Realistic 3D Cell Modeling for FEM Simulation

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Workshop on Mathematical and Computational Methods in Biomedical Imaging and Image Analysis
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Interdisciplinary research group

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Computer Science

James Sneyd
Shawn Means
Mathematics

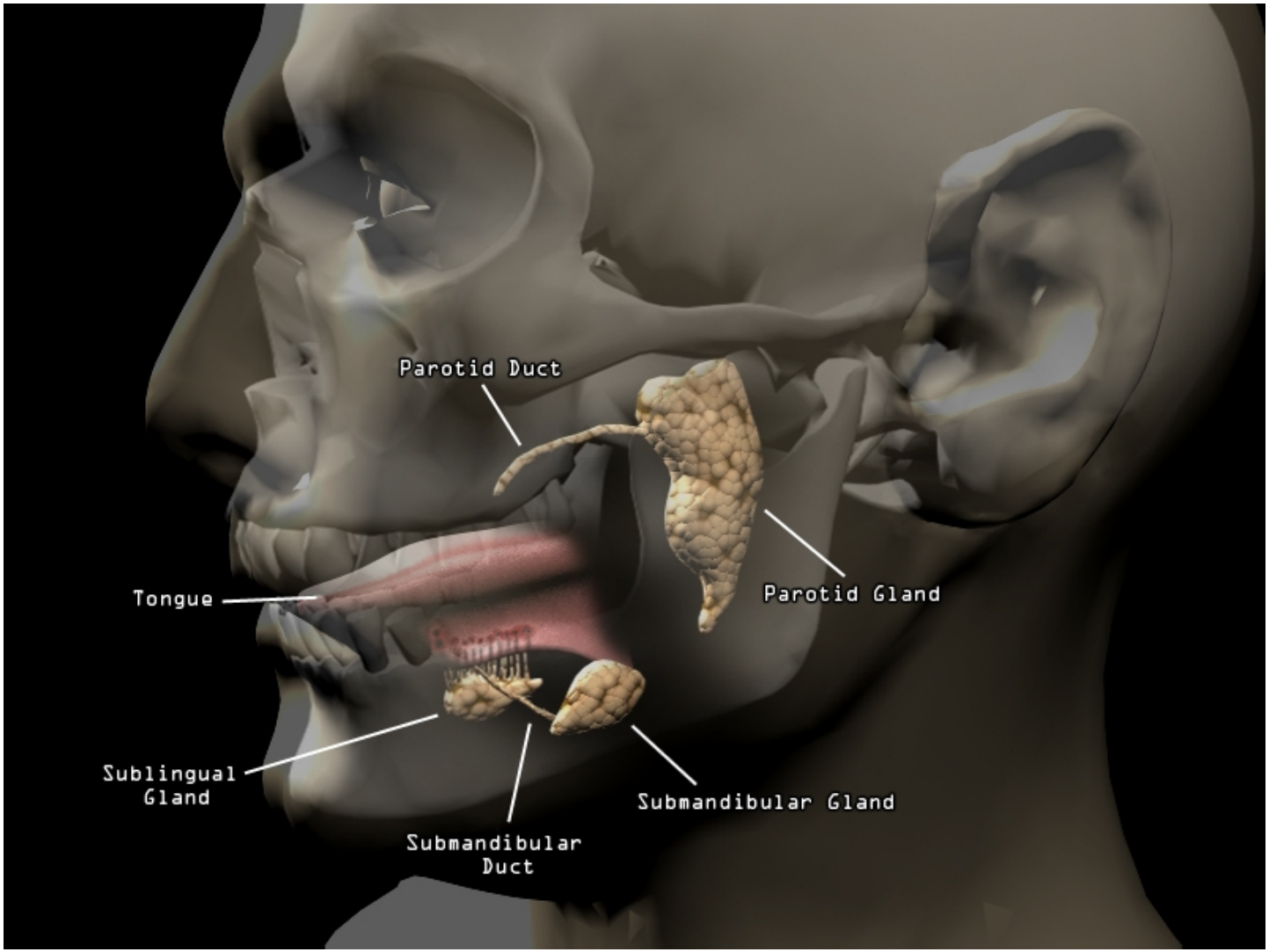
David Yule
Physiology

Project funding

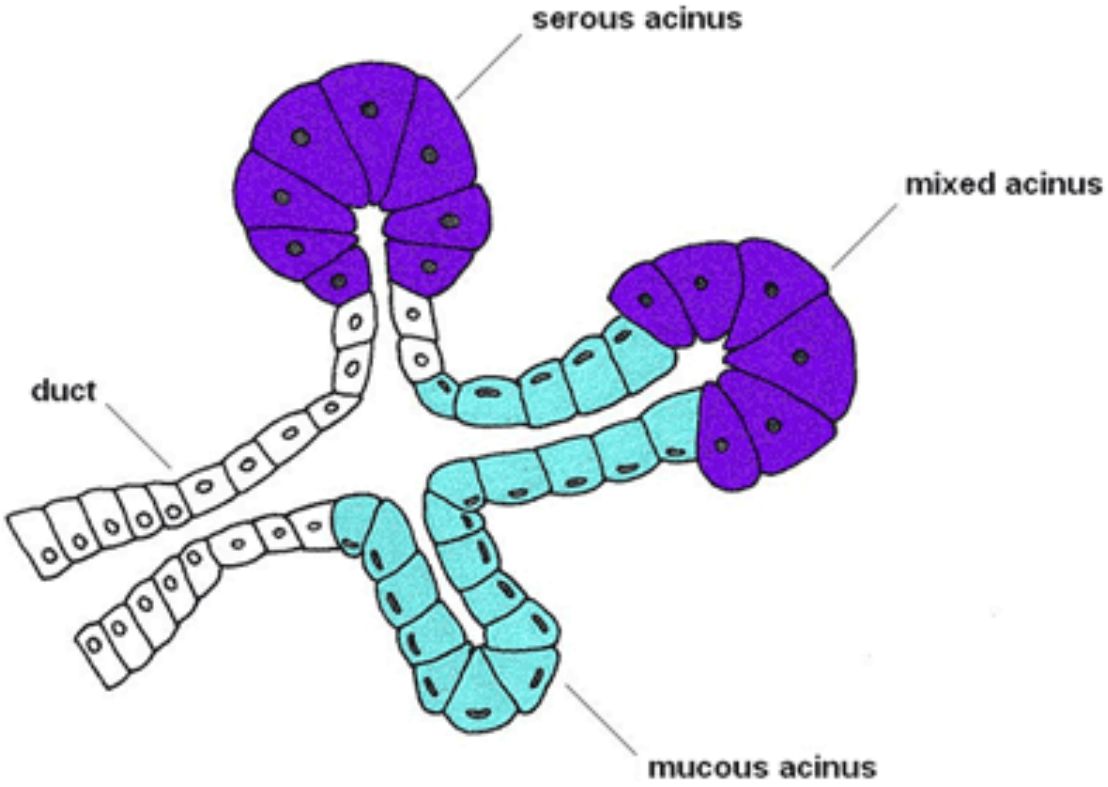
The goal:

Physically accurate modeling, simulation and visualisation of biological cell function.

Salivary glands



Salivary acinii



- **Three types:** serous, mucous and mixed

Data Acquisition: Confocal microscopy

2D image stacks

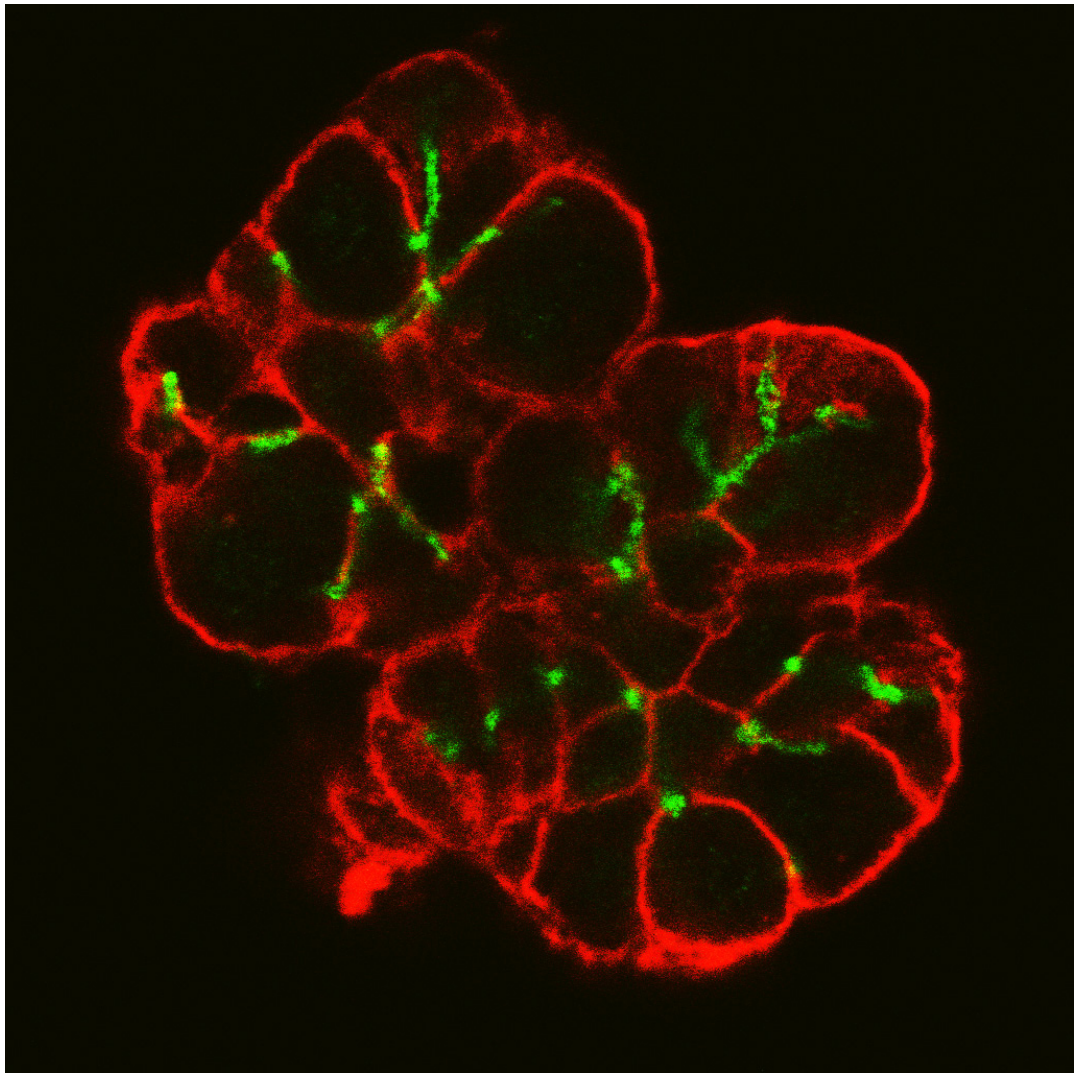
32 slices in Z direction.

Cells & Lumen

red: Na-KATPase
green: Cl Channel

Real dimensions used:
70.7μm^2, 2.2μm spacing

TIFF files: 1024x1024



D. Yule

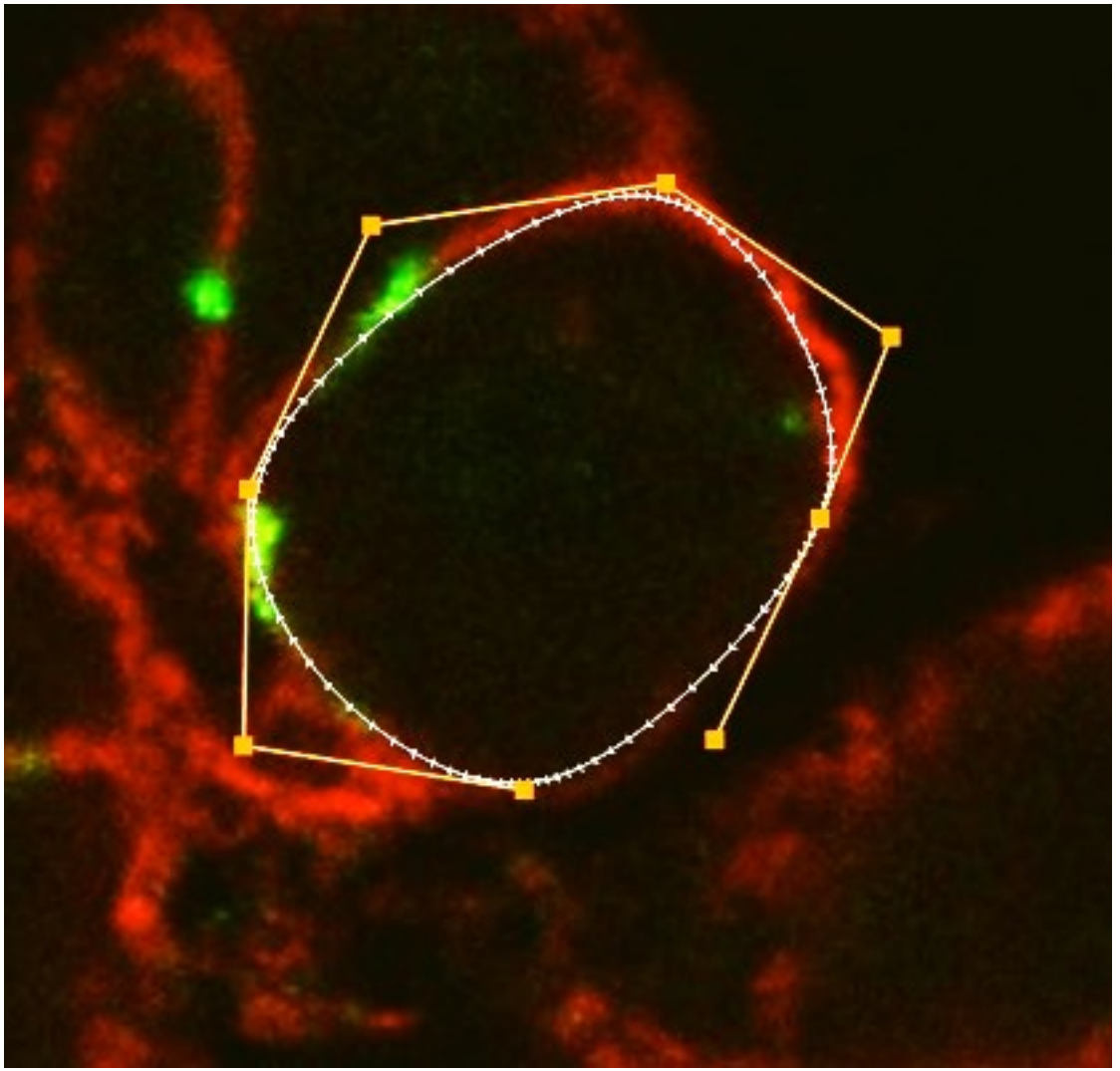
Mesh Modeling

3D reconstruction

Cells

1) Trace the outline of each cell in the image stack.

NURBS circles.



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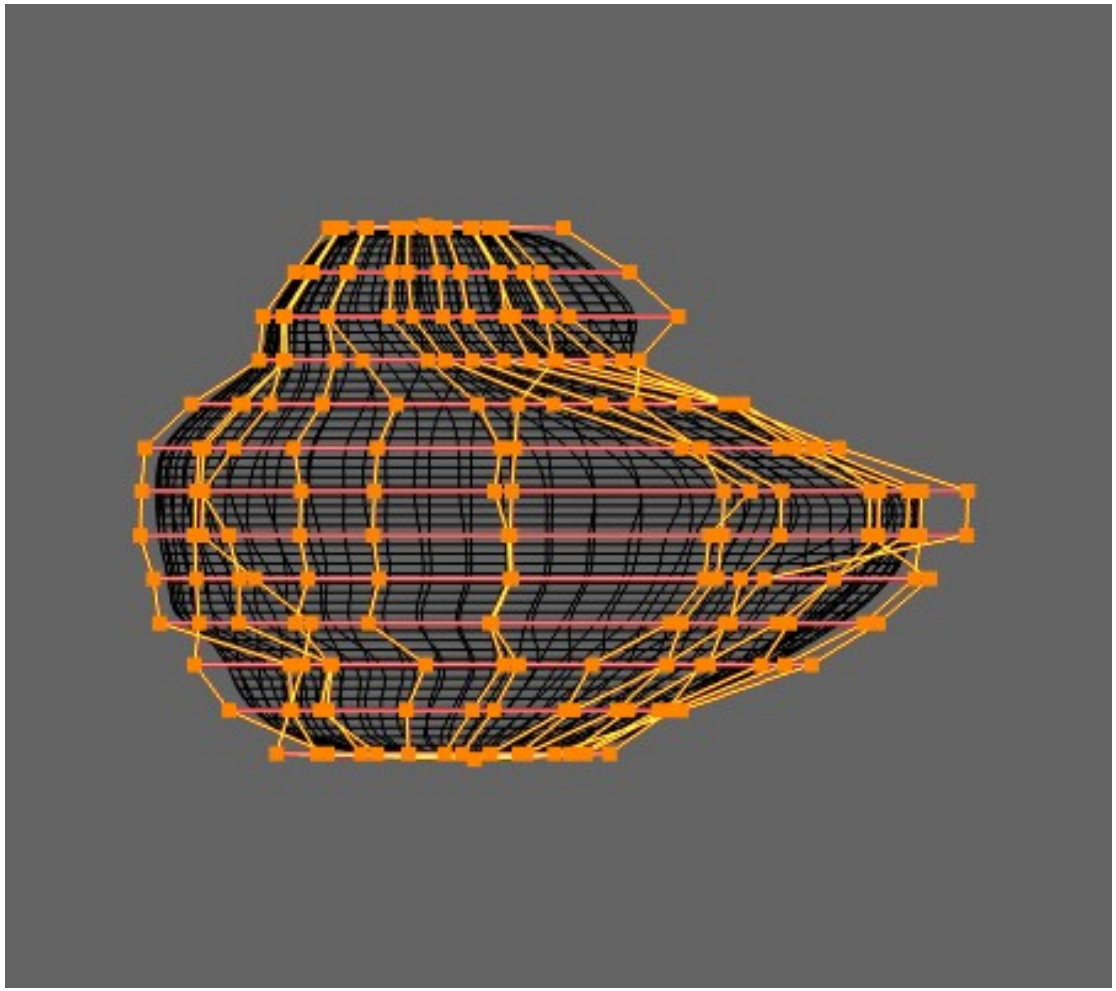
Mesh Modeling

3D reconstruction

Cells

2) Interpolate connections between the “level-set” outlines for each cell.

Results in a parametric NURBS surface.



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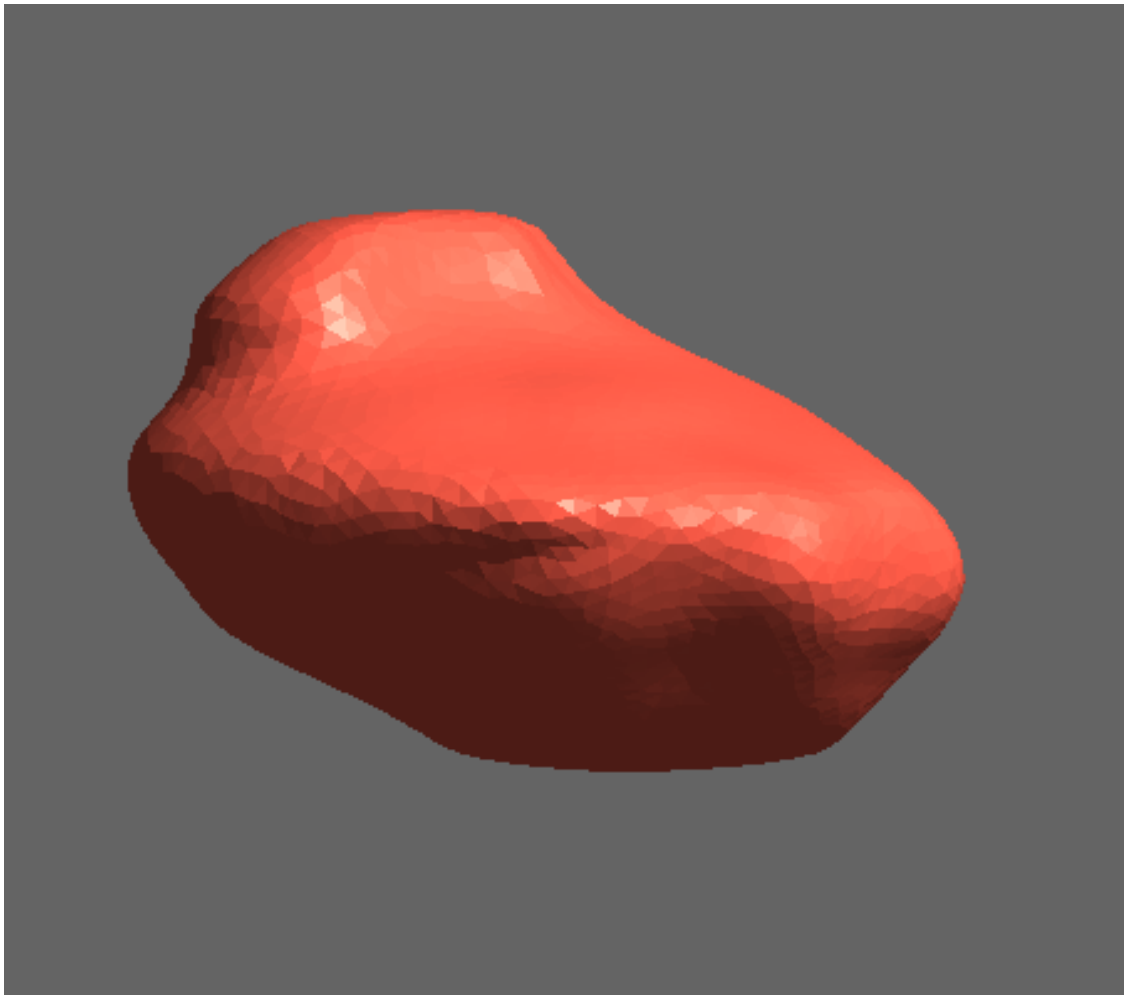
Mesh Modeling

3D reconstruction

Cells

For FEM:
Refine the mesh
surface triangulation.

Octree remesh.
STL files.
Harmonic maps.



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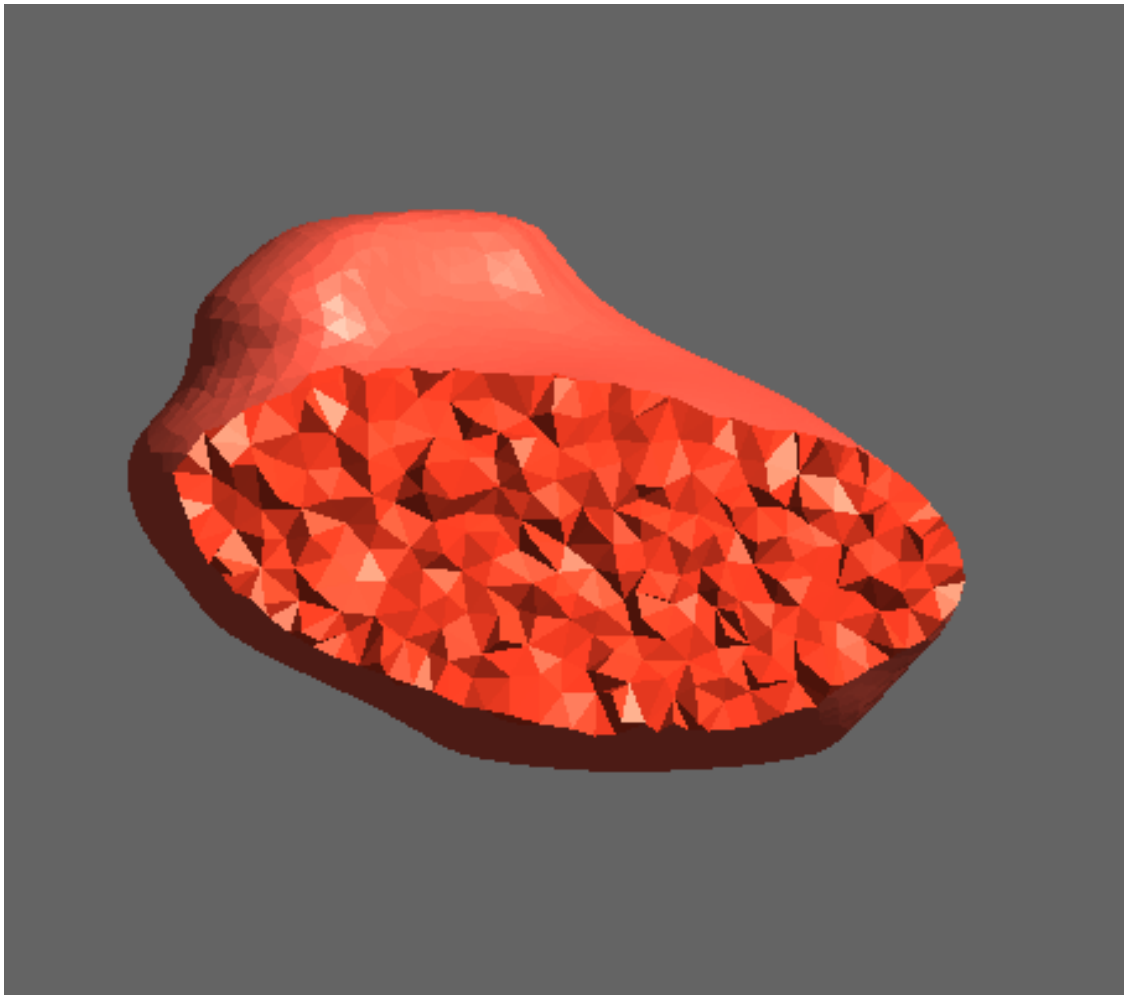
Mesh Modeling

3D reconstruction

Cells

For FEM:
Volumetric meshing
with tetrahedrons.

Harmonic maps.
MSH files.



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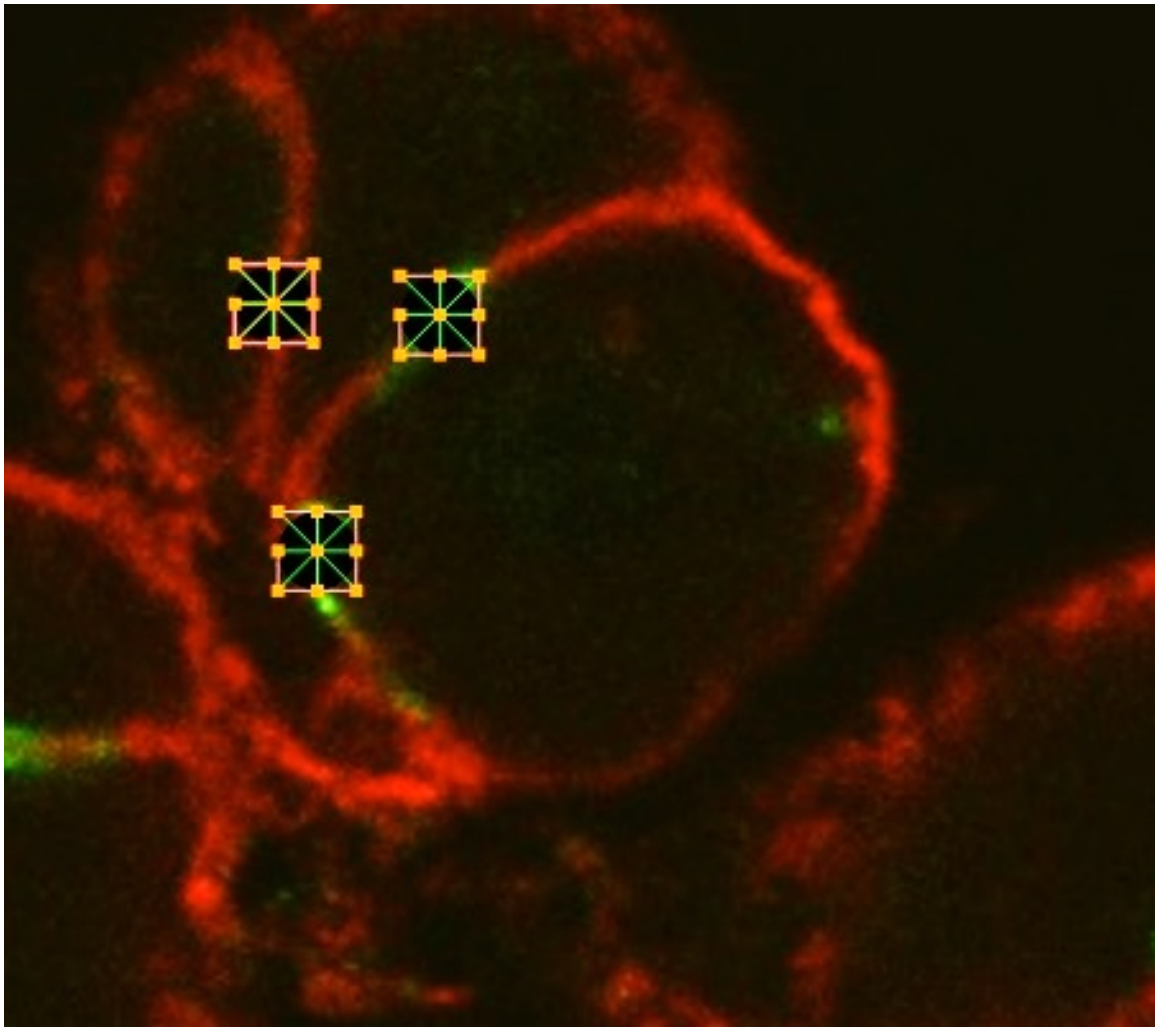
Mesh Modeling

3D reconstruction

Lumen

1) Place spheres on the lumen in each 2D image slice.



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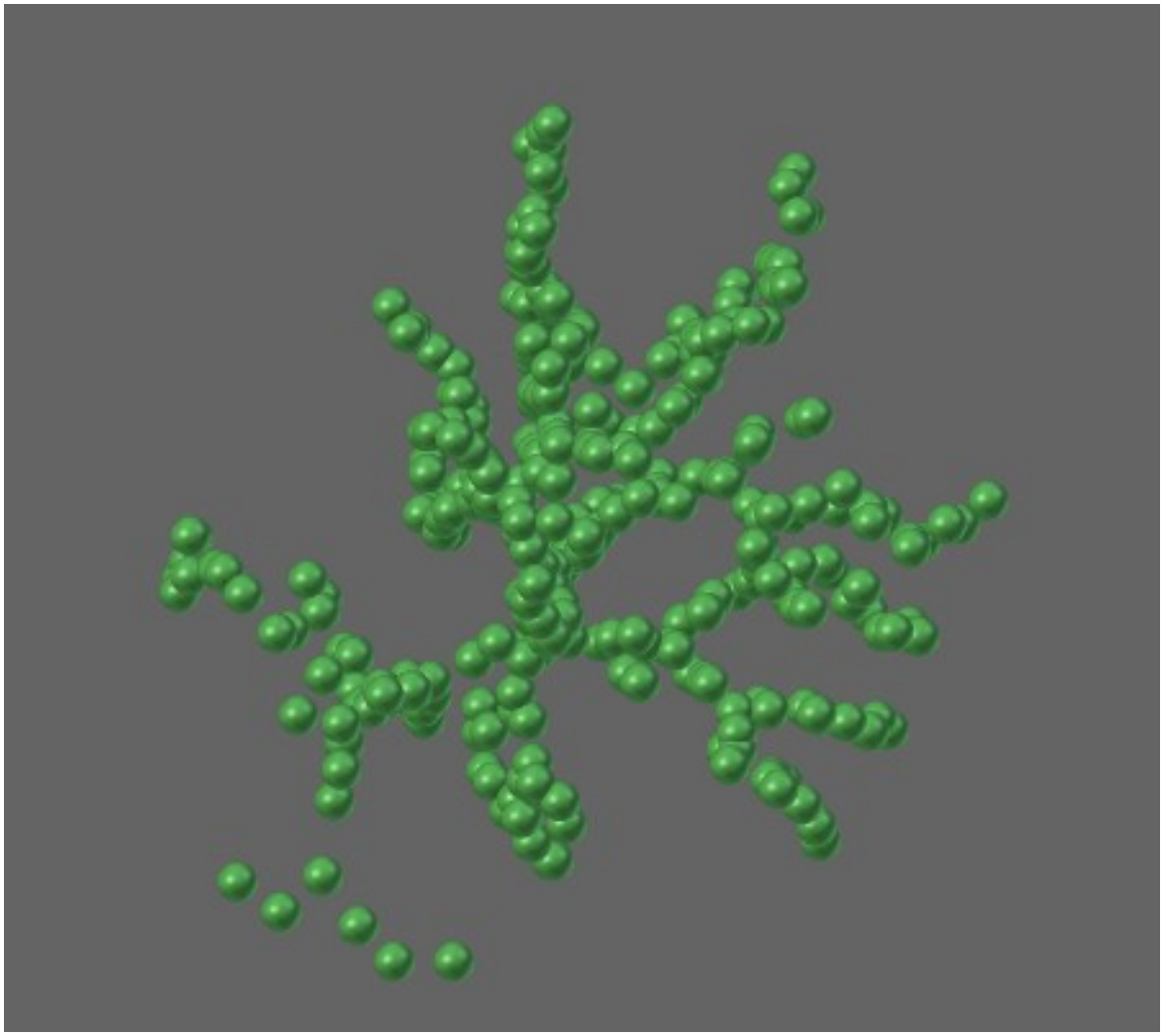
Mesh Modeling

3D reconstruction

Lumen

2) Collect all of the spheres together in 3D space.

Procedural “meta-balls”.



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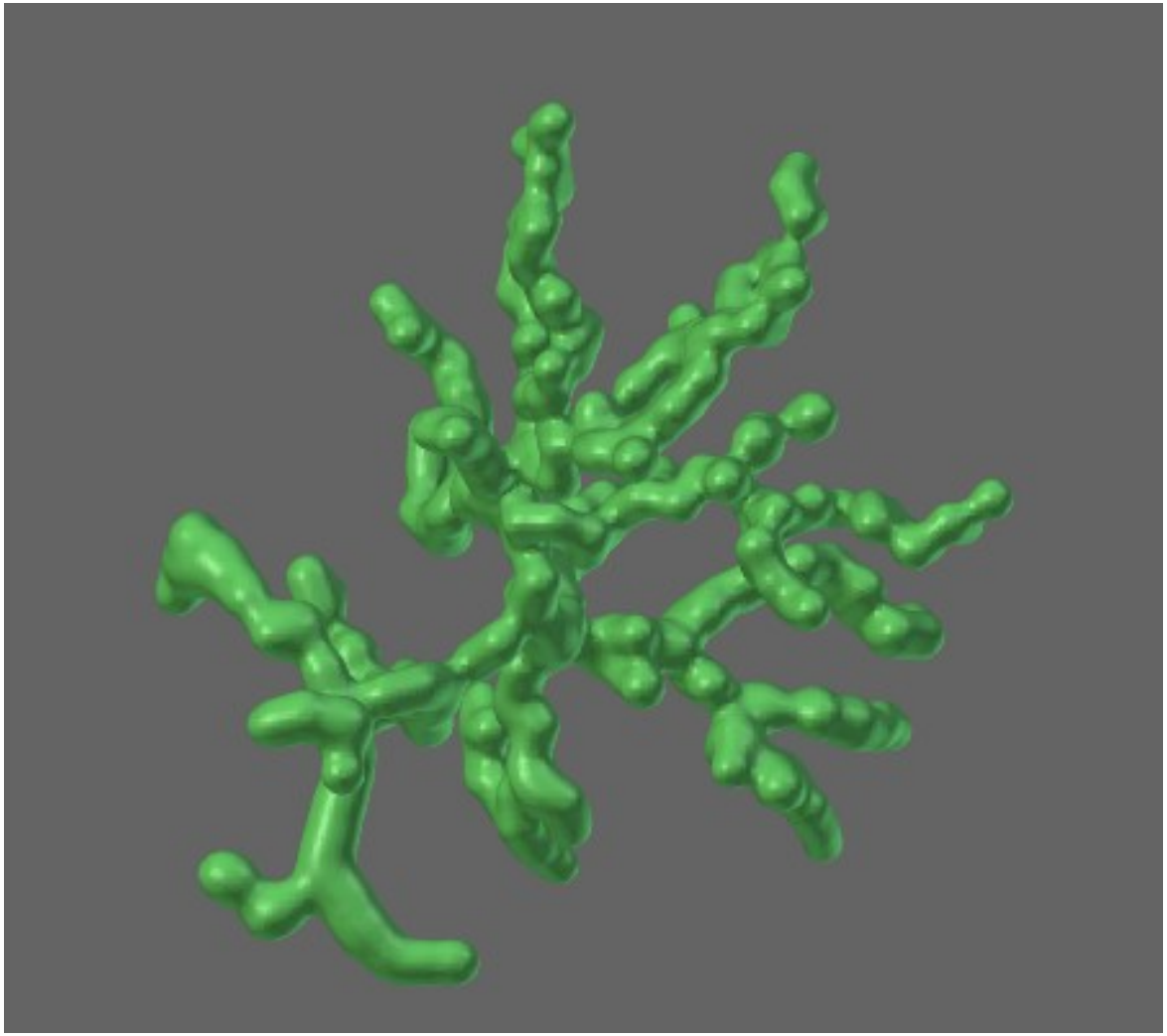
Mesh Modeling

3D reconstruction

Lumen

3) “Shrink-wrap” the spheres together.

Constructive Solid Geometry.
Octree remesh.
STL files.



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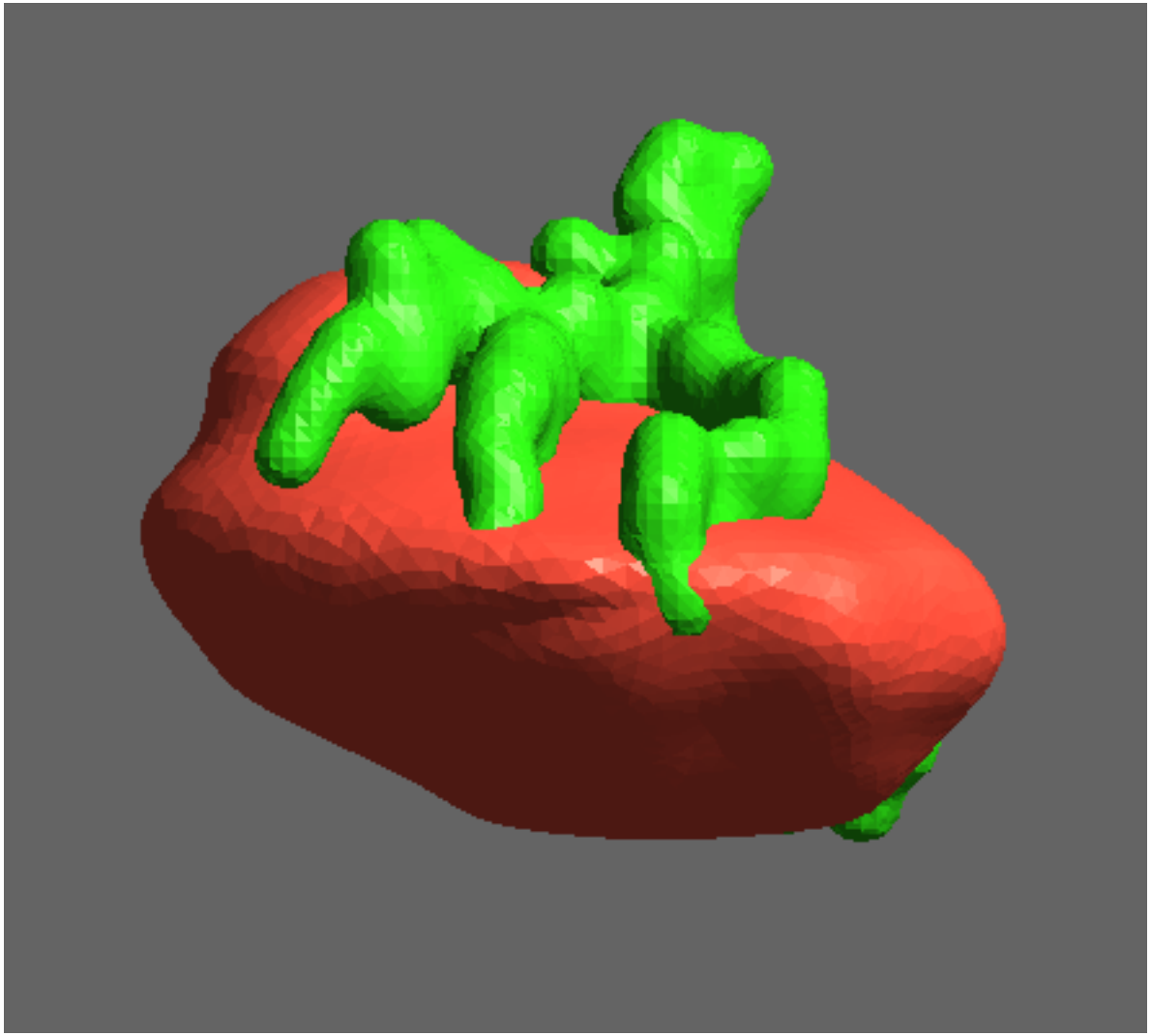
Reconstructed 3D Model

Cells & Lumen

Each cell is held by a lumen “claw”.

The lumen has a tree-like branching structure.



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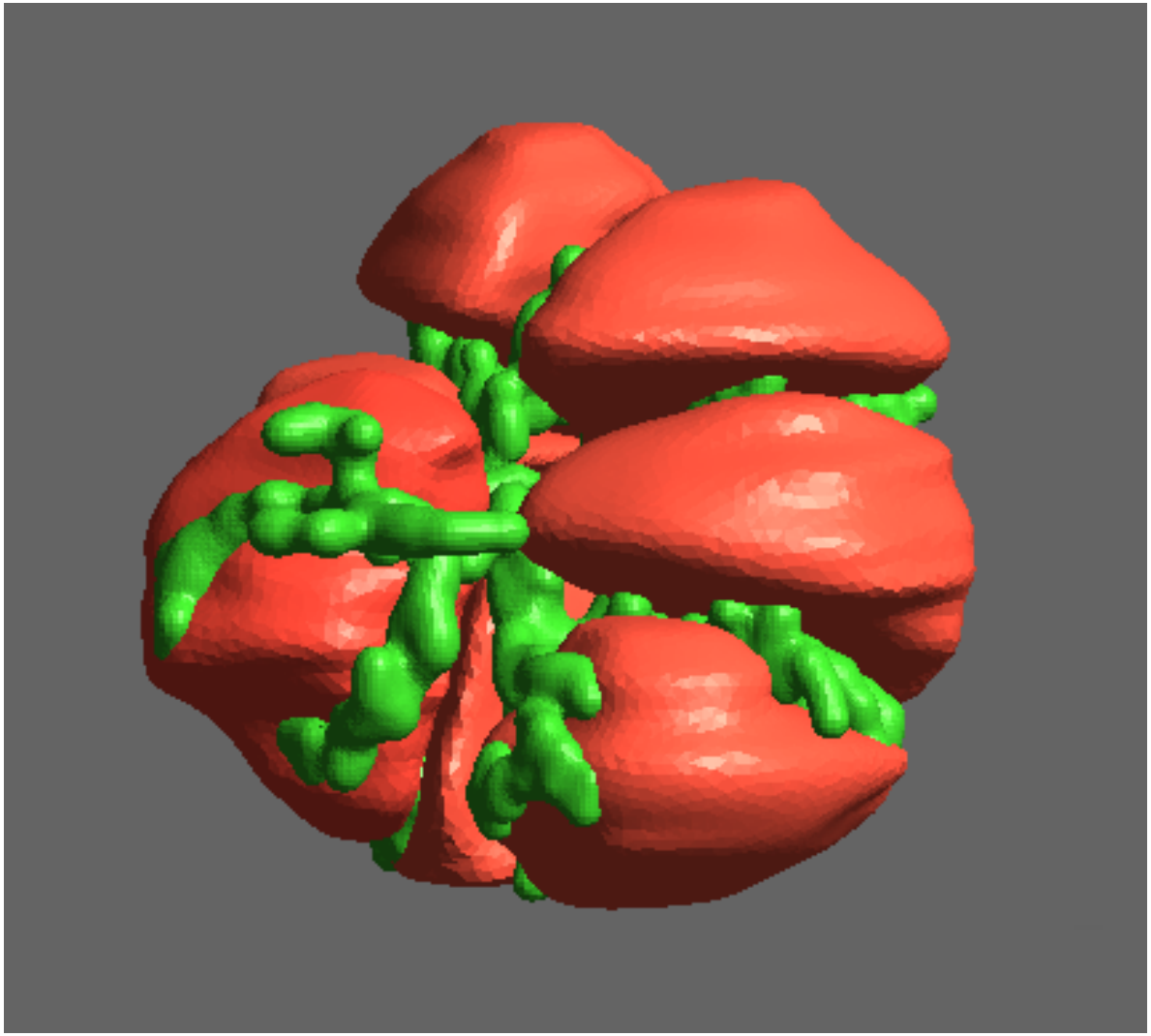
Reconstructed 3D Model

Cells & Lumen

The cells are grouped in tight clusters.

Each lumen has a central trunk.



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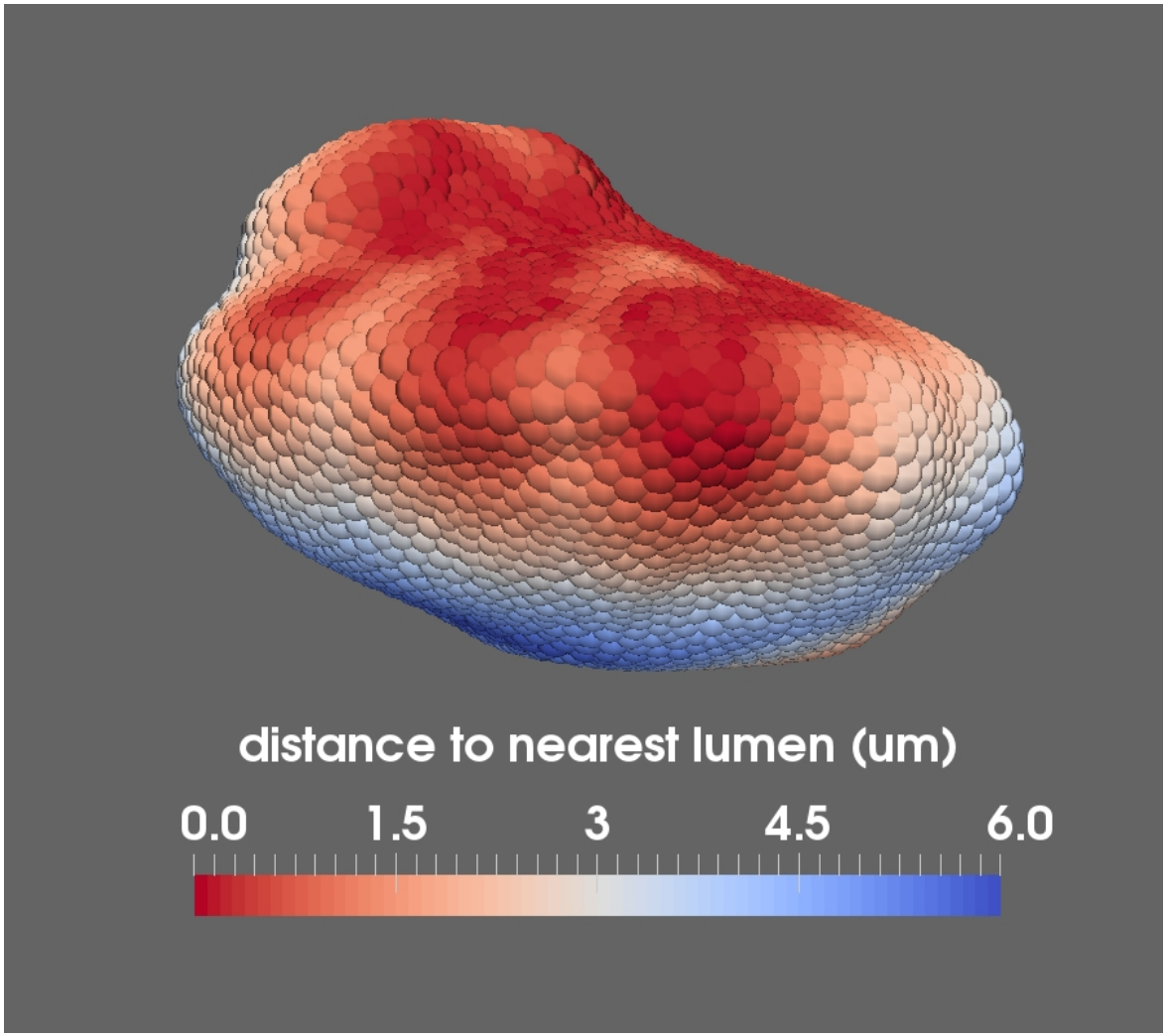
Solid Volumetric Mesh

Tetrahedral mesh for finite element simulation

Nodal view

Imprint of the lumenal "claw".



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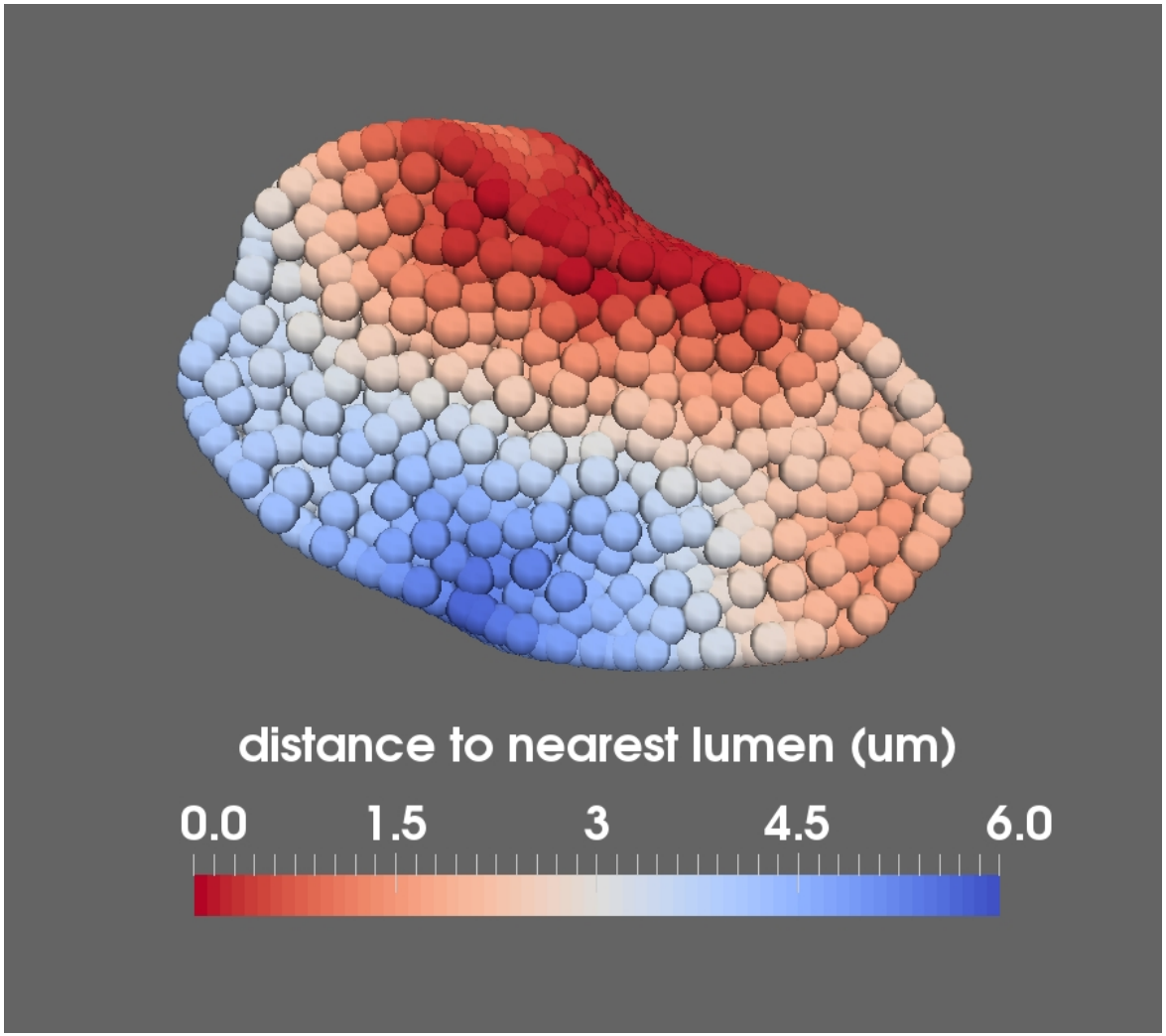
Solid Volumetric Mesh

Tetrahedral mesh for finite element simulation

Nodal view
(cut-away)

Imprint of the lumenal "claw".



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FEM Simulation

Calcium waves

Partial differential equations model the cell calcium dynamics.

Reaction-Diffusion

$$\frac{\partial c}{\partial t} = D_{\mathrm{c}} \nabla^2 c + (J_{\mathrm{IPR}} + J_{\mathrm{leak}})(c_{\mathrm{e}} - c) - J_{\mathrm{serca}}$$

$$\frac{\partial p}{\partial t} = D_{\mathrm{p}} \nabla^2 p + V_{\mathrm{PLC}}(\vec{x}) - V_{\mathrm{deg}} \left(\frac{c^2}{K_{3\mathrm{K}}^2 + c^2} \right) p$$

$$\frac{\partial h}{\partial t} = \frac{h_\infty - h}{\tau}$$

$$J_{\mathrm{serca}} = V_{\mathrm{s}} \frac{c^2}{K_{\mathrm{s}}^2 + c^2}$$

$$J_{\mathrm{IPR}} = k_{\mathrm{IPR}}(\vec{x}) P_O$$

$$P_O = \phi_c \phi_p h$$

$$\phi_c = \frac{c^3}{K_{\mathrm{a}}^3 + c^3}$$

$$\phi_p = \frac{p^4}{K_{\mathrm{p}}^4 + p^4}$$

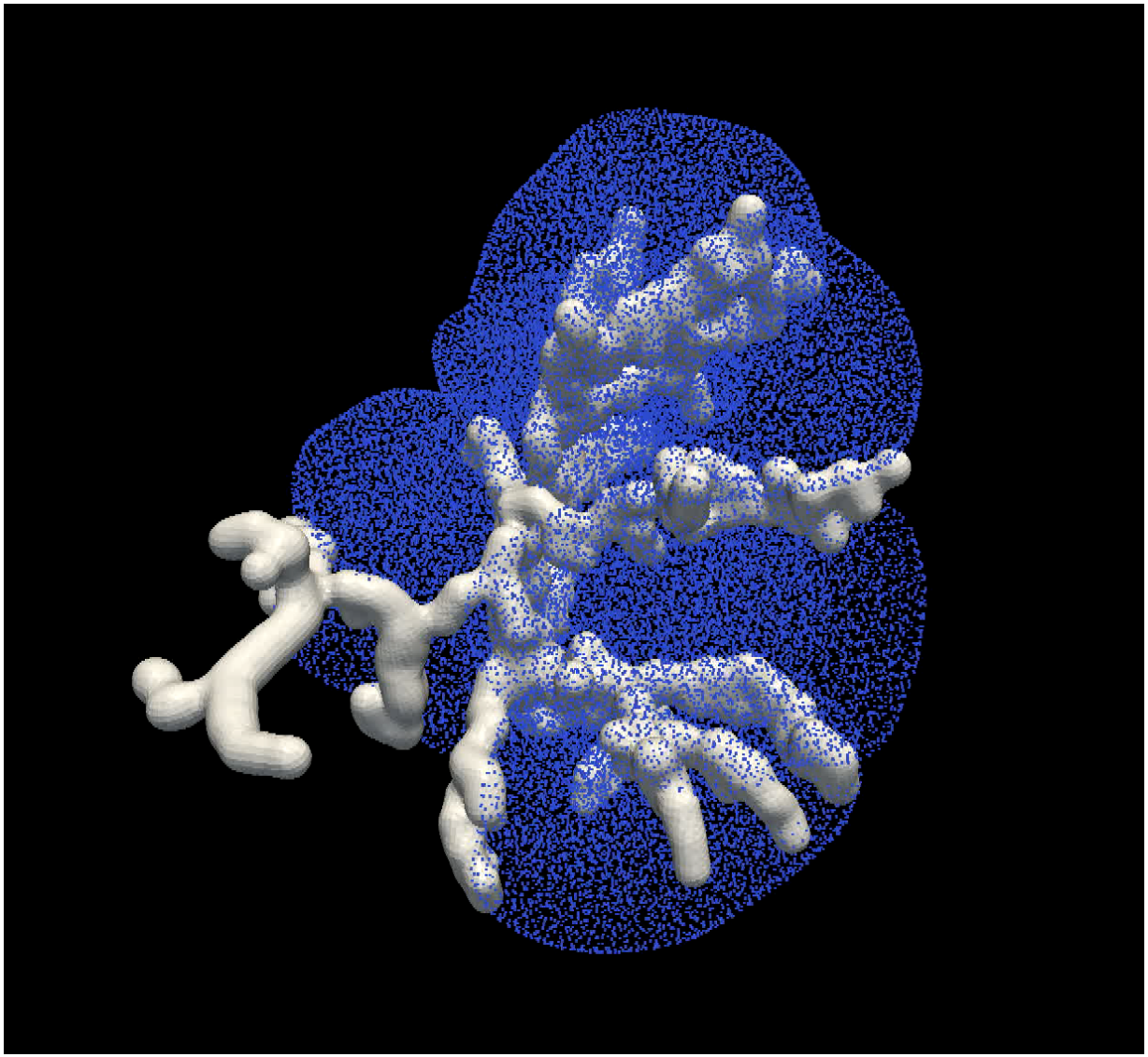
$$h_\infty = \frac{K_{\mathrm{i}}^2}{K_{\mathrm{i}}^2 + c^2}$$

$$c_{\mathrm{e}} = (c_{\mathrm{t}} - c)/\gamma$$

J. Sneyd, S. Means

FEM Simulation Results

Calcium waves



Wave-fronts propagate between the apical and basal ends of each cell.

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What's next?

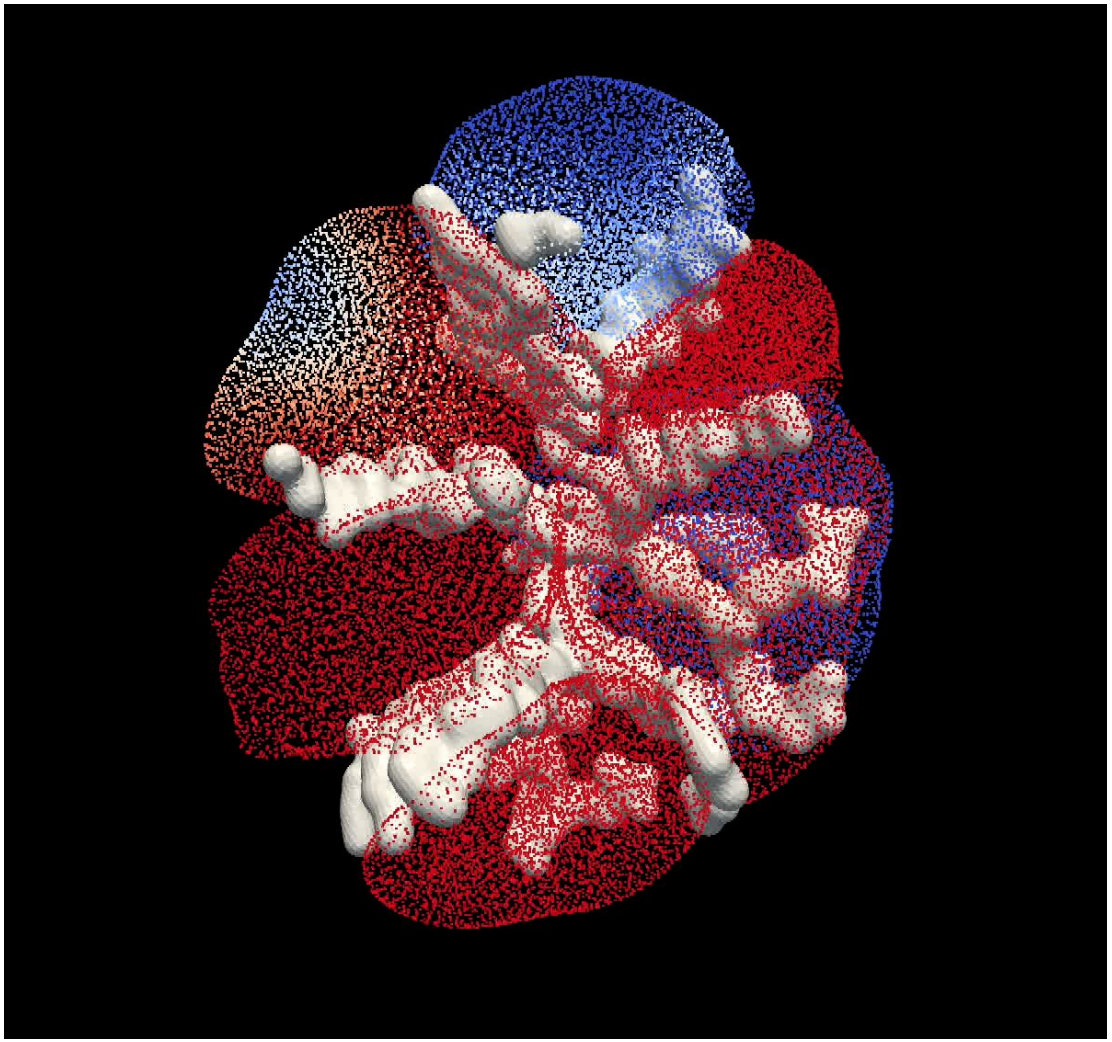
- Model and simulate interaction between cells (i.e. gap junctions)

- Include fluid flow in lumen (computational fluid dynamics)

- Scale up to a larger number of cells

More to come…

Questions & Answers?



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