Unstructured mesh generation for segmented images

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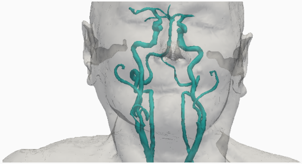
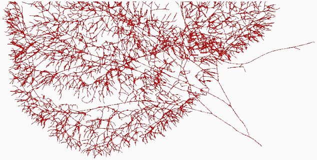
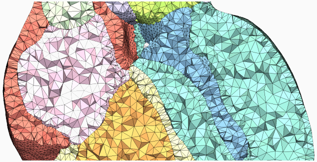
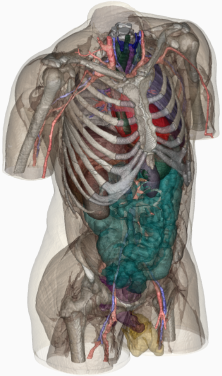




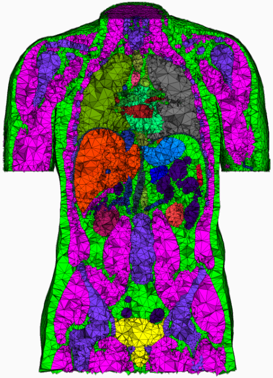


Modeling pipeline

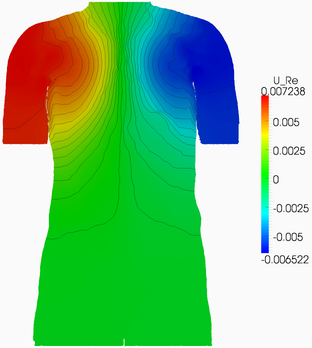
Segmentation



Meshing



FEM

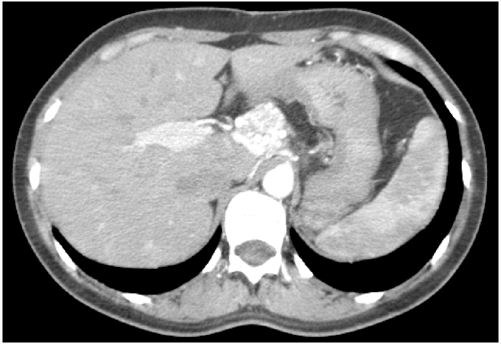


ITK-SNAP CGAL Mesh Ani3D ParaView

A. A. Danilov, et al. Modelling of bioimpedance measurements: unstructured mesh application to real human anatomy. Russian J. Numer. Anal. Math. Modelling, 2012, 27:431–440

Vessel networks

Intravenous contrast enhancement

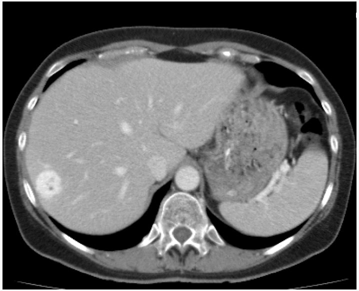


Arterial phase

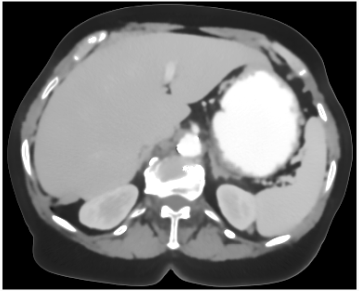
Venous phase

Contrast enhancement

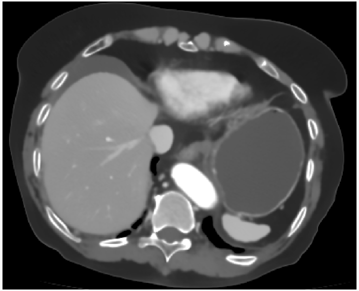
Oral contrast enhancement



Native phase

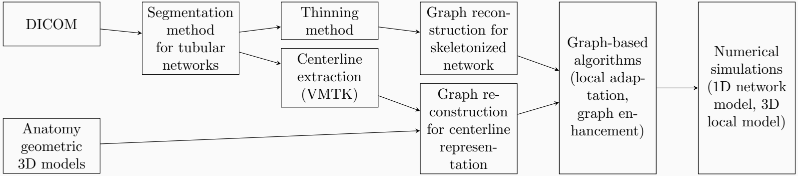


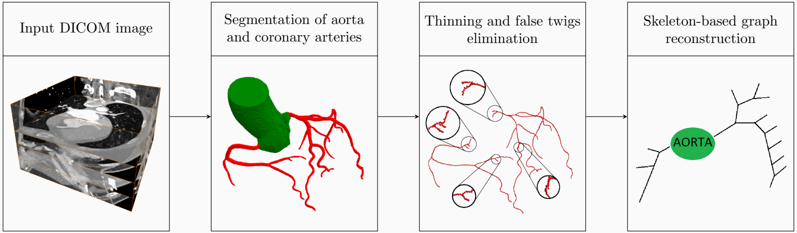
Positive contrast



Negative contrast

Segmentation and skeletonization – overview

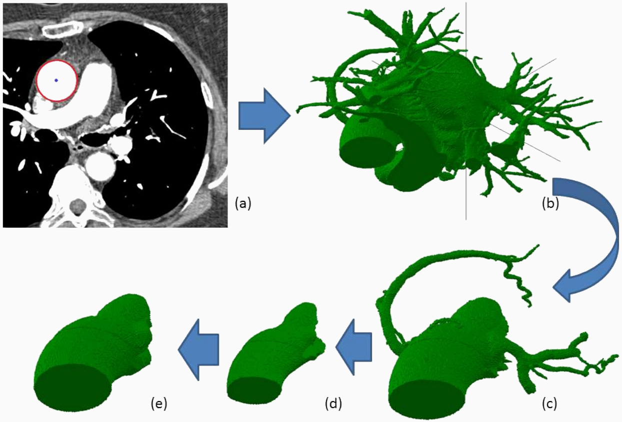




A. Danilov, et al. Methods of graph network reconstruction in personalized medicine. IJNMBE, 2015.

Aorta segmentation

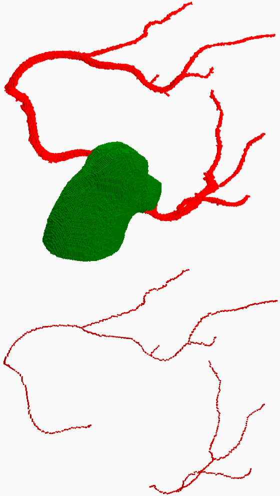
1. Hough circleness transform – brightest disk on image
2. Thresholding, connected region
3. Fast isoperimetric distance trees – cut bottlenecks
4. Mathematical morphology operations – smoothing



L. Grady. Fast, quality, segmentation of large volumes – isoperimetric distance trees. Computer Vision – ECCV 2006.

Coronary vessels extraction

1. Ostia points detection
2. Frangi vesselness filter
3. Distance ordered homotopic thinning
4. Skeleton cleaning

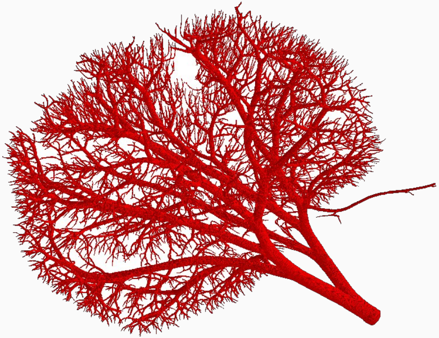


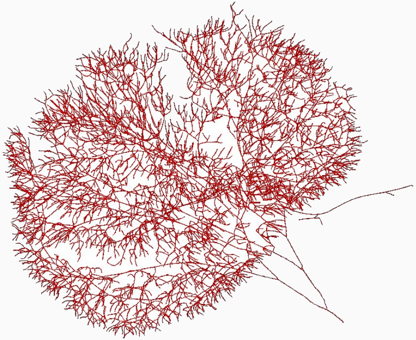
Tubular structure properties:

- $|\lambda_1| \leq |\lambda_2| \leq |\lambda_3|$ – eigenvalues of Hessian(smooth image)
- $|\lambda_1| \approx 0$
- $|\lambda_1| \ll |\lambda_2|$
- $\lambda_2 \approx \lambda_3$

A.F. Frangi et al. Multiscale vessel enhancement filtering. MICCAI'98, 1998.

Vessels skeletonization

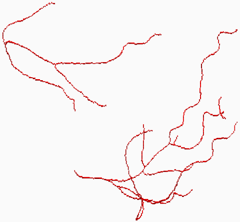


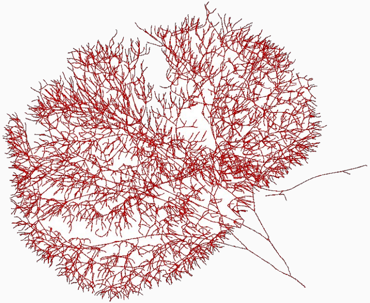


Micro-CT of vascular corrosion cast of rabbit kidney provided by J. Alastruey,
Department of Bioengineering, Imperial College London, UK.

C. Pudney. Distance-ordered homotopic thinning: A skeletonization algorithm for 3D digital images. Computer Vision and Image Understanding 1998.

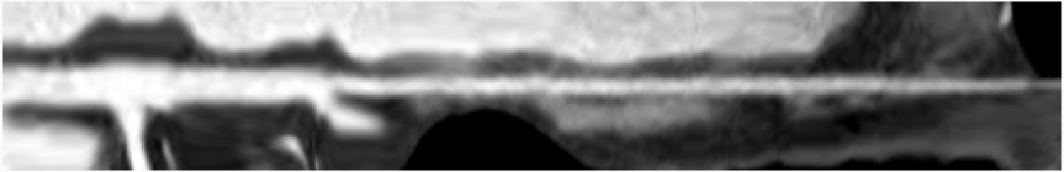
Skeletonization

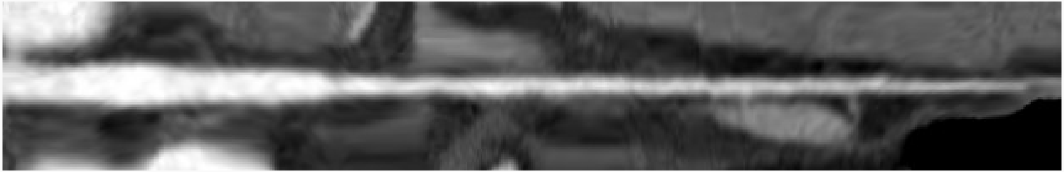




Resolution	$512 \times 512 \times 248$	$2000 \times 1989 \times 910$
Distance map	0.20 sec	58.12 sec
Thinning	0.79 sec	526.98 sec
False twigs cleaning	0.15 sec	16.61 sec
Graph construction	0.13 sec	12.27 sec
Skeleton segments	22 + 6	4302 + 2142

Detection of vessel lumen





A. Kanitsar, et al. CPR – curved planar reformation. IEEE Visualization, 2002.

M. Toledano, et al. Learning to Detect Coronary Artery Stenosis from Multi-Detector CT imaging. American Heart Association Conference, 2005.

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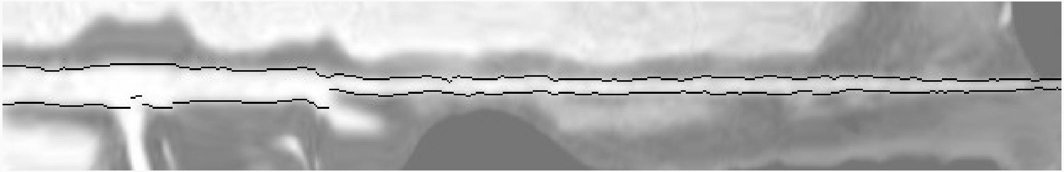
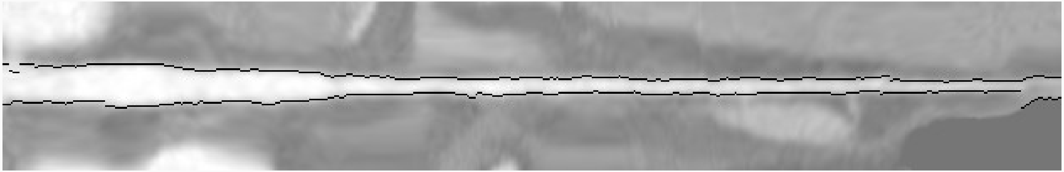
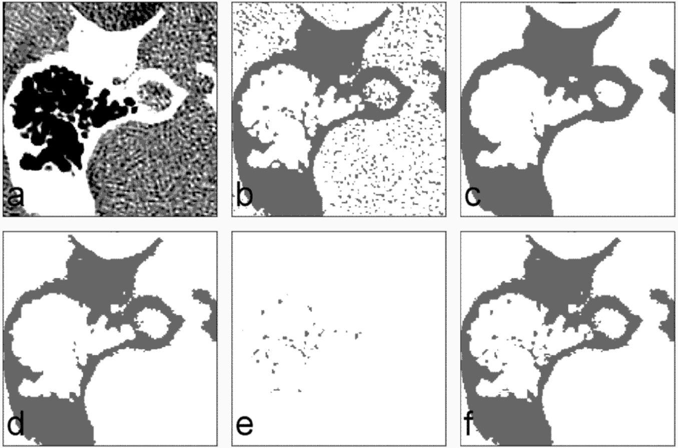




A. Kanitsar, et al. CPR – curved planar reformation. IEEE Visualization, 2002.

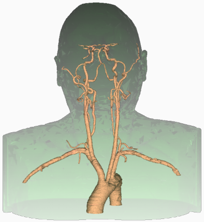
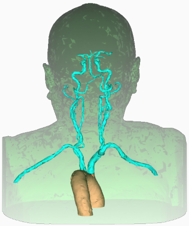
M. Toledano, et al. Learning to Detect Coronary Artery Stenosis from Multi-Detector CT imaging. American Heart Association Conference, 2005.

Bone elimination



H.A. Gratama van Andel. Removal of bone in CT angiography by multiscale matched mask bone elimination. Medical Physics, 2007.

Cerebral vessels segmentation

		
Resolution	$512 \times 512 \times 501$	$512 \times 512 \times 451$
Spacing	$0.76 \times 0.76 \times 0.80$	$0.62 \times 0.62 \times 0.80$
Multiscale MMBE	11.20 sec	10.10 sec
Cavities elimination	7.76 sec	7.04 sec
Aorta segmentation	16.61 sec	15.33 sec
Frangi Filter	196.40 sec	184.91 sec
Bifurcation detection	7.61 sec	6.67 sec
Leak elimination	7.39 sec	6.76 sec

Important notes

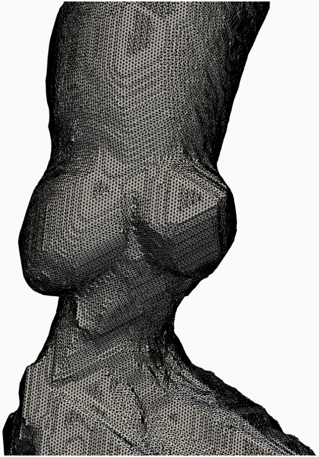
- Vessel segmentation require contrast enhanced CT (ceCT) images
- Additional native phase image may be required for bone elimination
- Most of the work may be performed automatically
- Open source code for vessels segmentation – ImageJ (`imagej.net`)
- Open source code for meshing vessels – VMTK (`vmtk.org`)

Mesh generation

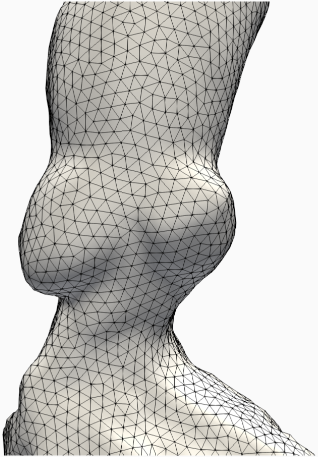
Preparing the segmented image

- Fill the holes in segmented image (mathematical morphology, remove islands)
- Apply *smoothing+voting* operation:
  for each label smooth the binary mask,
  then for each voxel select label with the biggest value of smoothed mask
- Upscale images for better resolution using smoothing+voting approach
- Check preservation of the total volume for each label
- Check connectivity and topology preservation of labeled domains during pre-processing

Surface generation for one material



Marching cubes

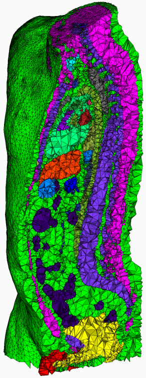


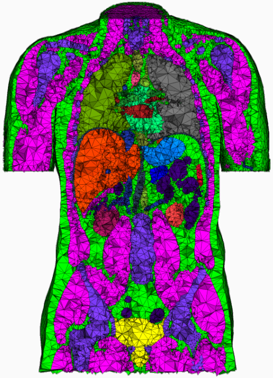
Remeshed surface

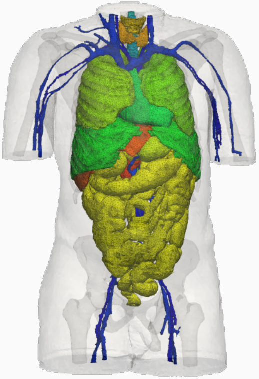
Remesh the surface if the mesh size should be bigger than the voxel size

Mesh generation for multi-material image

CGAL Mesh (`www.cgal.org`) – Delaunay mesh generation



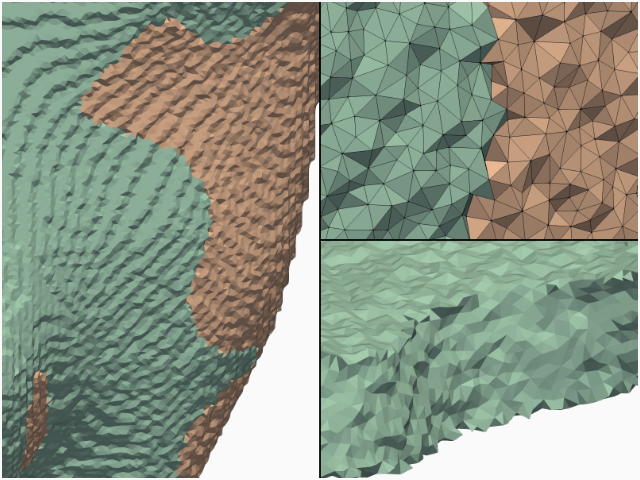




The domain is defined explicitly by the segmentation image

Improving the smoothness of boundaries

1. Surface snaps to the voxel grid
2. Smoothing+voting approach provides smooth boundaries
3. Some artifacts still appear
4. Explicit 1D features improve the mesh



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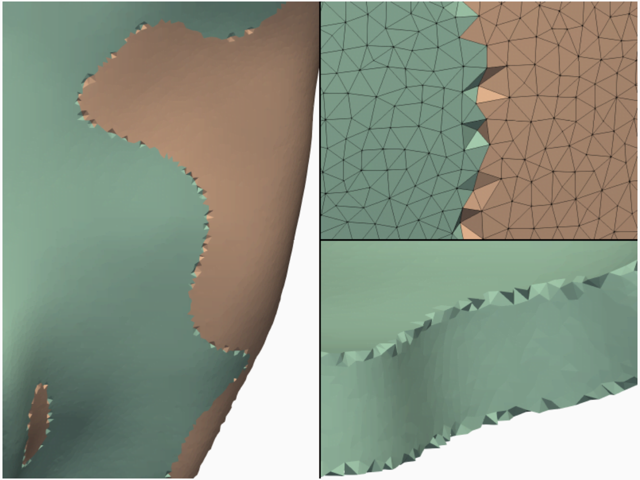

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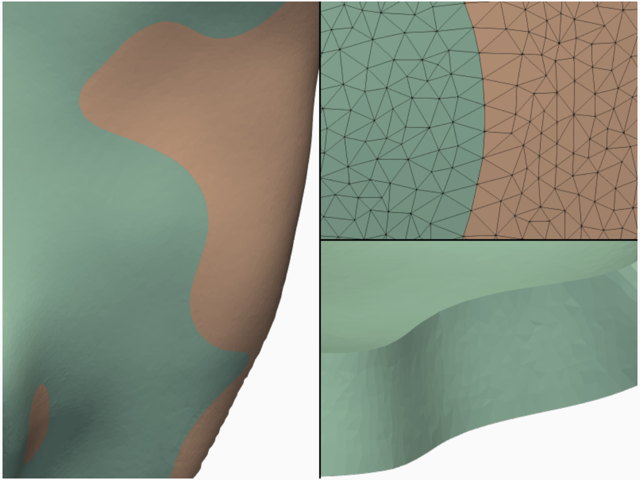

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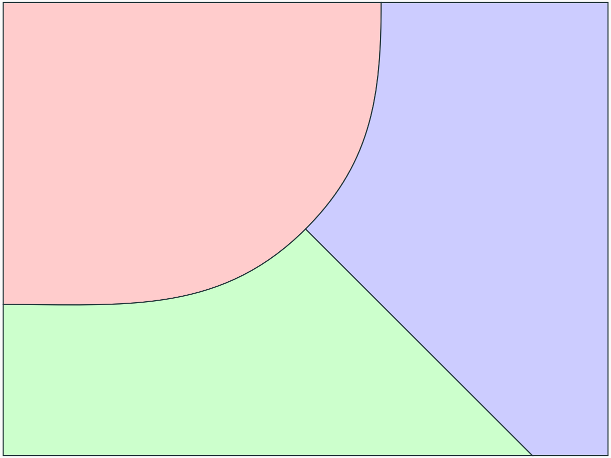

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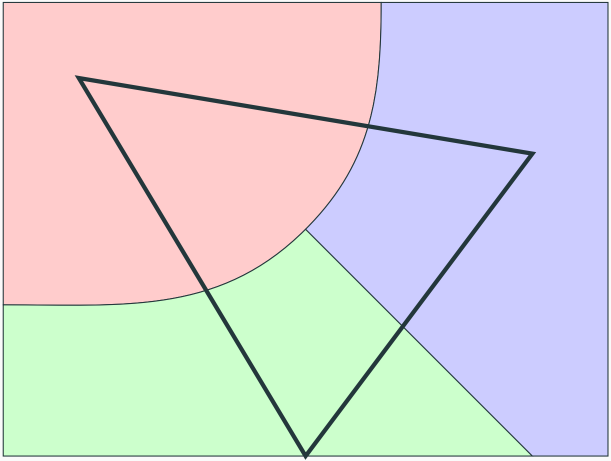

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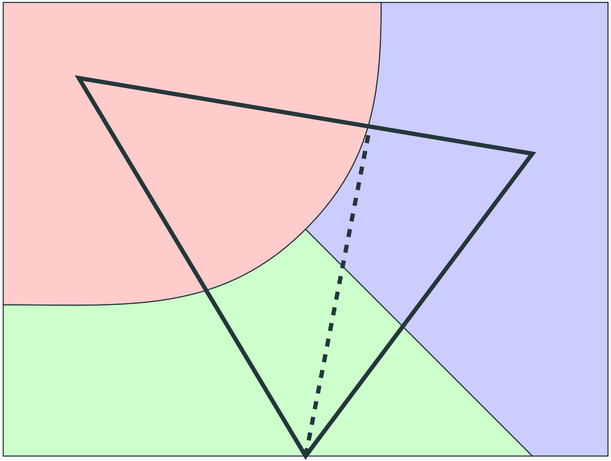

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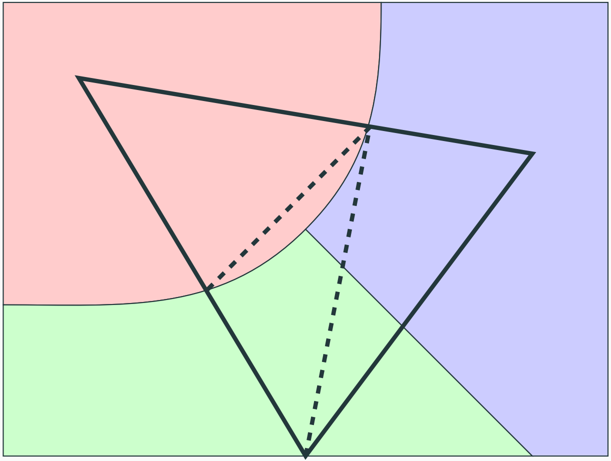

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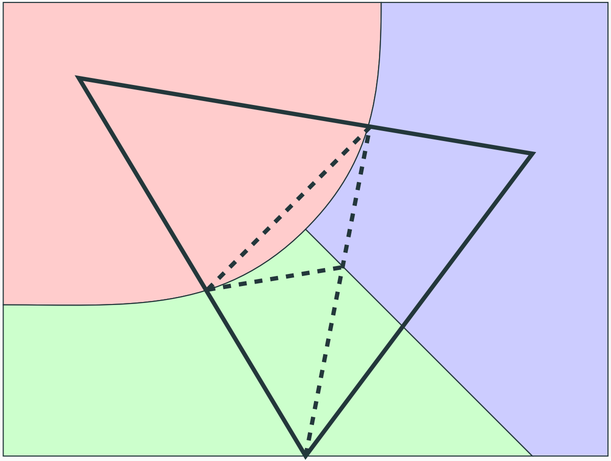

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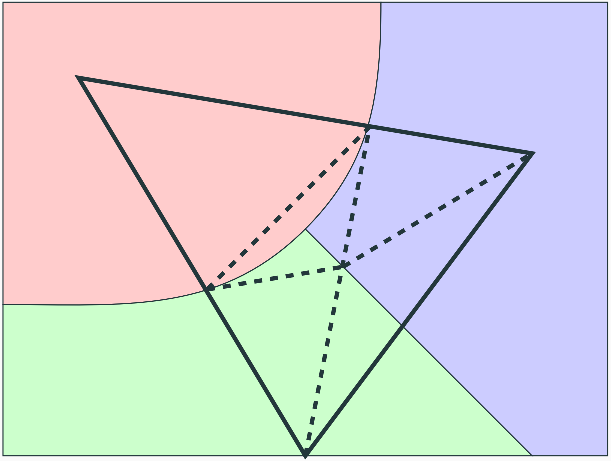

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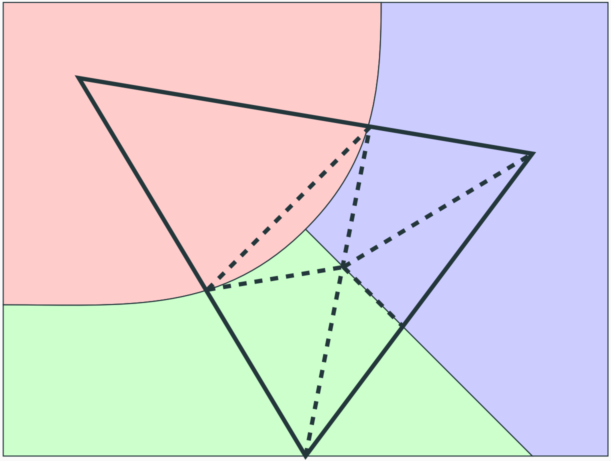

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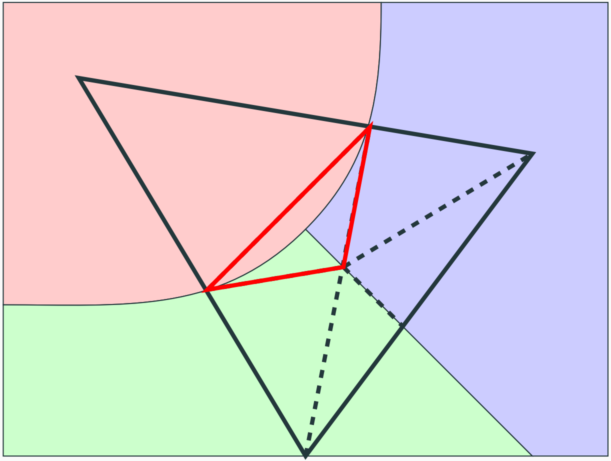


Important notes

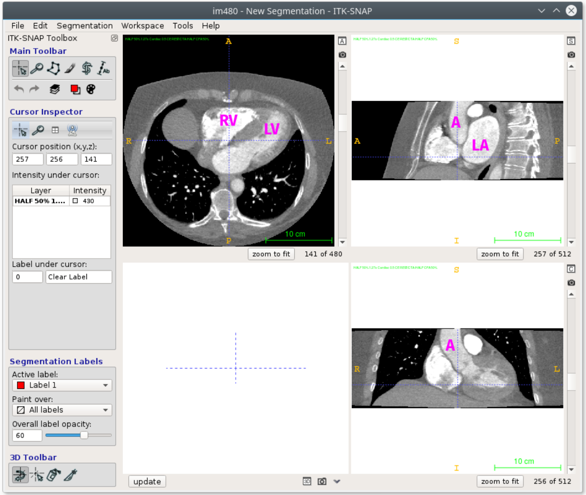
- Prepare the segmented image to greatly improve the final mesh quality
- Carefully check the segmented image for obvious errors
- Generate mesh for all materials simultaneously to avoid non-conformity in the mesh
- Include explicit 1D features to improve geometry shape
- Check preservation of the total volume for each subdomain
- Check connectivity and topology preservation of subdomains

Dynamic meshes

Dynamic left ventricle model

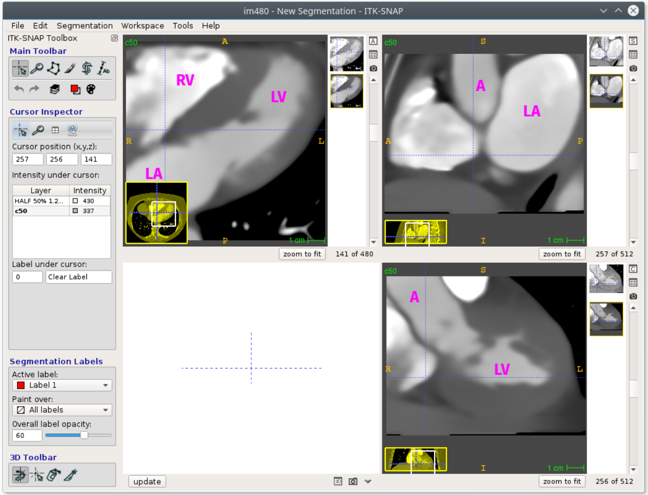
- Aim: hemodynamics modeling in heart ventricles
- Equations: 3D Navier-Stokes, Arbitrary Lagrange-Euler
- Domain: left ventricle, valves – boundary conditions
- Dynamics: ventricle walls reconstructed from ceCT images
- Data: ceCT, 100 images, 1.27 seconds
- Resolution: $512 \times 512 \times 480$, raw data – 24 Gb
- Patient: anonymized, female, 50 years old
- Problem: generation of dynamic mesh from ceCT images

Automatic segmentation



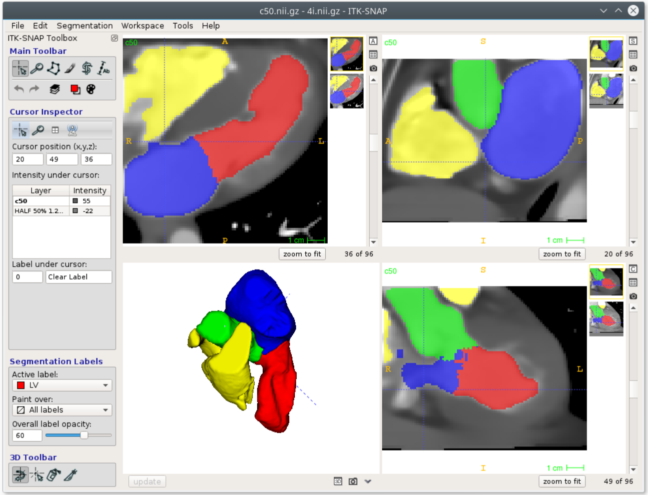
Initial ceCT image №50

Automatic segmentation



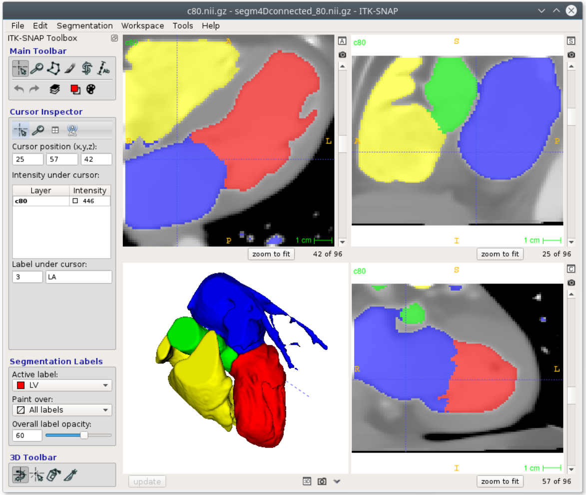
Smoothed ceCT image №50

Automatic segmentation



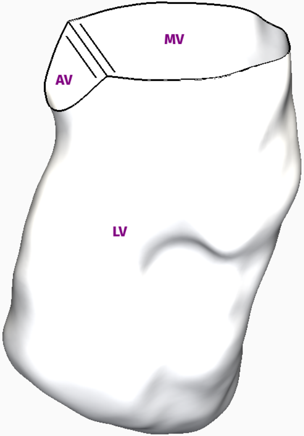
Manual segmentation №50

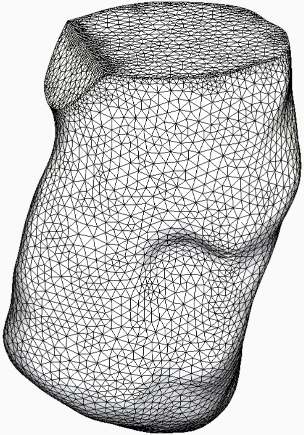
Automatic segmentation



Automatic segmentation №80

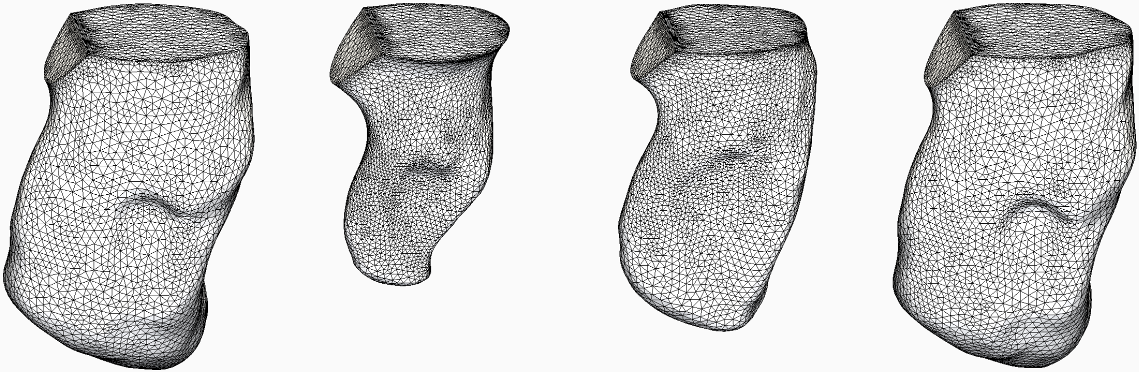
Moving the mesh





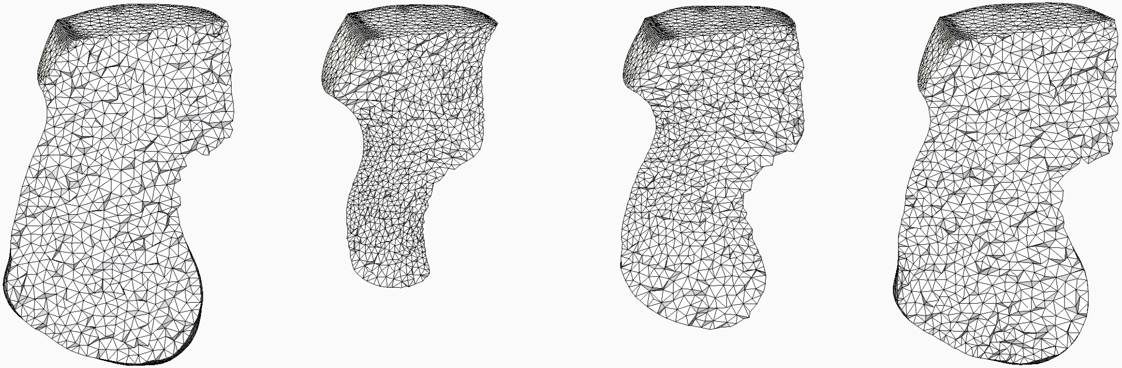
Initial mesh – CGAL Mesh + Ani3D

Moving the mesh



0 30 50 80

Moving surface mesh



0 30 50 80

Simultaneous untangling and smoothing – SUS code

J. M. Escobar, et al, SUS code: simultaneous mesh untangling and smoothing code. http://www.dca.iusiani.ulpgc.es/SUScode

Thank you!

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