19	+	$0.045 \cdot j$
Lungs	0.27	+	$0.025 \cdot j$

Gabriel S., Lau R.W., Gabriel C. The dielectric properties of biological tissue: III. Parametric models for the dielectric spectrum of tissues. // Phys.Med.Biol. 1996. V.41(11). P.2271-2293.

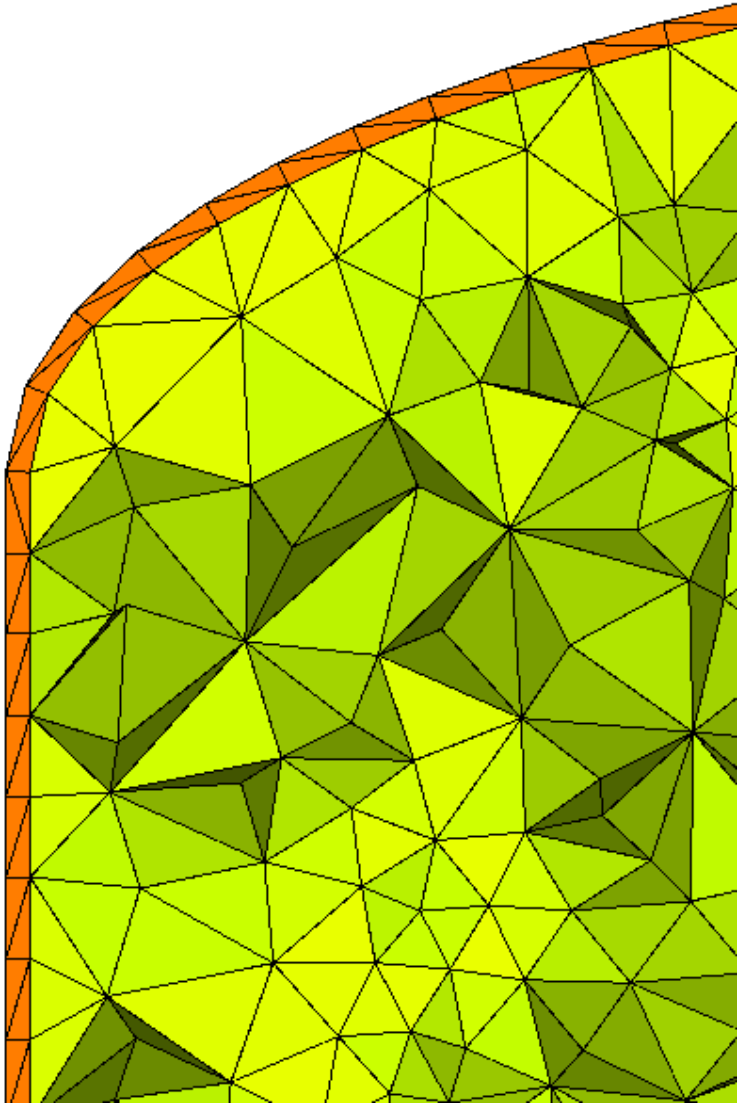
Simple geometrical model



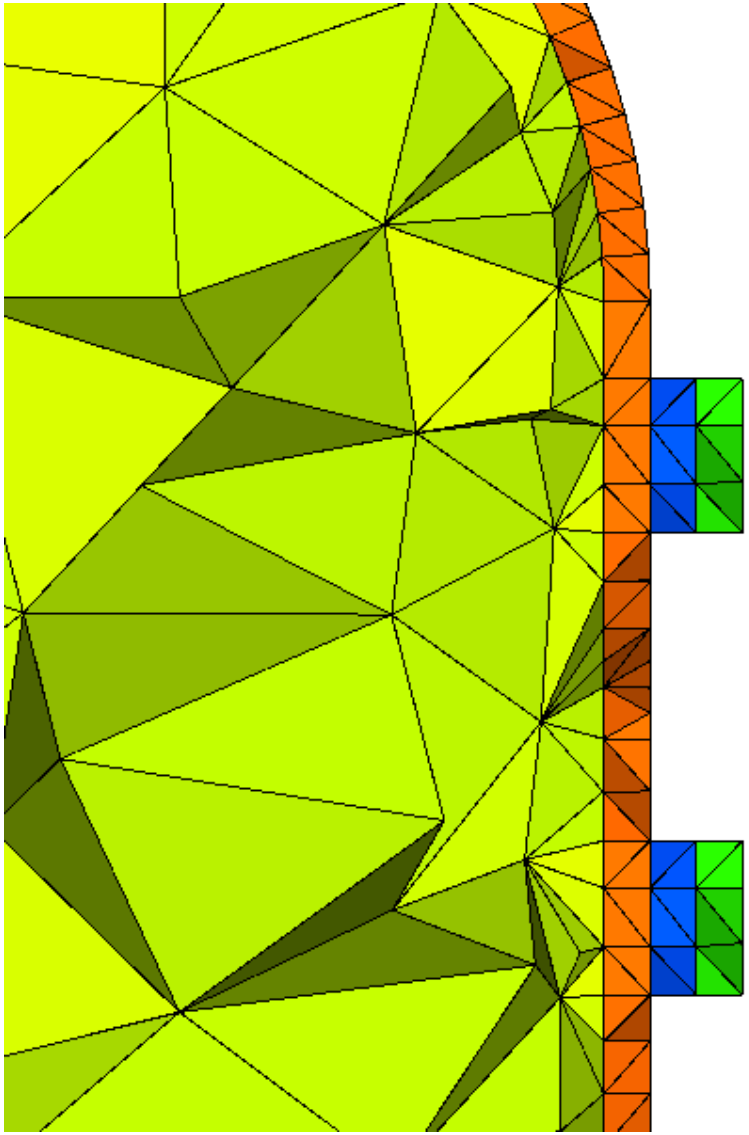


AniAFT + AniMBA (Ani3D package, `sf.net/projects/ani3d`)

Anisotropic conductivity coefficients



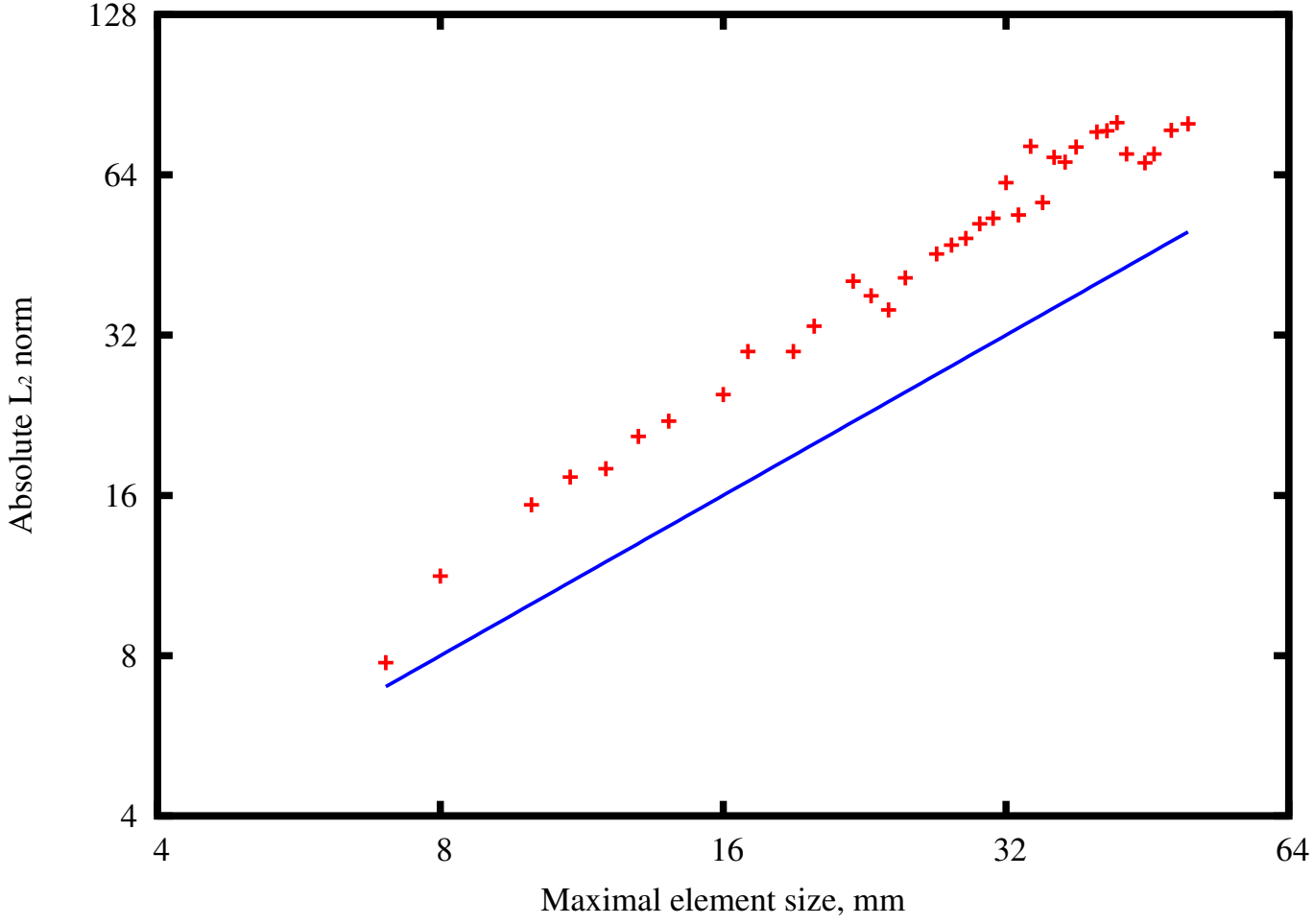
skin – 1 mm



gel – 2 mm, copper – 0.5 mm

Convergence analysis

Series of unstructured meshes



Convergence analysis

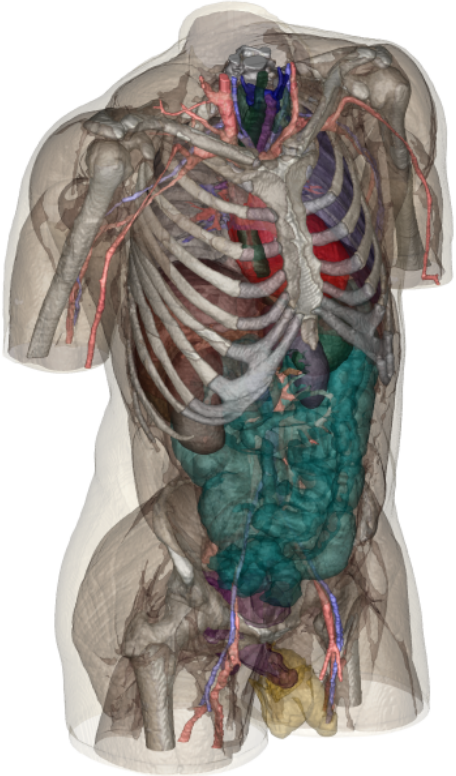
Series of hierarchically refined meshes

N_V	N_T	Memory, Mb	N_{it}	Time, s	L_2-norm
2032	9359	7.16	13	0.02	1.24E-03
14221	74872	37.3	23	0.18	9.31E-04
106509	598976	299.1	58	3.70	5.07E-04
824777	4791808	2437.5	127	68.55	1.53E-04
6492497	38334464	20015.3	353	2634.15	–

Asymptotically second order convergence

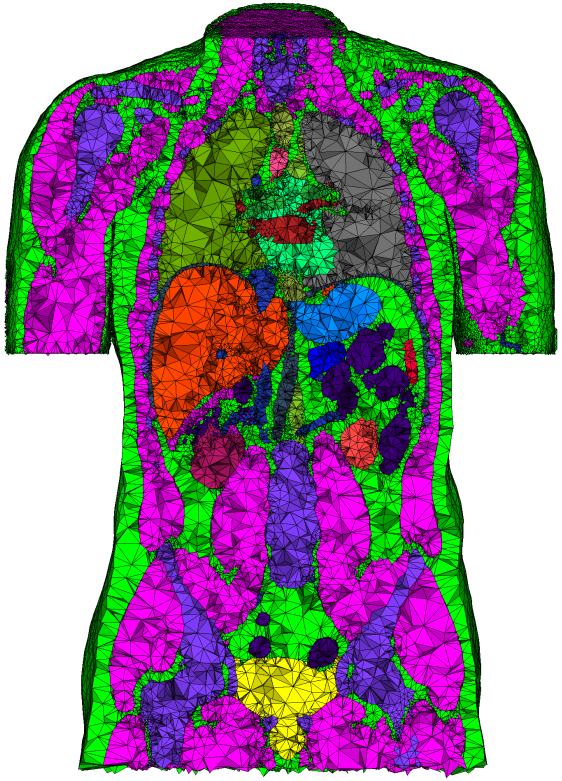
Modeling technology

Segmentation



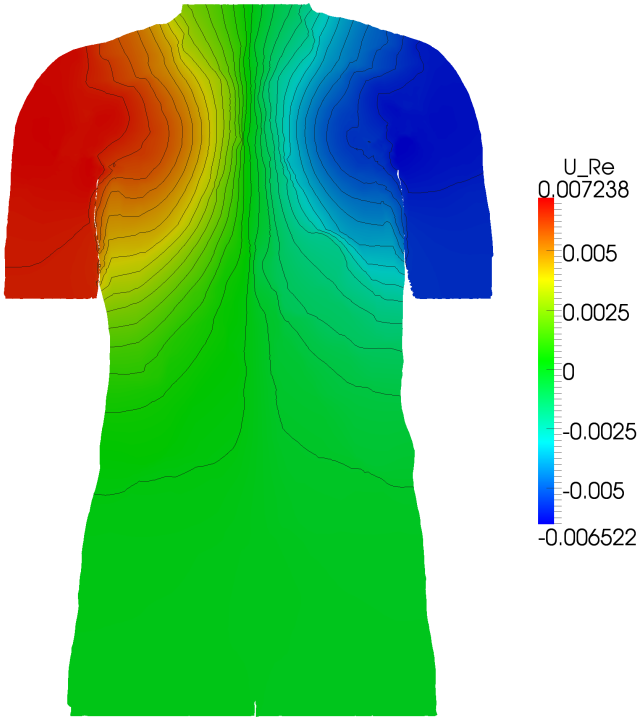
ITK-SNAP

Meshing



CGAL Mesh

FEM



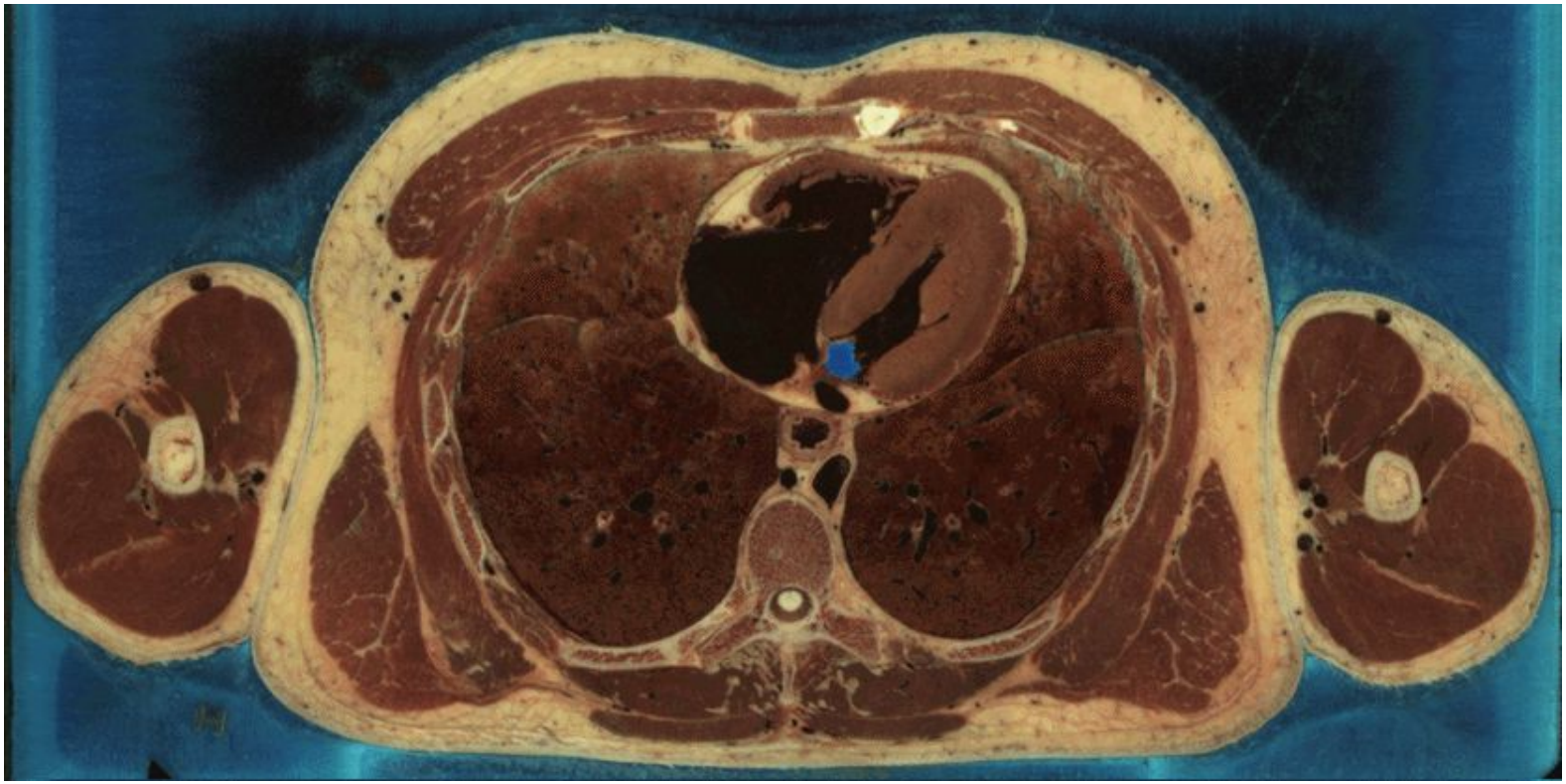
Ani3D

ParaView

A. A. Danilov, D. V. Nikolaev, S. G. Rudnev, V. Yu. Salamatova and Yu. V. Vassilevski, Modelling of bioimpedance measurements: unstructured mesh application to real human anatomy. *Russ. J. Numer. Anal. Math. Modelling* (2012) **27**, No 5, 431–440

Visible Human Project

Visible Human Project
U.S. National Library of Medicine
www.nlm.nih.gov/research/visible

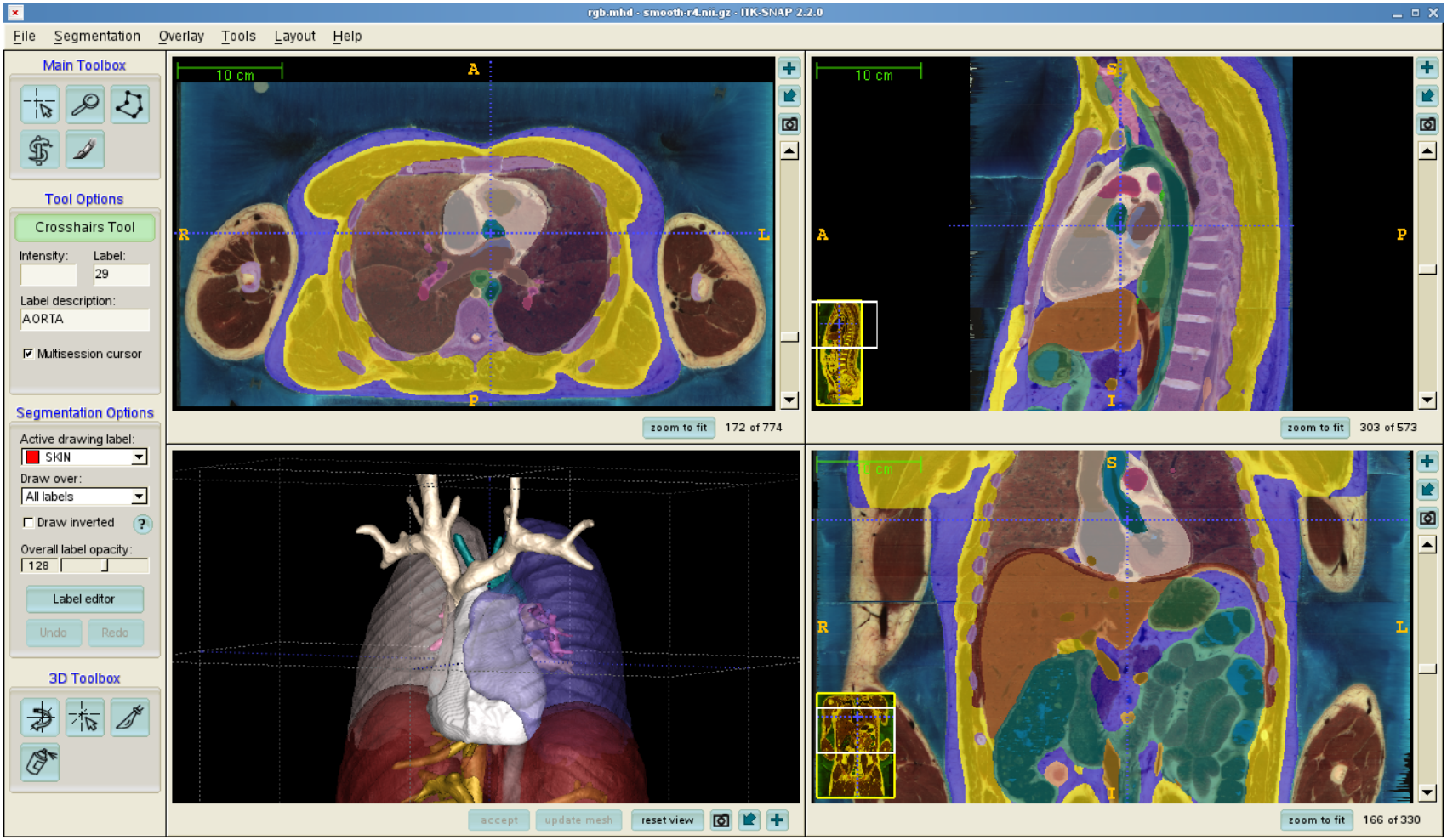


ITK-SNAP software

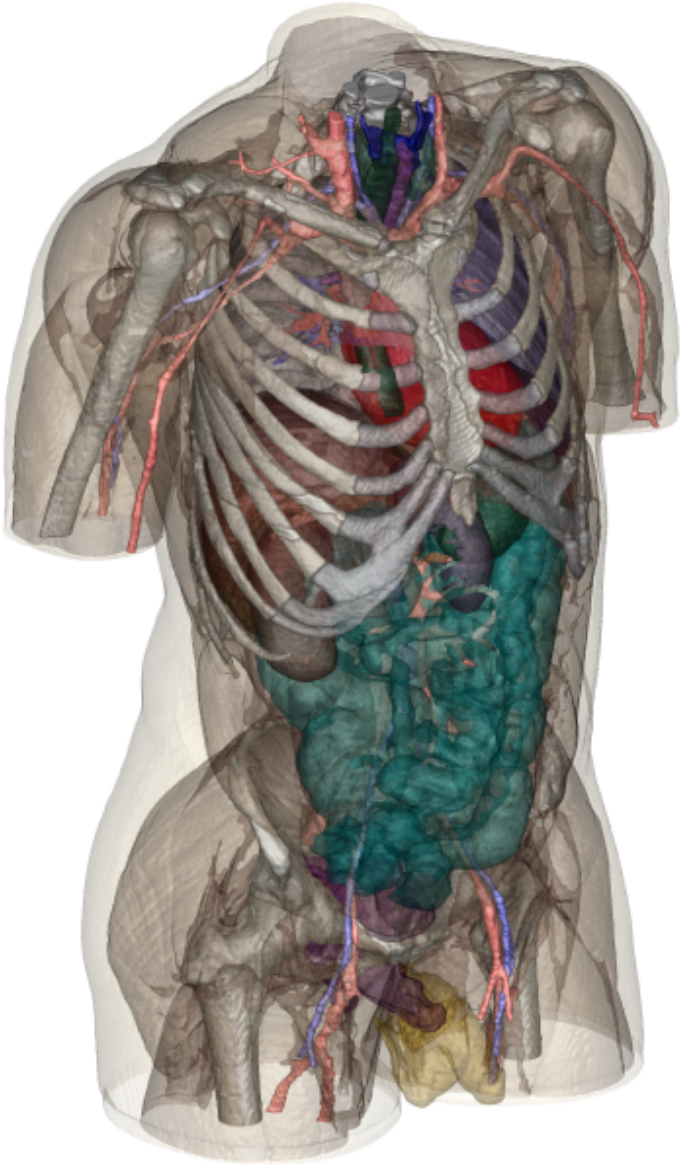
Manual and semi-automatic tissue segmentation

ITK-SNAP (`www.itksnap.org`)

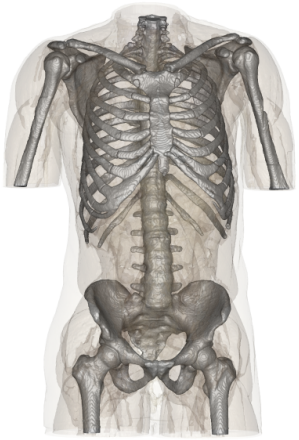
Free software for Visualization and Segmentation

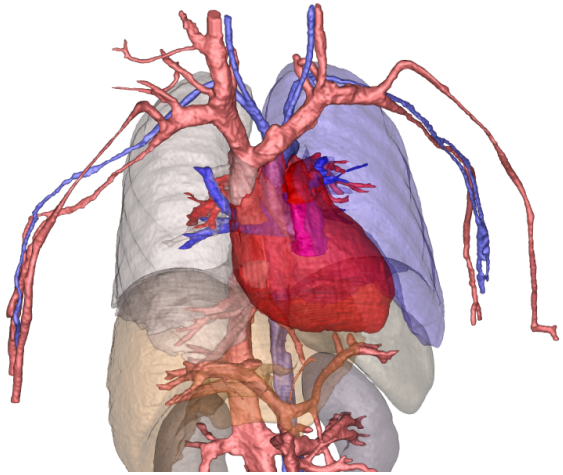


High resolution segmented model of VHP torso



$567 \times 305 \times 843$ voxels
$1 \times 1 \times 1$ mm
26 organs and tissues

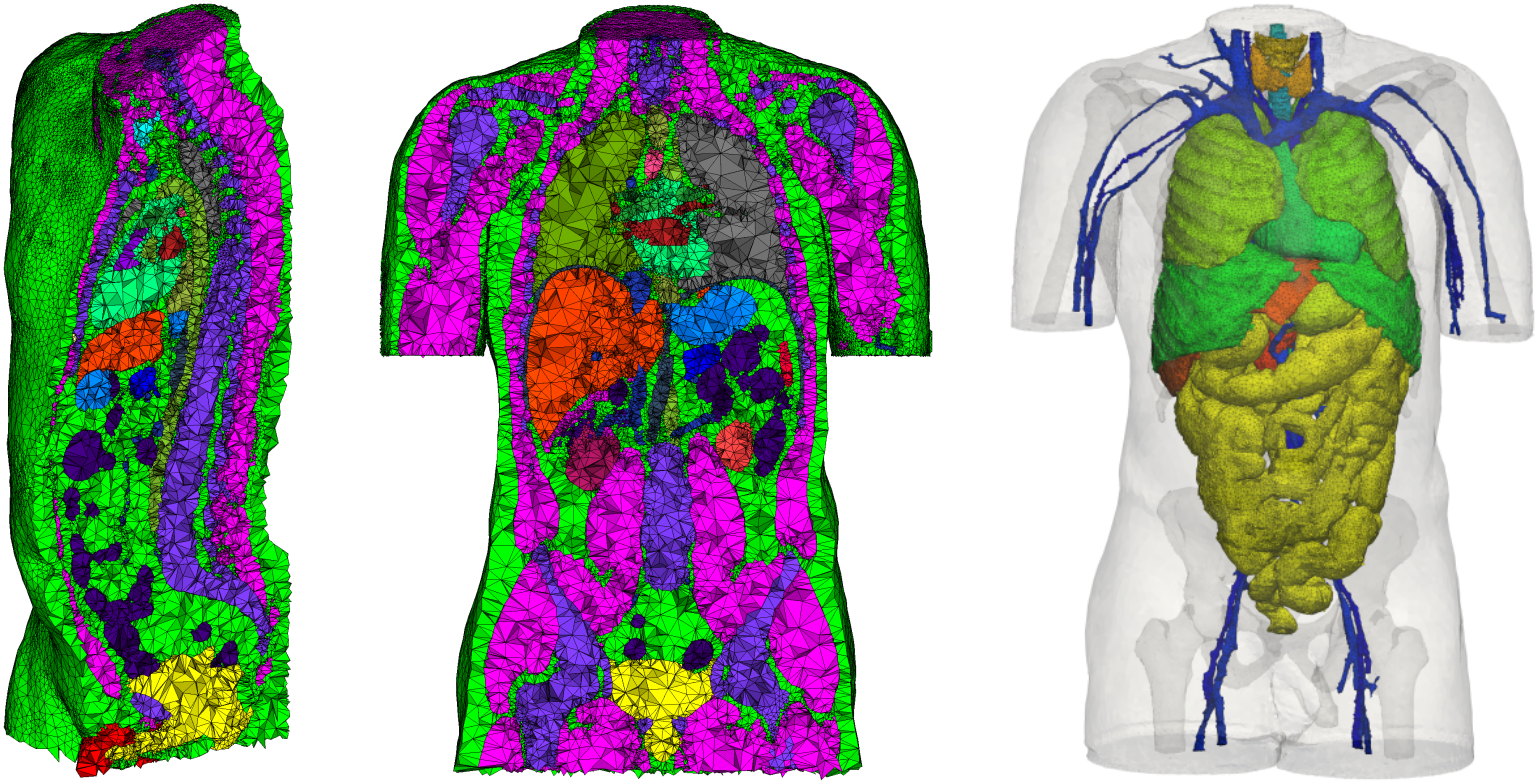




Total 146m voxels, 68m material voxels

Unstructured tetrahedral meshes

CGAL Mesh (`www.cgal.org`) – Delaunay mesh generation
Ani3D (`sf.net/projects/ani3d`) – mesh cosmetics

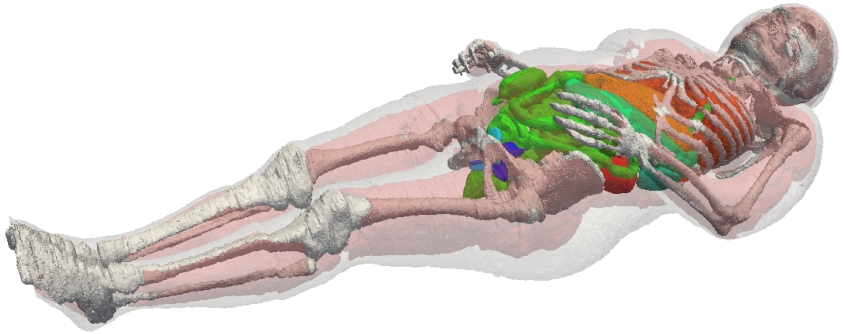


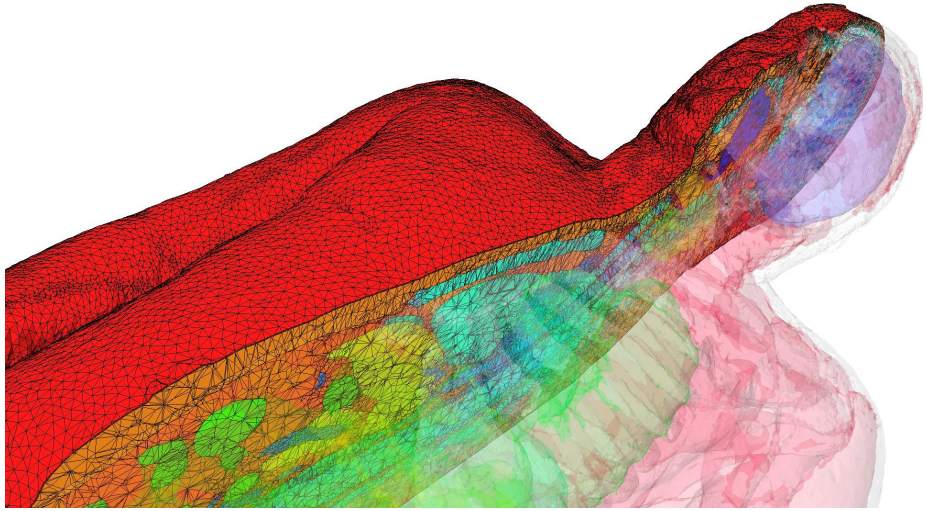
413 508 vertices, 2 315 329 tetraedra, 84 430 boundary faces

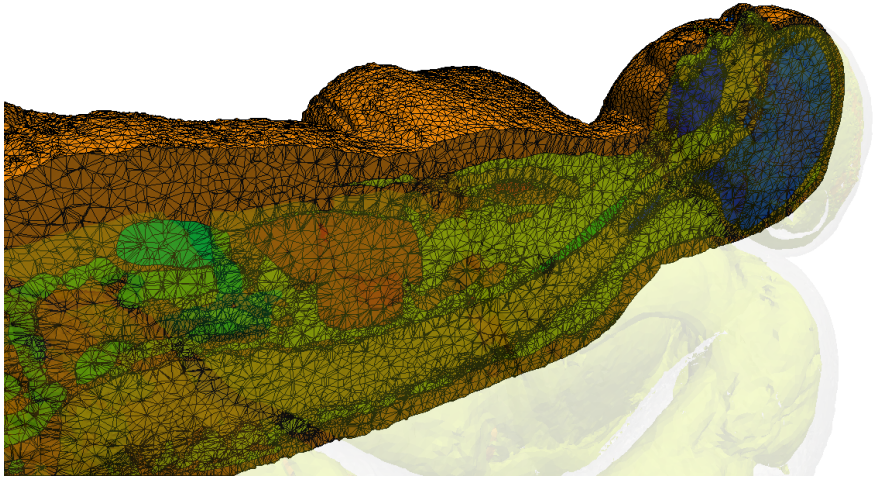
Full body male and female models

VHP-Man

VHP-Woman



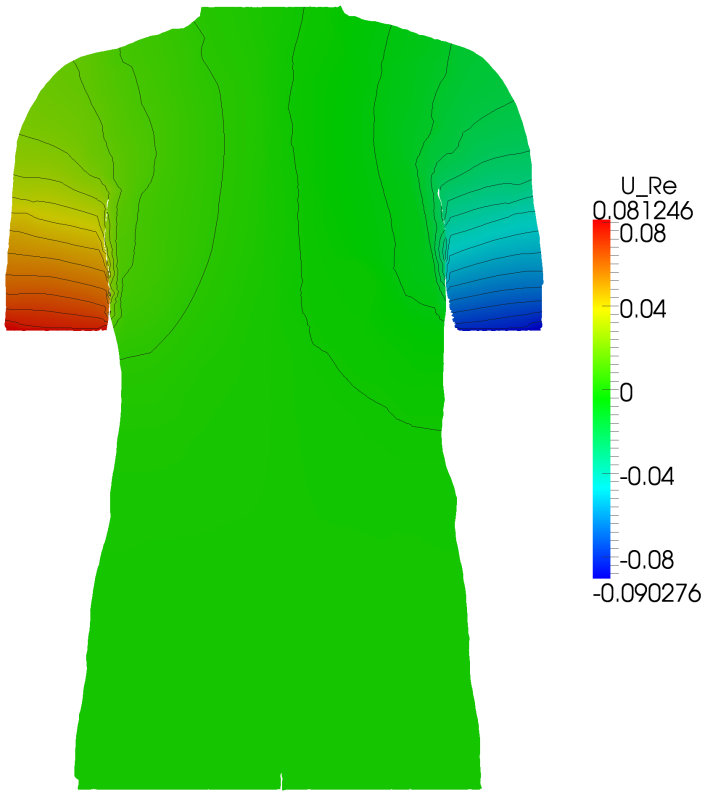


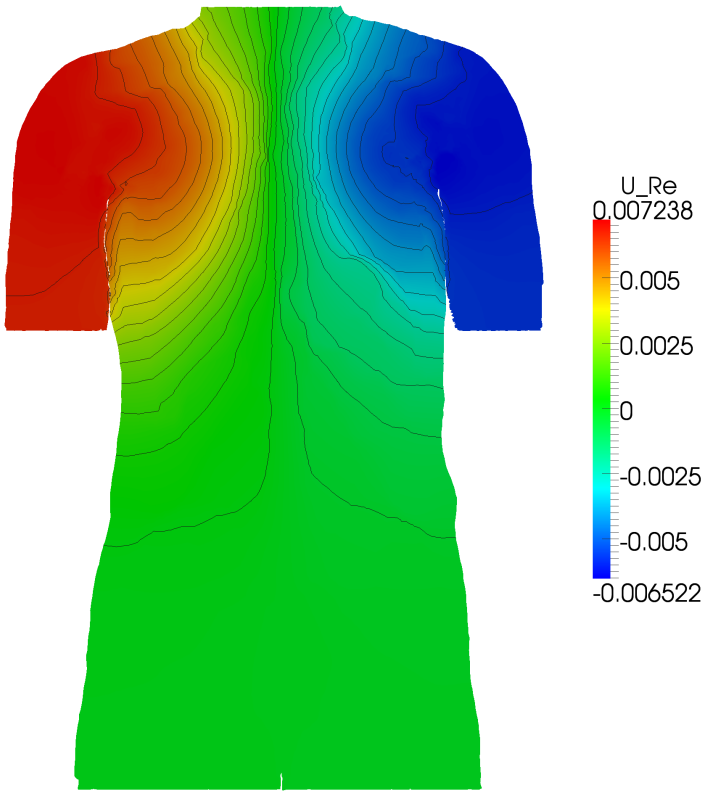


3m tetrahedra effective resolution: $1 \times 1 \times 1$ mm 30 tissues

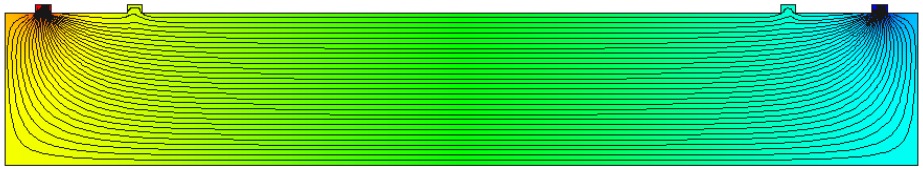
Numerical solution

P1 FEM by Ani3D package (GMRes + ILU2 solver)

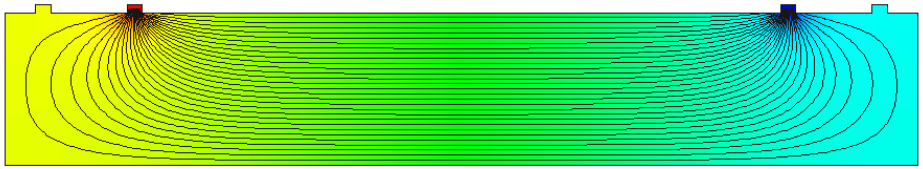




Sensitivity field



current lines for current-carrying electrodes – $\mathbf{J}_{\mathrm{cc}}$



current lines of reciprocal lead field for pick-up electrodes – $\mathbf{J}_{\mathrm{reci}}$

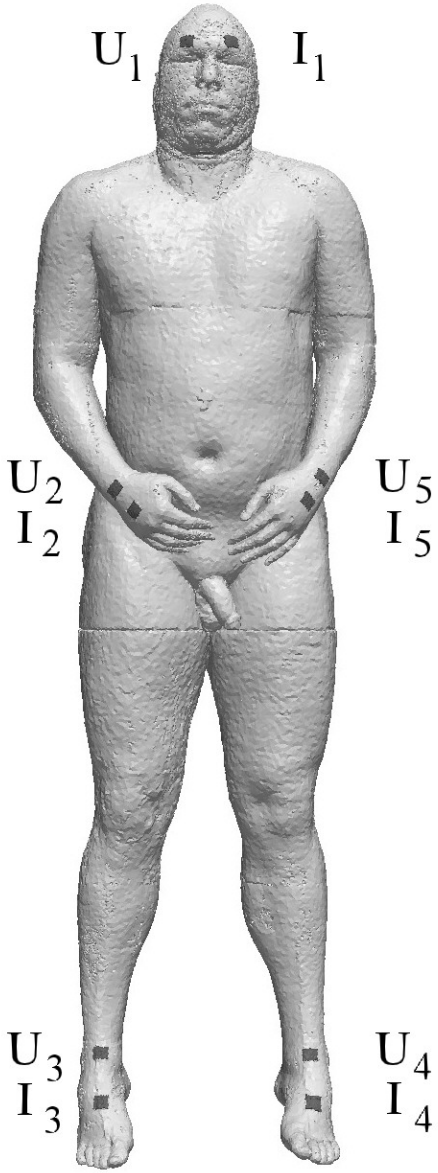
sensitivity function

$S = \mathbf{J}_{\mathrm{reci}} \cdot \mathbf{J}_{\mathrm{cc}}$

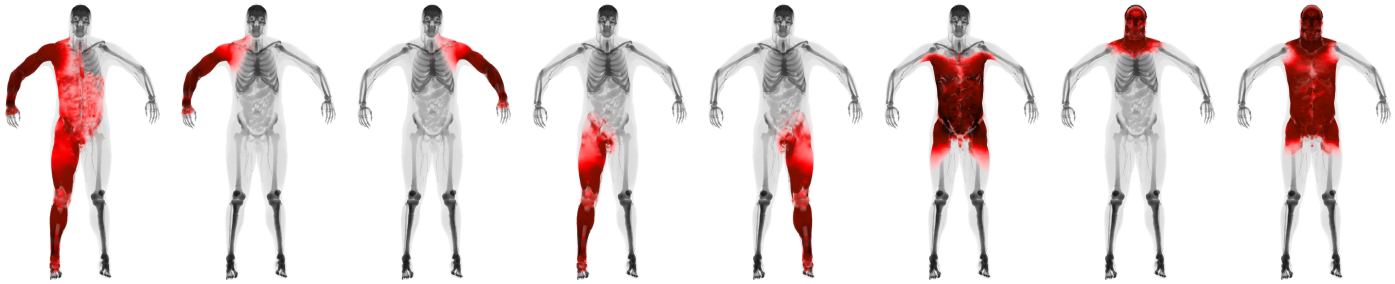
$Z_t = \int_V S(x, y, z)\rho(x, y, z)dv$

Ten-electrode configuration

Sensitivity analysis



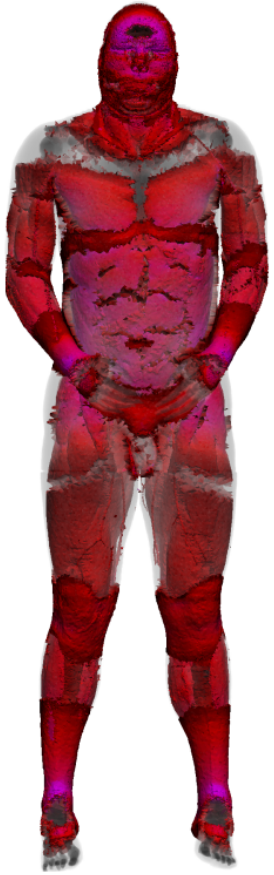
- Conventional scheme (I_2-I_3, U_2-U_3)
- Hands (I_2-I_1, U_2-U_3) and (I_5-I_1, U_5-U_4)
- Legs (I_3-I_2, U_3-U_4) and (I_4-I_5, U_4-U_3)
- Torso (I_5-I_3, U_2-U_4) and (I_5-I_4, U_2-U_3)
- Head (I_1-I_2, U_1-U_5)
- Head+Torso (I_1-I_3, U_1-U_4)



A. A. Danilov, V. K. Kramarenko, D. V. Nikolaev, S. G. Rudnev, V. Yu. Salamatova, A. V. Smirnov and Yu. V. Vassilevski, Sensitivity field distributions for segmental bioelectrical impedance analysis based on real human anatomy. *J. Phys.: Conf. Ser.* (2013) **434**, 012001, doi: 10.1088/1742-6596/434/1/012001.

Patient position adaptation

Arms position does affect the measurements

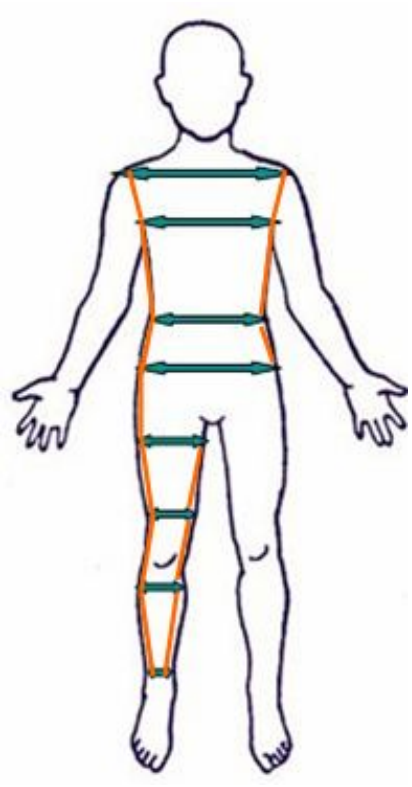


reference model

adapted model

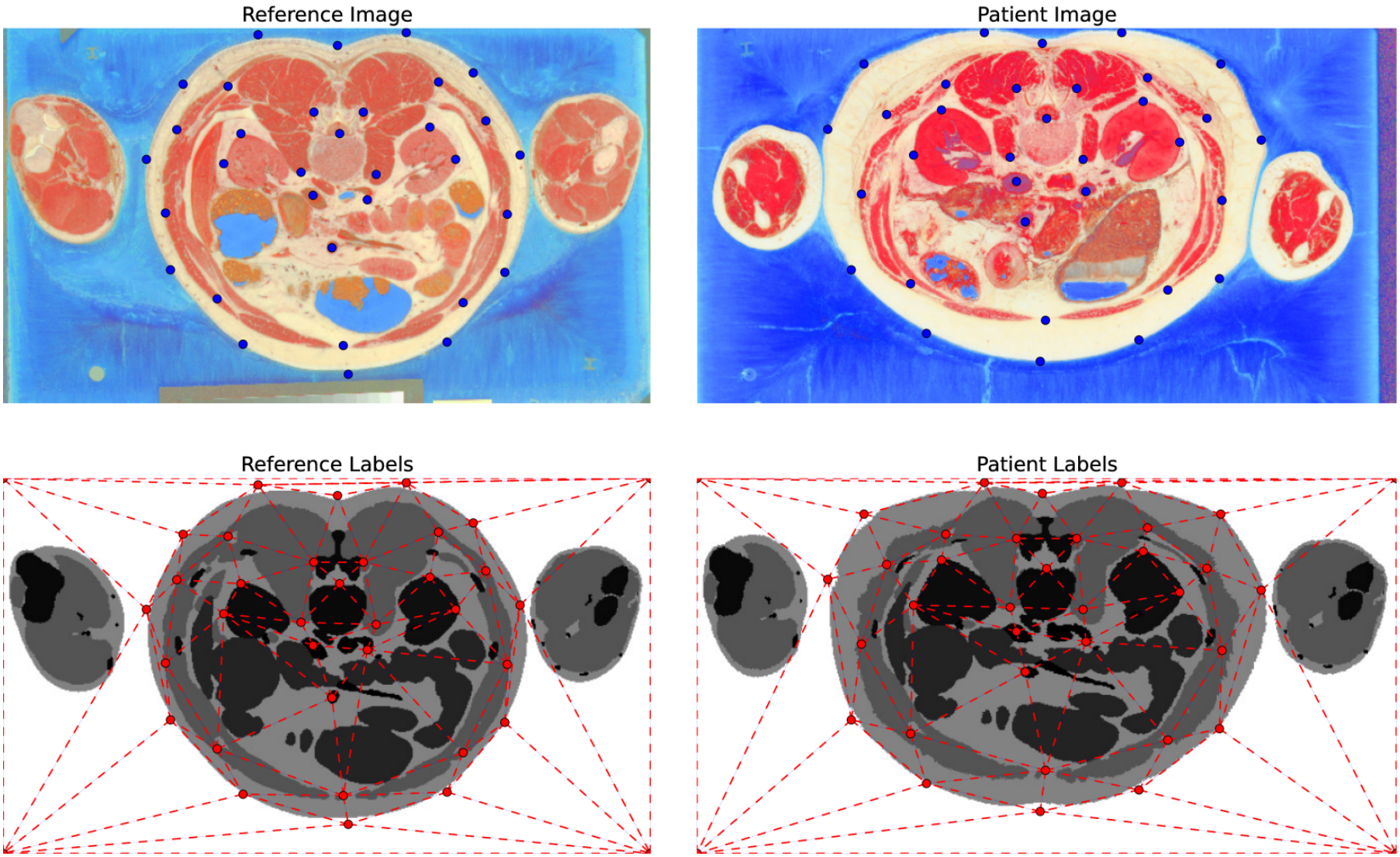
Future work – patient specific models

First step – anthropometric adaptation



Simple fitting of the model

Control points adaptation



Piecewise affine mapping on control plane

Conclusion

- Developed numerical scheme for modelling bioimpedance measurements
- Created high-resolution 3D segmented and FEM models of male and female bodies
- Demonstrated high sensitivity of standard electrode schemes
- Models will be used for developing new schemes of bioimpedance measurements
- Models may be used for other FEM analysis of human body
- Current work – patient specific models