Simulating Blood Flow and Mass Transport in the Rabbit Aorta.

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Nektar++ Workshop 2015

Why simulate blood flow?

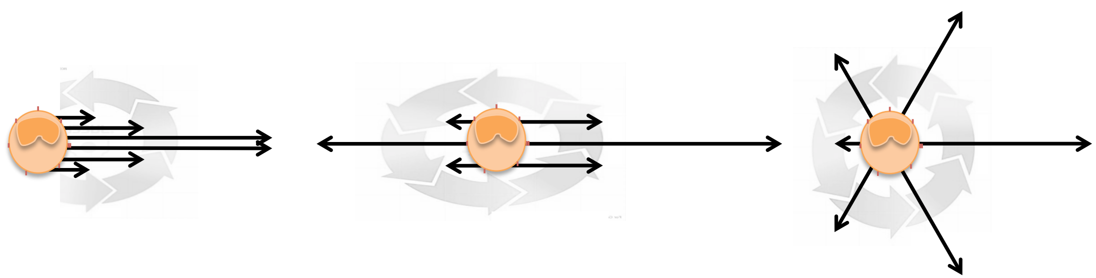
- Atherosclerosis: disease characterized by the progressive narrowing and hardening of the arterial wall due to a build of fatty plaques.

- Focal nature: has a predilection for areas of branching and curvature

- Blood flow dynamics are critical
  - Mechanical forces on the wall (shear stress)
  - Flow-dependent mass transport of particles in the blood involved in the initiation of the disease: LDL (low density lipoprotein)

Re-evaluation of current consensus

- Low/oscillatory shear theory currently underlies most research into localising factors.
- Challenge: age-related change in disease in rabbits and humans.
- Recent studies casting doubts on the robustness and strength of this theory.



	Purely forward flow	Pulsatile flow with reversal	Multi-directional disturbed flow
TAWSS:	2.5	2.5	2.5
OSI:	0	0.367	0.367
TransWSS:	0	0	1.1547

Transverse wall shear stress

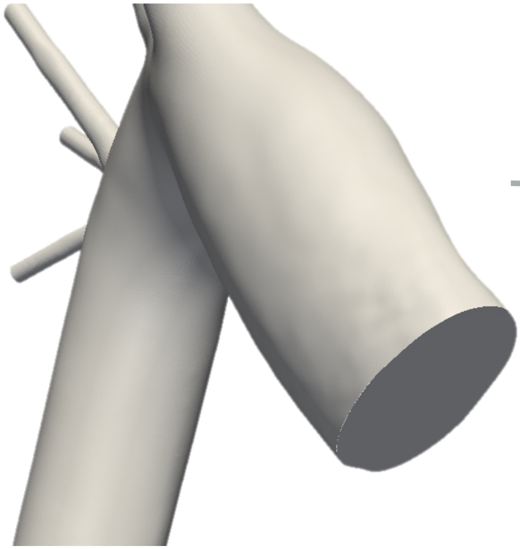
= the time-average of wall shear stress components perpendicular to the mean flow direction [2].

Meshing

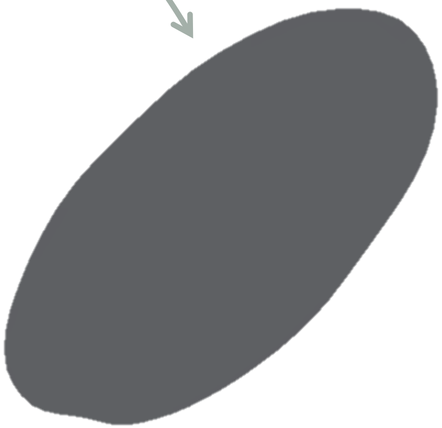
- Volume meshing in Starccm+
  - Curvature dependent surface triangulation.
  - Extrude surface inwards creating a prism layer to capture the boundary layer
  - Fill remaining volume with tetrahedral elements.

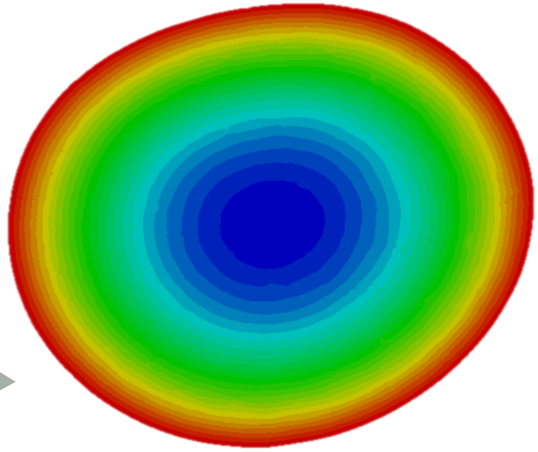
- Nektar++ MeshConvert utility
  - *spherigon* module
  - Curves surface elements using SPHERIGON patches

Dirichlet Boundary Conditions



MeshConvert
extract & detect





ADRSolver - Poisson eqn
or
FieldConvert *interppointdatatofld*

Outflow Boundary Condition

- Influx of kinetic energy at outflow due to waveform
- Apply an absorption layer – Forcing function: *Absorption*
  - A region immediately upstream of outflow boundary specified
  - Damping momentum forcing function added to the NS eqn: $F = -D_p(\mathbf{u} - \mathbf{u}|_{\delta\Omega})$

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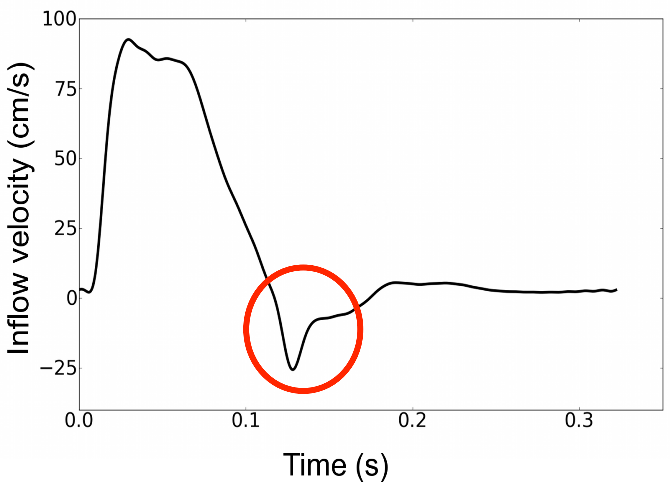
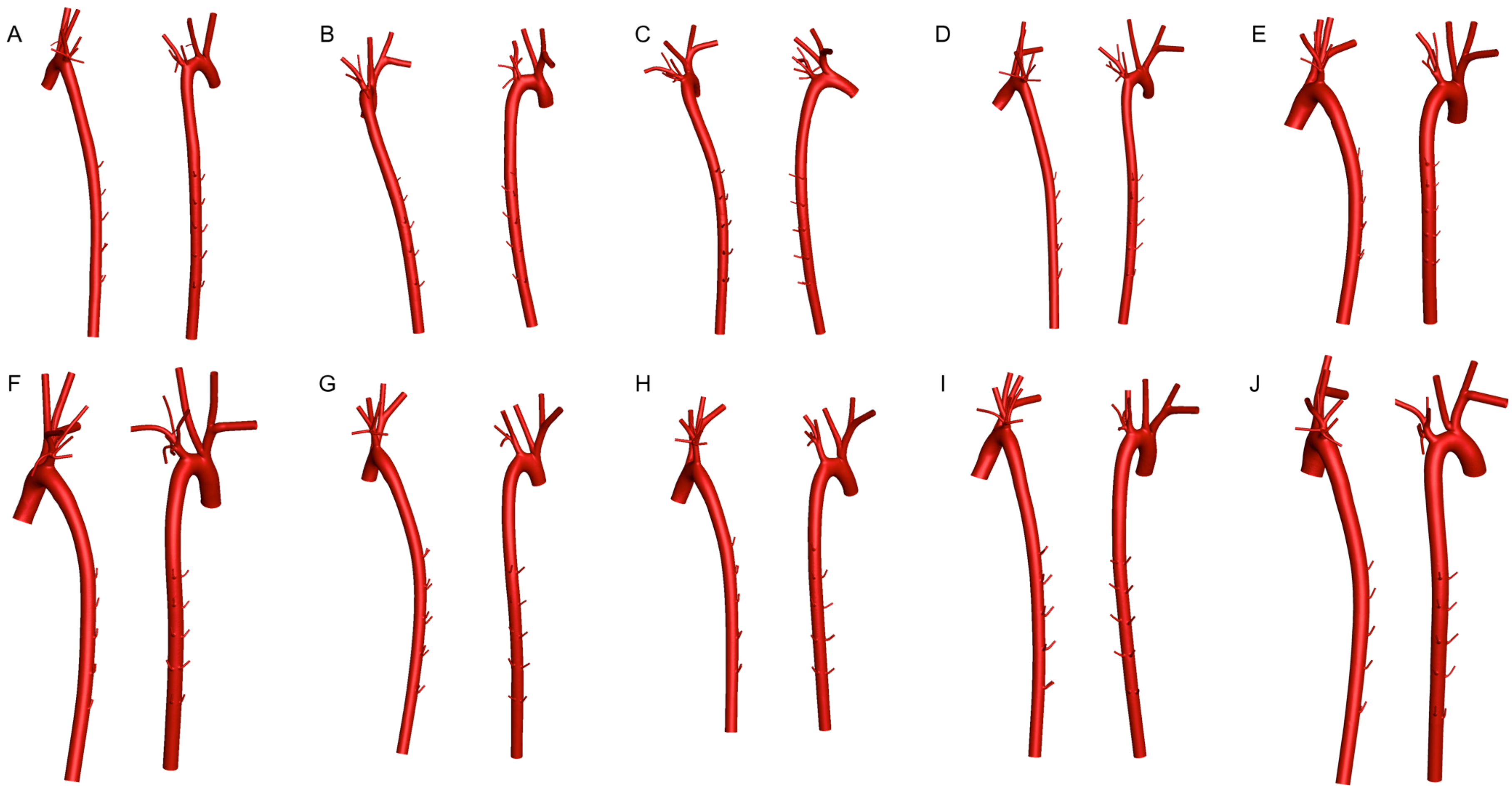


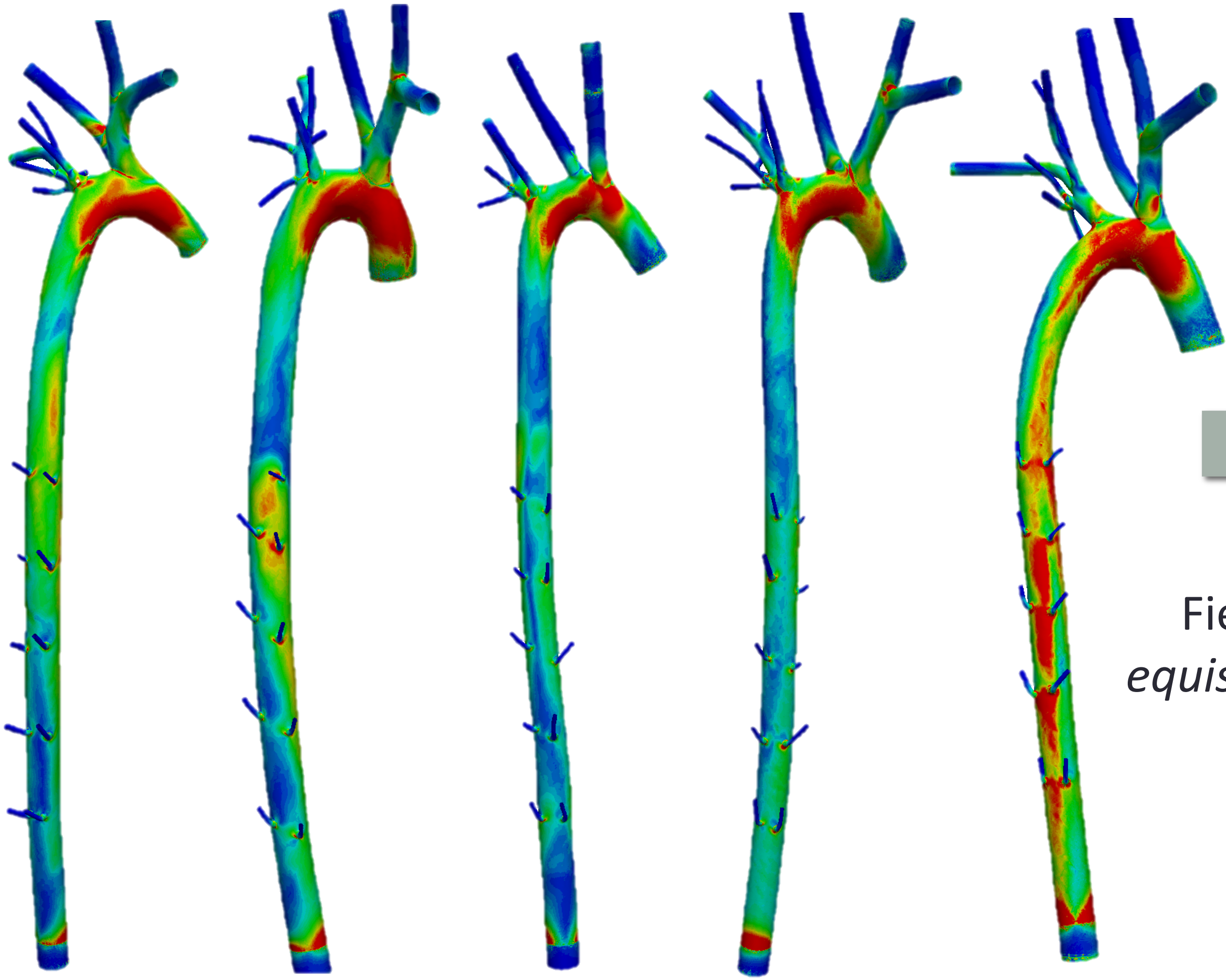
Rabbit Geometries



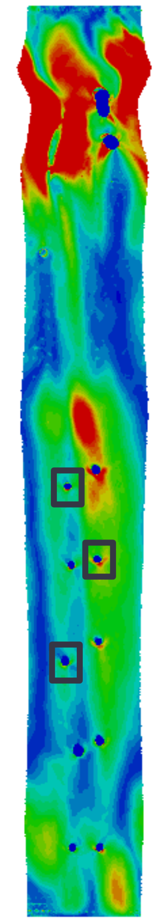
Simulation Details

- ~ 150k elements (35k prisms, 115k tets) -> ~ 50M linear mesh.
- Re_{in} = 300, Wo = 4.
- Solver info:
  - Unsteady Navier-Stokes
  - Velocity correction scheme – decoupling pressure and velocity.
  - CG approach
  - Full linear space with low energy block preconditioner
  - Iterative solver tolerance = 1e-8
- Varying time-steps through-out cycle.
- ~ 24h per cycle using ~300 cores
- Iteration count per time-step:
  - p: 35
  - u,v,w: 8

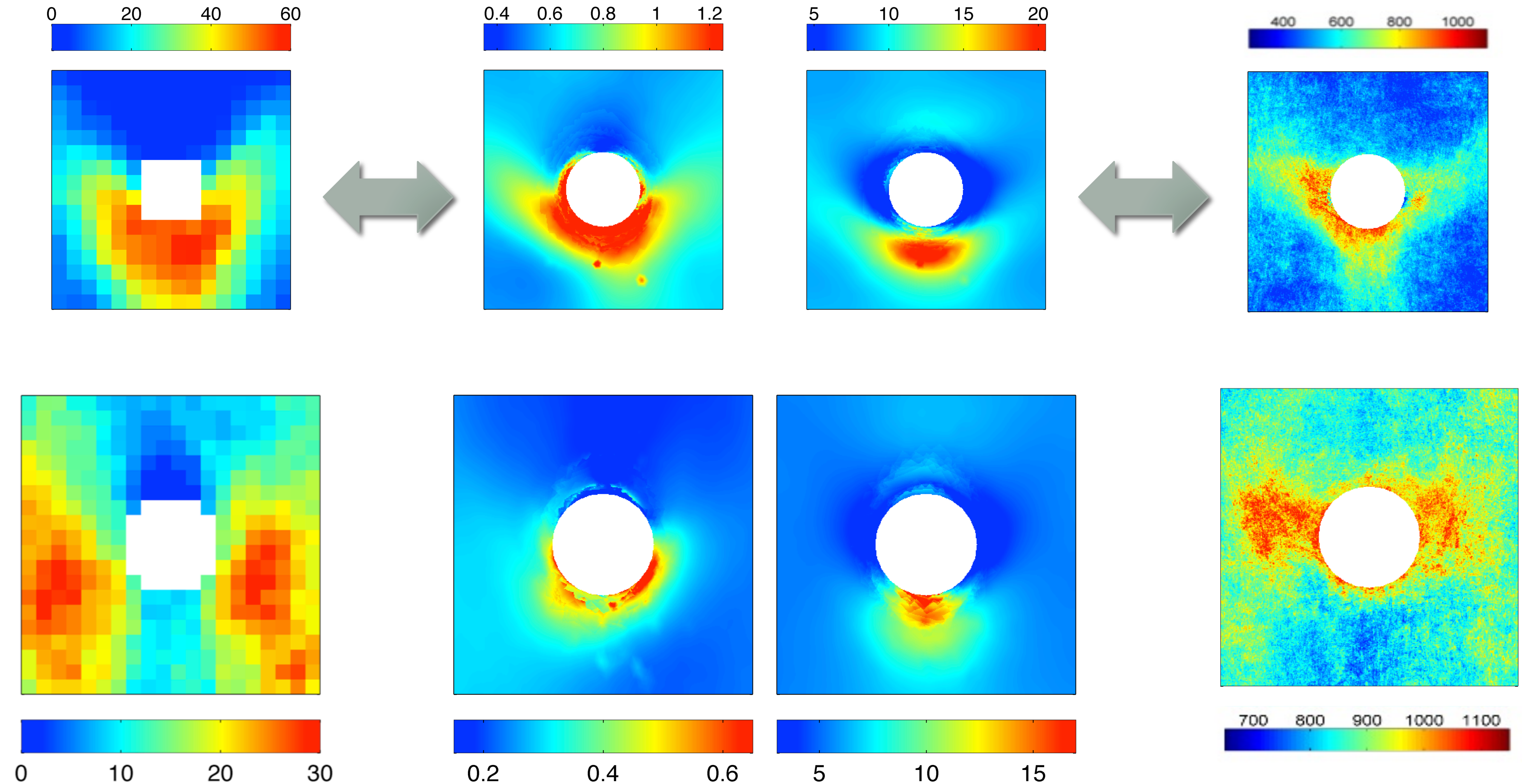
transWSS Patterns



FieldConvert
equispacedoutput
+
VMTK
+
Matlab



Lesions vs Shear Metrics vs Permeability



Lesion Prevalence (%)

transWSS (Pa) Novel Metric

TAWSS (Pa)

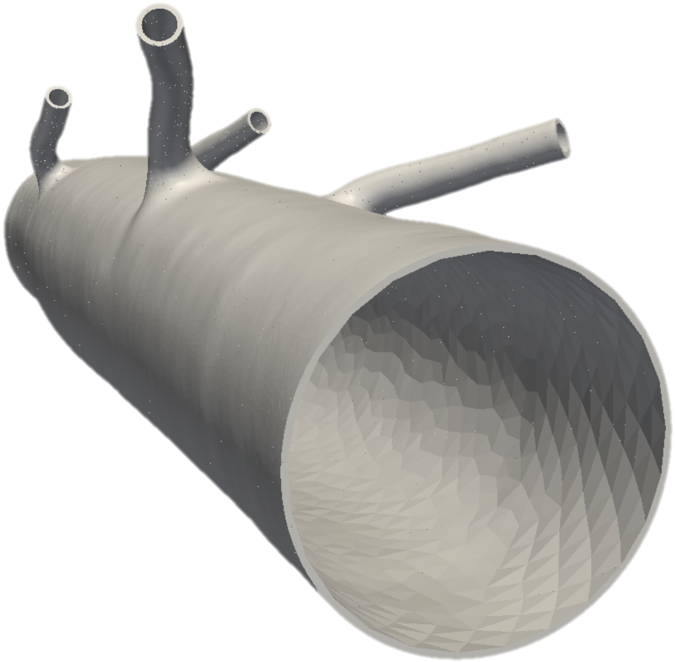
Permeability (fluorescent units)

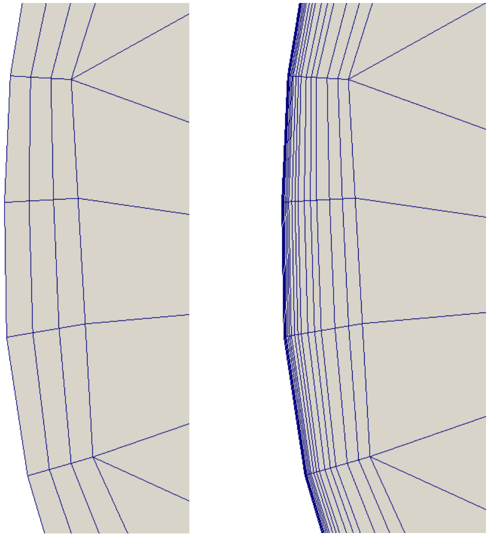
Mass transport of LDL

- MeshConvert *bl* – boundary layer splitter to refine prism bl.
  - Diffusion coefficient O(10^{-12}). Transport is advection dominated
    -> very fine boundary layer.

- MeshConvert *extracttetprism* – remove tets, extract interface between tets and prisms (interior surface)
  - feature/extract-ptinterface

- FieldConvert *interpfield* – NS solution interpolated to modified mesh as input for the *AdvectionVelocity* function





Simulation Details

- Pe = 2×10^8
- Solver info:
  - Unsteady Advection Diffusion
  - Continuous Galerkin projection
  - Full linear space with low energy block preconditioner
- Steady-state boundary conditions
- On-going work – robin BC to capture water transport across the wall.

Thank you