

Персонализированная вычислительная гемодинамика

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XII Конференция “Математические модели и численные методы в биологии и медицине”
ИВМ РАН
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Marchuk Institute of
Numerical Mathematics
of the Russian
Academy of Sciences



Moscow Center for
Fundamental and
Applied Mathematics
at INM RAS



SECHENOV
LIFE SCIENCES

Соавторы

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- М.А.Ольшанский
- А.А.Данилов
- А.В.Лозовский
- В.Ю.Саламатова
- А.А.Легкий

часть научной группы, базирующейся в ИВМ РАН, МФТИ, Сеченовском Университете

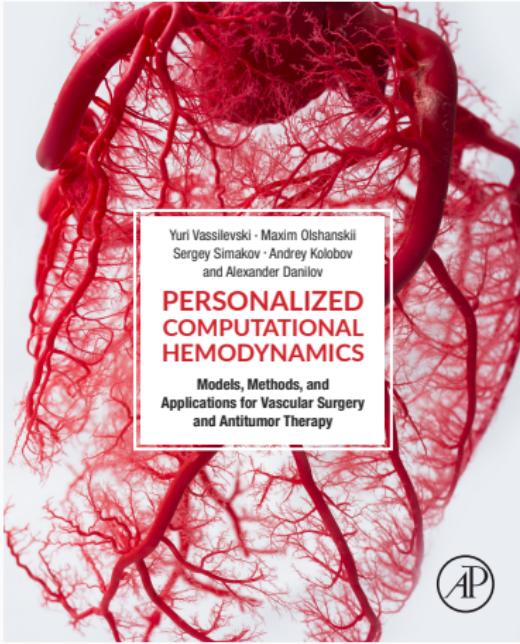
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Финансовая поддержка

- РНФ 2014-2018 (Рабочая группа по моделированию кровотока и сосудистых патологий), 2019-н.в.
- РФФИ 2010-2018



Y.Vassilevski, M.Olshanskii, S.Simakov,
A.Kolobov, A.Danilov

**Personalized Computational
Hemodynamics:
Models, Methods, and Applications for
Vascular Surgery and Antitumor Therapy**

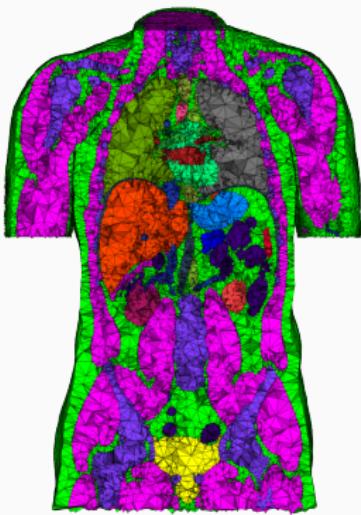
Academic Press 2020

- Персонализированная область
- Персонализированные параметры (коэффициенты, краевые условия)

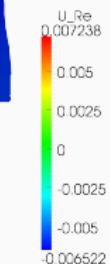
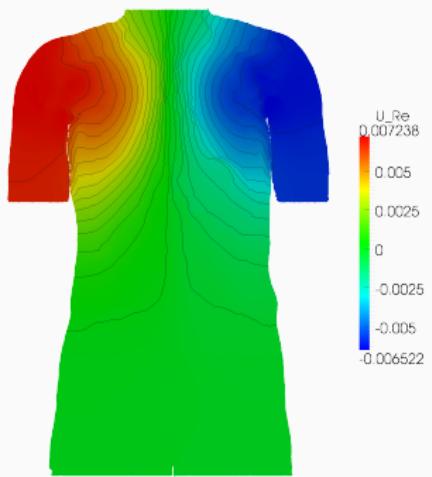
Сегментация



Сетки



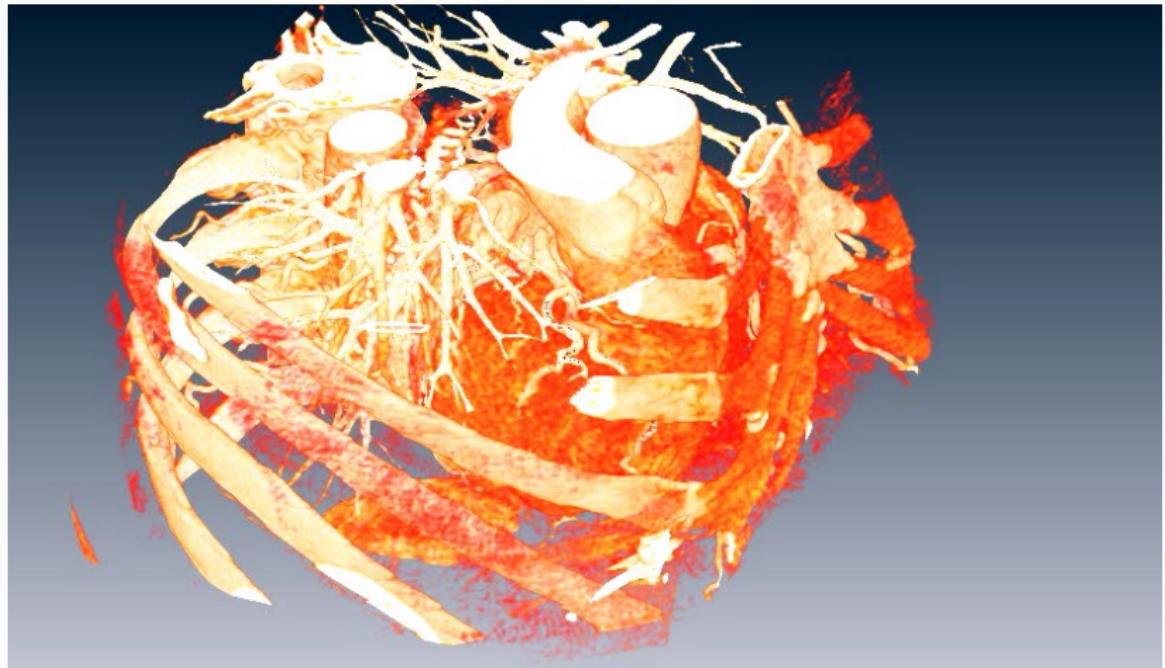
Дискретизация



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** (5), 431–440

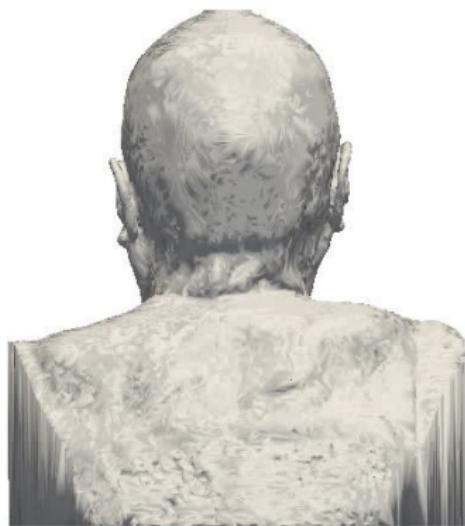
Персонализированная модель коронарной гемодинамики

Сегментация сосудов



Коронарные артерии

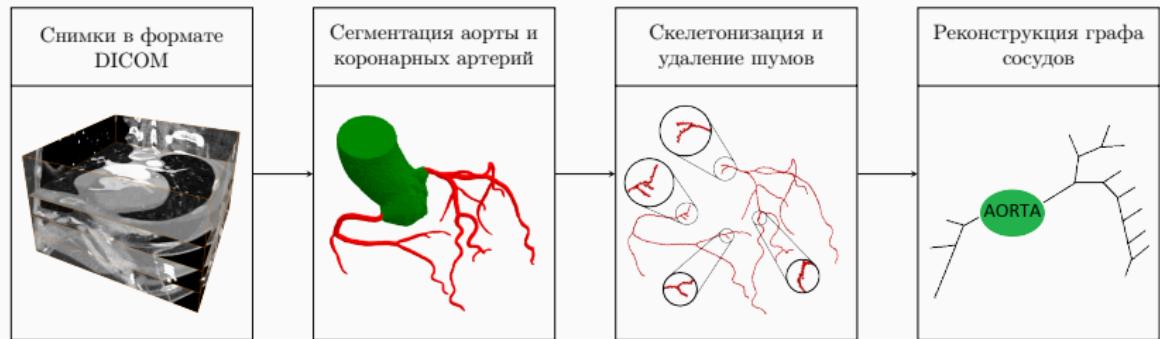
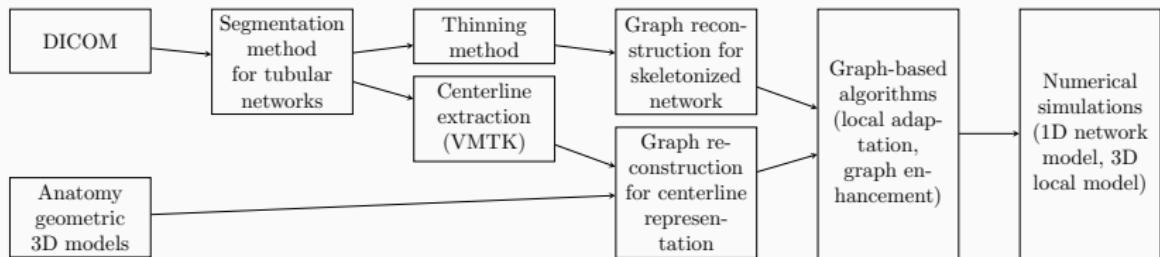
Сегментация сосудов



Церебральные артерии

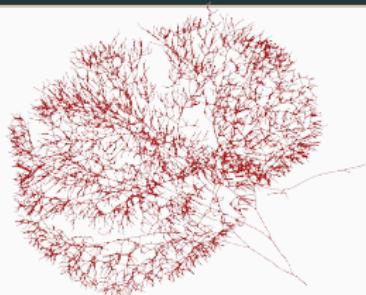
Сегментация и скелетонизация

Р.Прямоносов, А.Данилов



Обзор технологической цепочки

Skeletonization efficiency



Skeletons of a coronary tree and of a micro-CT of vascular corrosion cast of rabbit kidney provided by J. Alastruey, Department of Bioengineering, King's College London, UK

	Case 1	Rabbit kidney
Resolution	$512 \times 512 \times 248$	$2000 \times 1989 \times 910$
Distance map	0.20 sec	58.12 sec
Thinning	0.79 sec	526.98 sec
False twigs cleaning	0.15 sec	16.61 sec
Graph construction	0.13 sec	12.27 sec
Skeleton segments	22	4302

1D hemodynamic equations

A.Kholodov, S.Simakov,

A.Favorski, S.Mukhin, N.Sosnin

A.Quarteroni,L.Formaggio,E.Toro,...

Mass and momentum balance

$$\begin{aligned}\partial S_k / \partial t + \partial(S_k u_k) / \partial x &= 0, \\ \partial u_k / \partial t + \partial\left(u_k^2/2 + p_k/\rho\right) / \partial x &= f_{fr}(S_k, u_k),\end{aligned}$$

k is index of the tube, t is the time, x is the distance along the tube, ρ is the blood density (constant), $S_k(t, x)$ is the cross-section area, $u_k(t, x)$ is the linear velocity averaged over the cross-section, $p_k(S_k)$ is the blood pressure, f_{fr} is the friction force

1D hemodynamic equations

At the vessels junctions the Poiseuille's pressure drop and mass conservation

$$p_k(S_k(t, \tilde{x}_k)) - p_{node}^l(t) = \varepsilon_k R_k^l S_k(t, \tilde{x}_k) u_k(t, \tilde{x}_k), k = k_1, k_2, \dots, k_M,$$

$$\sum_{k=k_1, k_2, \dots, k_M} \varepsilon_k S_k(t, \tilde{x}_k) u_k(t, \tilde{x}_k) = 0,$$

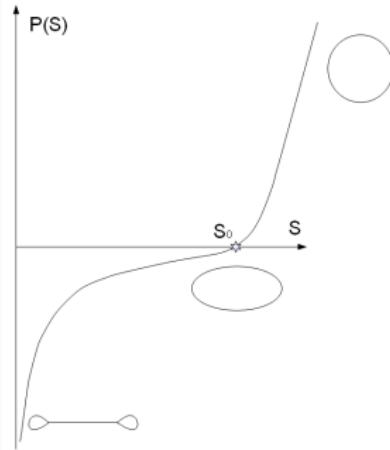
$\varepsilon = 1$, $\tilde{x}_k = L_k$ for incoming tubes, $\varepsilon = -1$, and $\tilde{x}_k = 0$ for outgoing tubes, R_k^l is the hydraulic resistance

1D hemodynamic equations

T.Gamilov, I.Nizhenko

Elasticity of the tube wall:

$$p_k(S_k) - p_{*k} = \rho c_k^2 f(S_k)$$



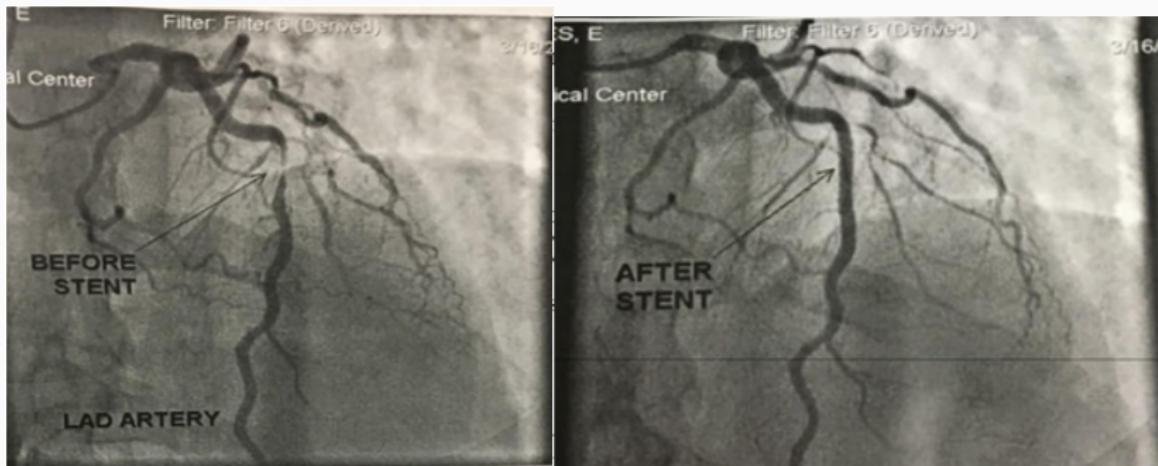
Vassilevski Yu., Salamatova V., Simakov S. On the elasticity of blood vessels in one-dimensional problems of hemodynamics.

Computational Mathematics and Mathematical Physics, V.55, No.9, p.1567-1578, 2015.

Coronary hemodynamics

Ischemic heart disease is caused by

- pathology of microvasculature (therapy)
- pathology of coronary arteries (revascularization)



Indication for revascularization

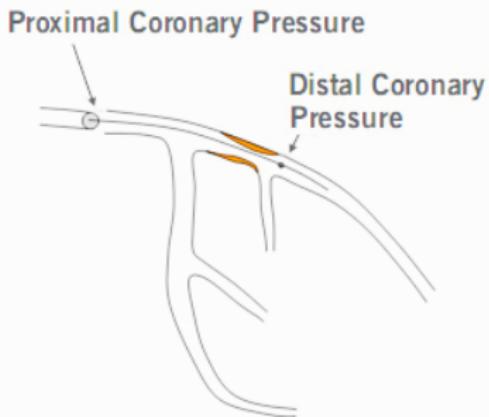
- before 2014: Vascular occlusion factor (relative lesion cross-sectional area) $VOF > 0.7$
- after 2014: Fractional flow reserve $FFR < 0.75$

2014 ESC/EACTS Guidelines on myocardial revascularization. Eur.Heart J., 2014 35 (37)

Fractional flow reserve (FFR)

$$FFR = \frac{\text{Distal Coronary Pressure}}{\text{Proximal Coronary Pressure}}$$

(During Maximum Hyperemia)



Clinical practice: endovascular intervention, expensive transducer

Pijls NH, Sels JW, Functional measurement of coronary stenosis. *J Am Coll Cardiol*, 2012 **59** (12)

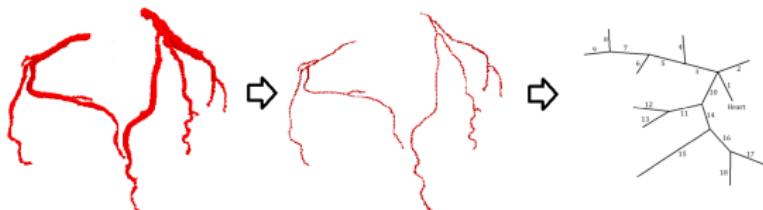
Kopylov Ph., Bykova A., Vassilevski Yu., Simakov S. Role of measurement of fractional flow reserve (FFR) in coronary artery atherosclerosis. *Therapeutic archive*, 2015 **87** (9)

Computation of virtual fractional flow reserve

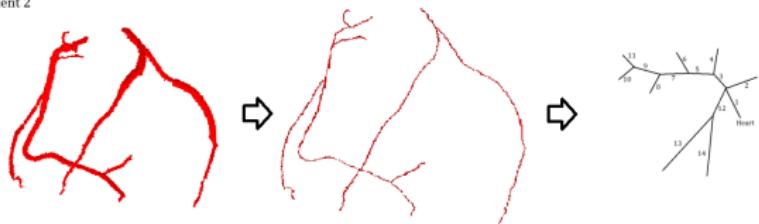
T.Gamilov, S.Simakov

the 1D equations may be adopted to coronary hemodynamics

Patient 1



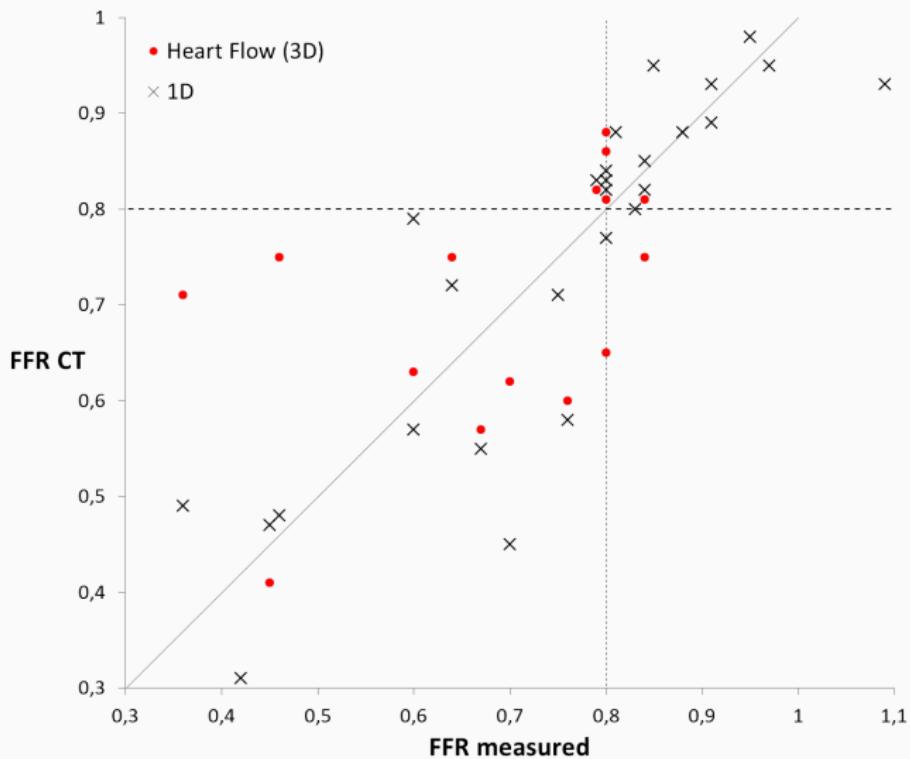
Patient 2



reconstructed arterial part based on two anonymous patient-specific data sets

Computation of virtual fractional flow reserve

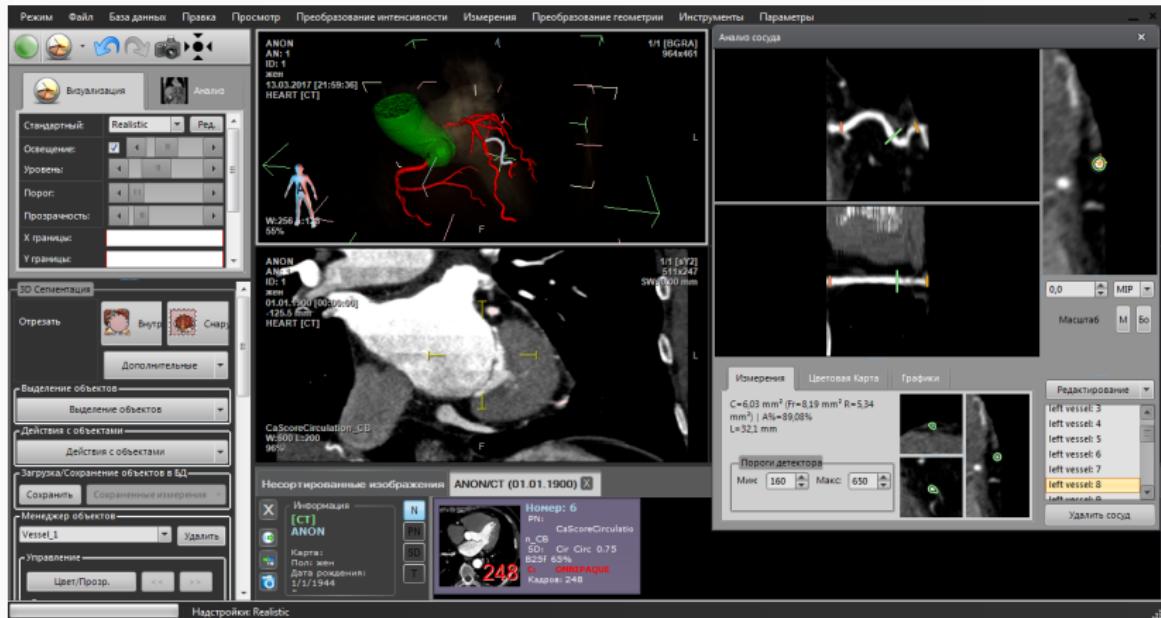
T.Gamilov, S.Simakov



FFR_{CT} within Multivox toolbox

Medical computer systems, Lomonosov Moscow State Univ.

T.Gamilov, R.Pryamonosov, A.Danilov

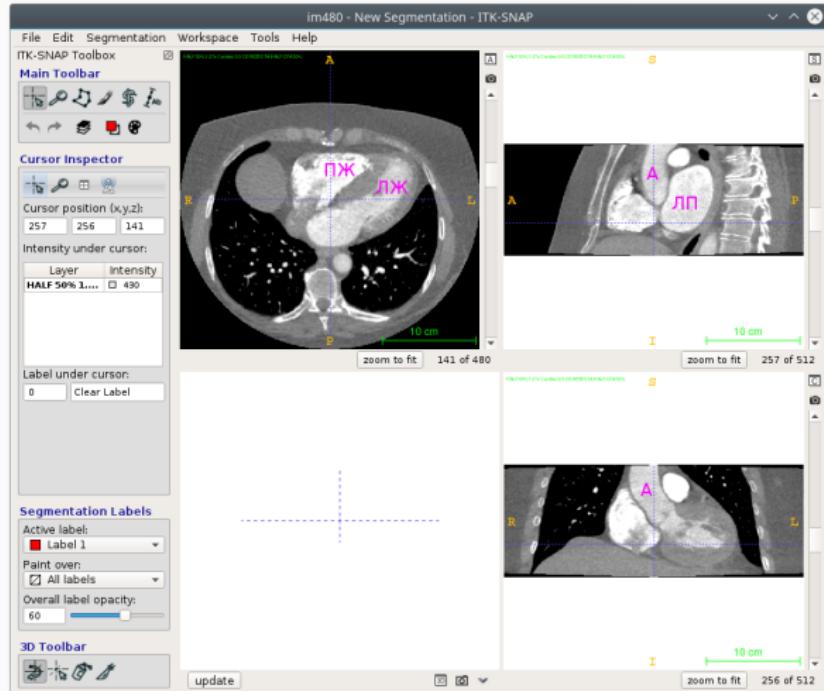


Персонализированная модель гемодинамики в левом желудочке сердца

- Aim: hemodynamic modeling in heart ventricles
- Dynamics: ventricle walls reconstructed from ceCT images
- Data: ceCT, 100 images, 1.27 seconds
- Resolution: $512 \times 512 \times 480$, raw data – 24 Gb
- Patient: anonymized, female, 50 years old
- Problem: generation of dynamic mesh from ceCT images

Segmentation of ceCT heart images and ML

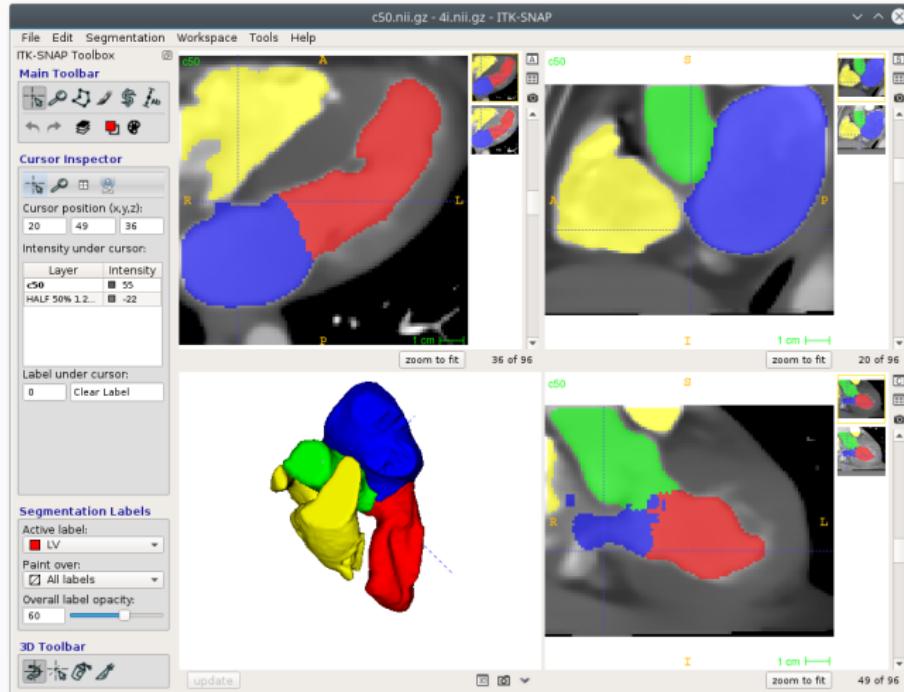
A.Danilov



Initial ceCT image 50

Segmentation of ceCT heart images and ML

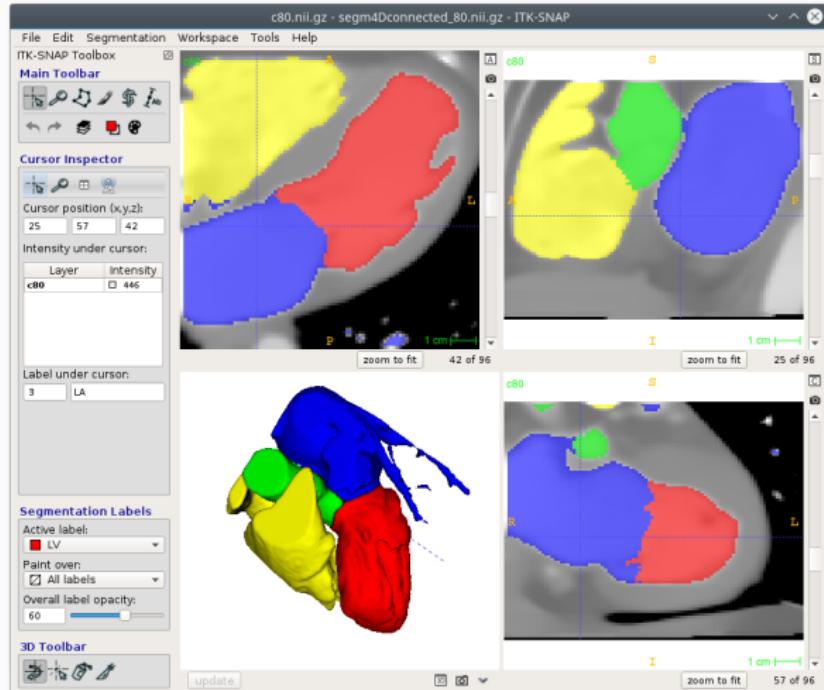
A.Danilov



Manual segmentation 50

Segmentation of ceCT heart images and ML

A.Danilov



Automatic segmentation 80

Incompressible fluid flow in a moving domain

Let ξ mapping Ω_0 to $\Omega(t)$, $F = \nabla \xi = I + \nabla u$, $J = \det(F)$ be given

Dynamic equations

$$\frac{\partial v}{\partial t} = (J\rho_f)^{-1} \operatorname{div}(J\sigma_f F^{-T}) - \nabla v \left(F^{-1} \left(v - \frac{\partial u}{\partial t} \right) \right) \quad \text{in } \Omega_0$$

Fluid incompressibility

$$\operatorname{div}(JF^{-1}v) = 0 \quad \text{in } \Omega_0 \quad \text{or} \quad J\nabla v : F^{-T} = 0 \quad \text{in } \Omega_0$$

Constitutive relation for the fluid stress tensor

$$\sigma_f = -p_f I + \mu_f ((\nabla v) F^{-1} + F^{-T} (\nabla v)^T) \quad \text{in } \Omega_0$$

Mapping ξ does not define material trajectories \rightarrow quasi-Lagrangian formulation

3D: left ventricle of a human heart

A.Danilov, A.Lozovskii

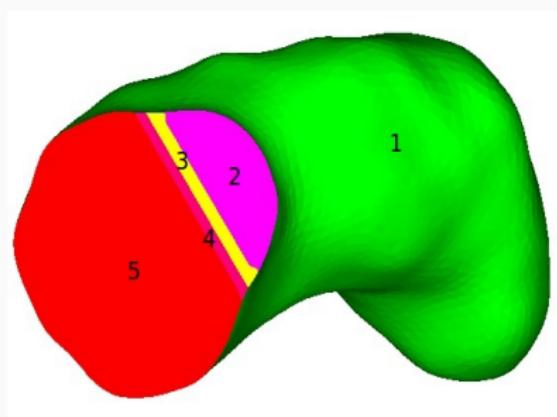


Рис. 1: Left ventricle

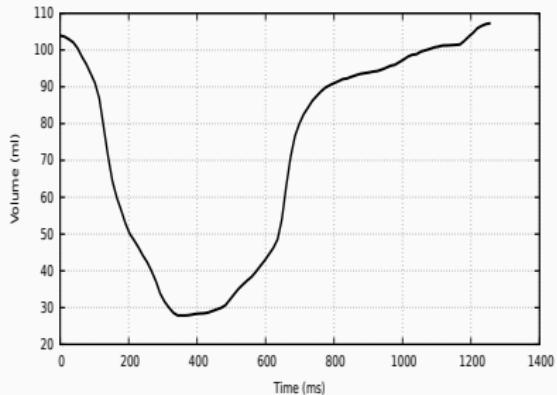
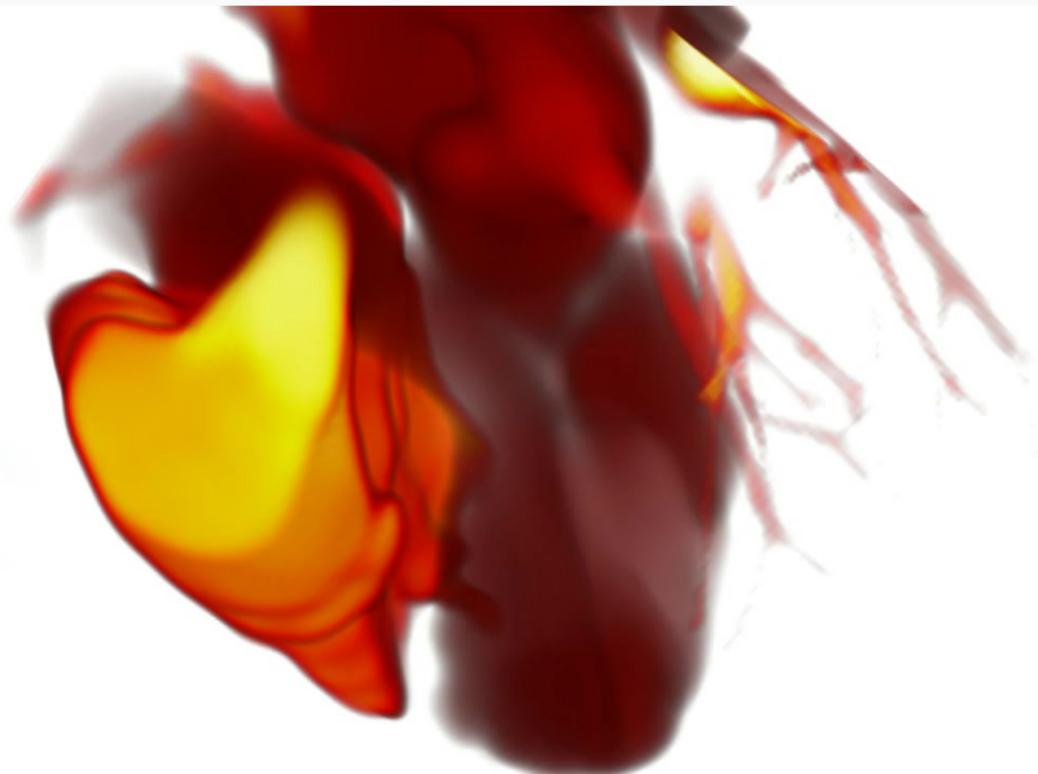


Рис. 2: Ventricle volume

The law of motion for the ventricle walls is known thanks to ceCT scans → 100 mesh files with time gap 0.0127 s → \mathbf{u} given as input → FSI reduced to NSE in a moving domain

- 2 - aortic valve (outflow)
- 5 - mitral valve (inflow)

Dynamic left ventricle model



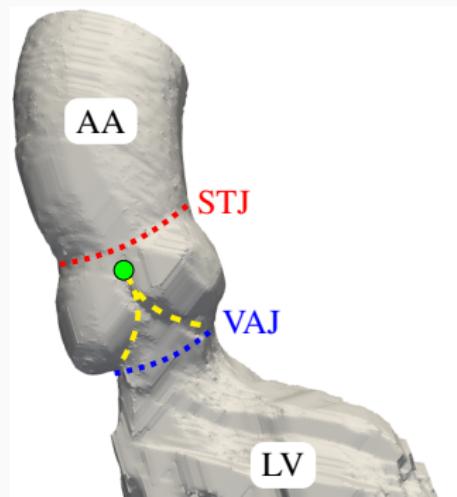
Персонализированная модель закрытия аортального клапана

Mathematical modeling of AV replacement

V.Salamatova, A.Legkii

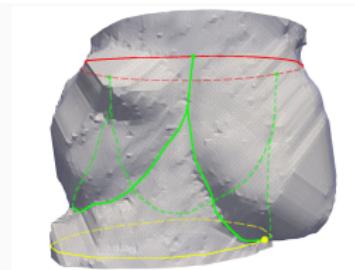
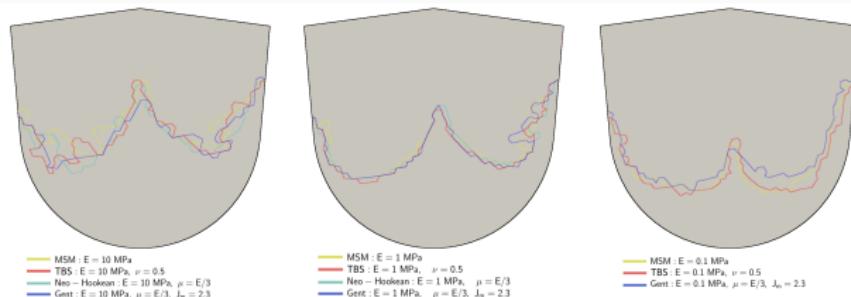
Objectives of modeling:

- degree of regurgitation
- coaptation zone (heights) [demand on computation time for real-time surgical planning system: the results within a few minutes on a personal computer.]



Coaptation profiles for different elastic models

Models and elastic modulus were varied



Где этому научиться?

- МФТИ, физтех-школа ПМИ: кафедра вычислительных технологий и моделирования в геофизике и биоматематике
- ВМК МГУ: кафедра вычислительных технологий и моделирования
- Сеченовский Университет: кафедра высшей математики, механики и математического моделирования
(биопринтинг, ФРК, гемодинамика в желудочке, аортальный клапан, тромбогенезис, АВК, абляция)