A Multiphysics Model of O_2 Transport and Recirculation During Venovenous Extracorporeal Life Support

Steven Conrad, MD PhD

Louisiana State University Health Sciences Center
Shreveport, Louisiana

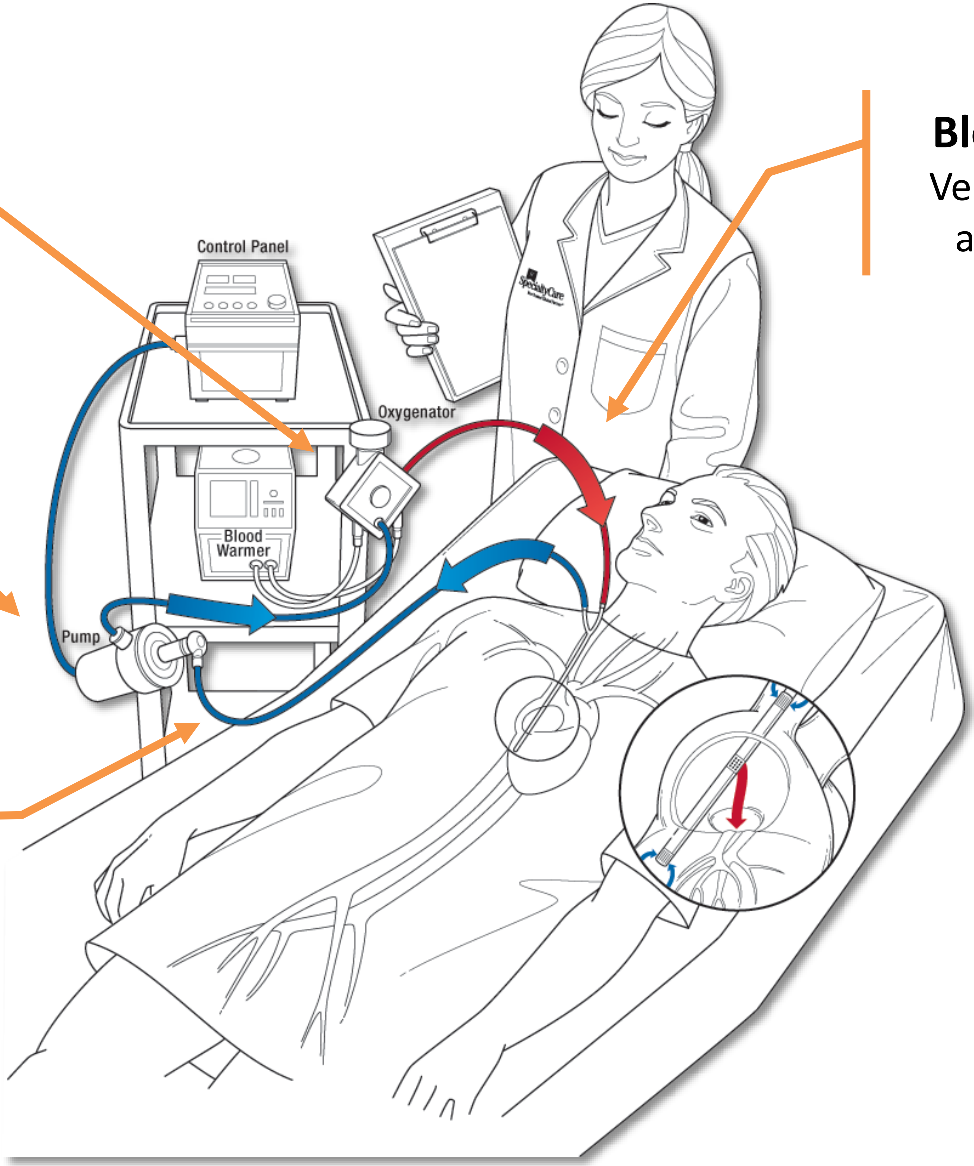
COMSOL CONFERENCE 2017 BOSTON

Extracorporeal life support (ECLS)

Gas exchange
Oxygen and CO_2

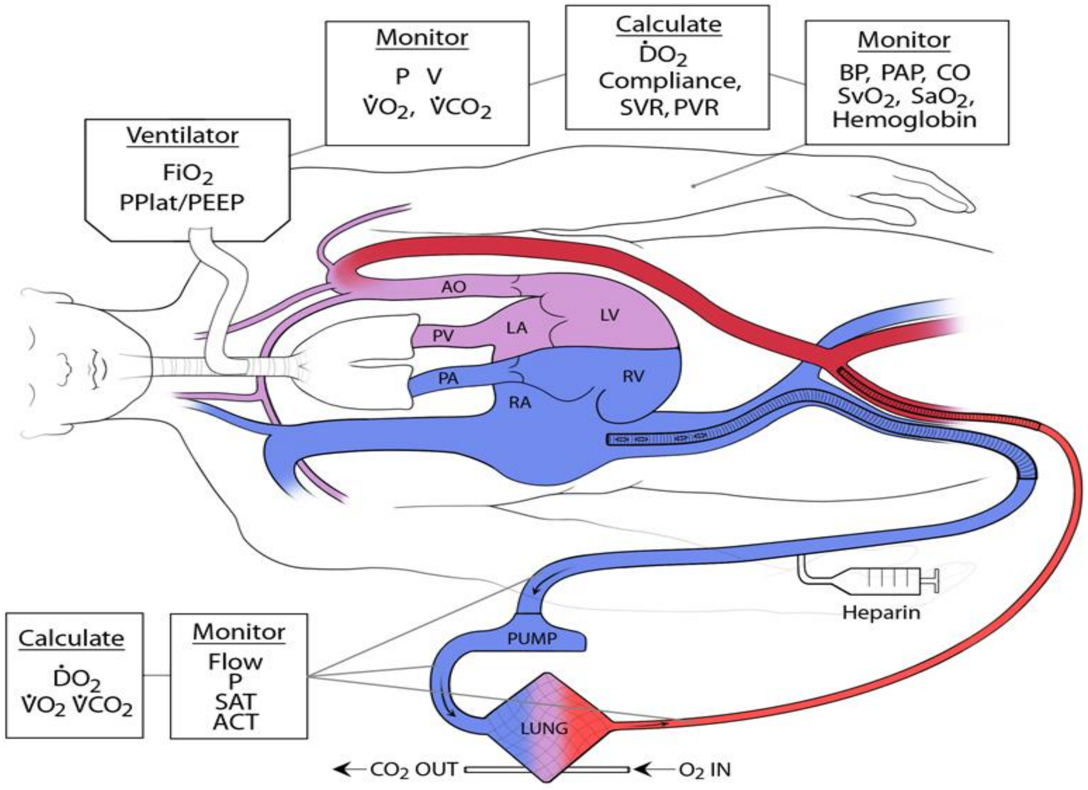
Pump-driven flow
Centrifugal

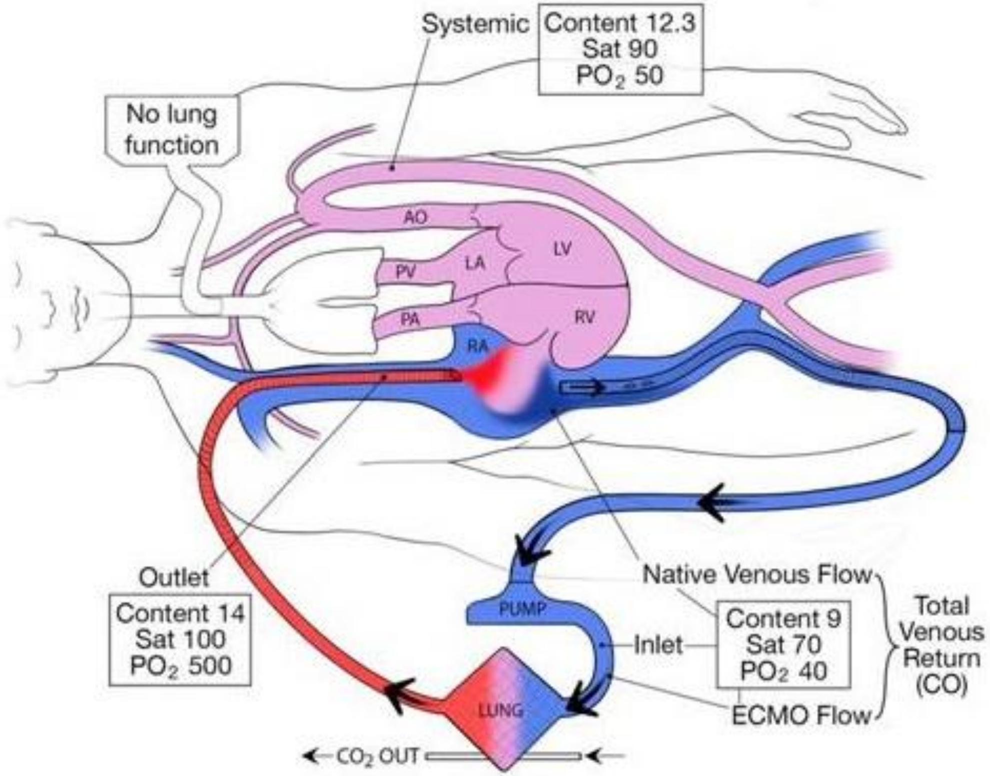
Venous drainage
Central circulation



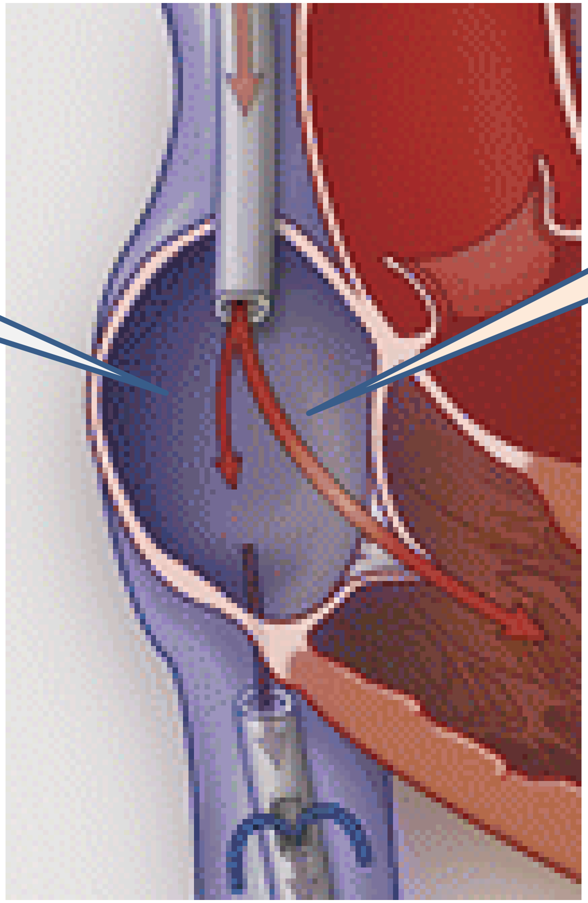
Blood return
Venous (VV) or arterial (VA)

Venoarterial vs. venovenous ECLS





Cannulation and recirculation in venovenous ECLS

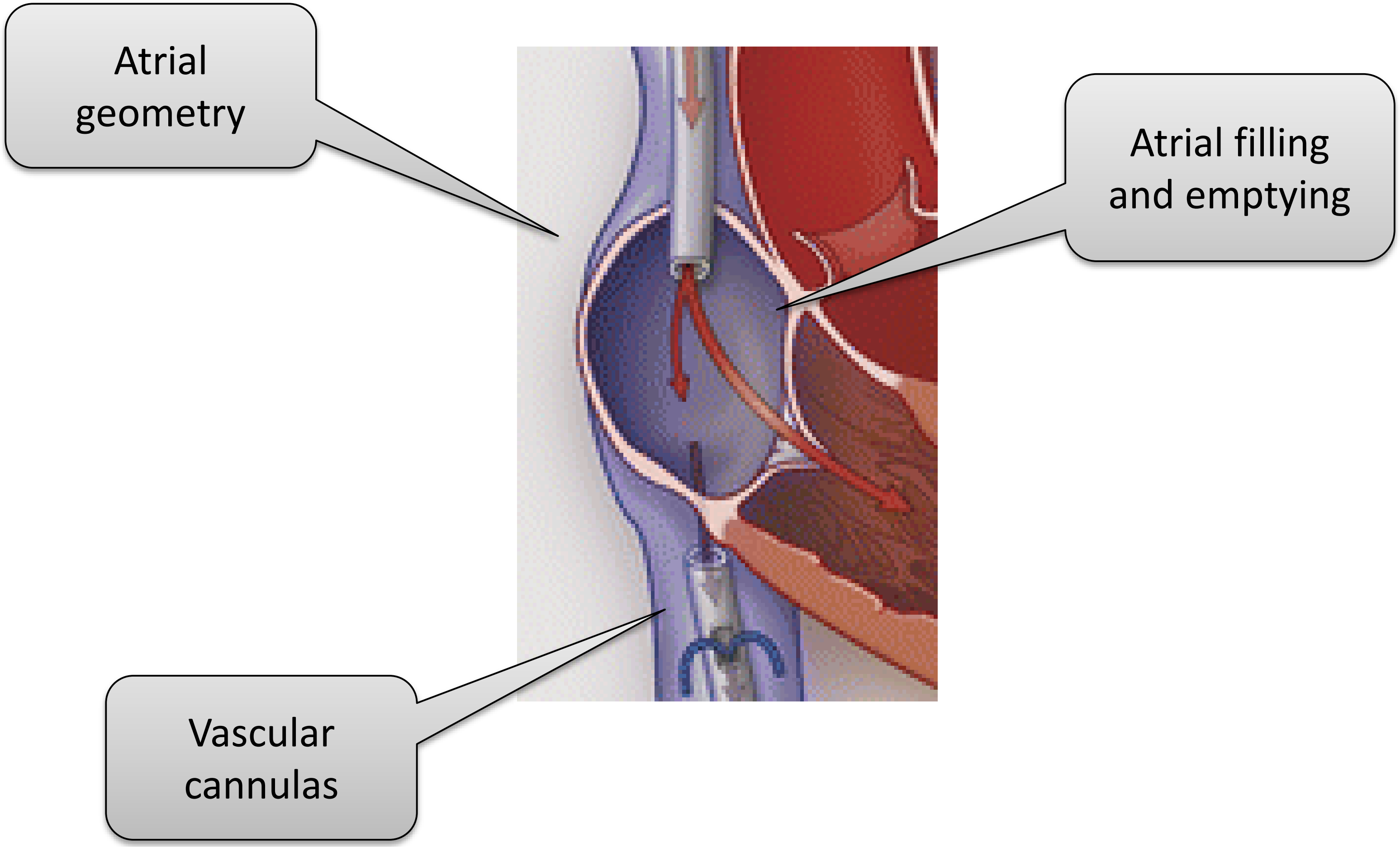


Recirculation factors

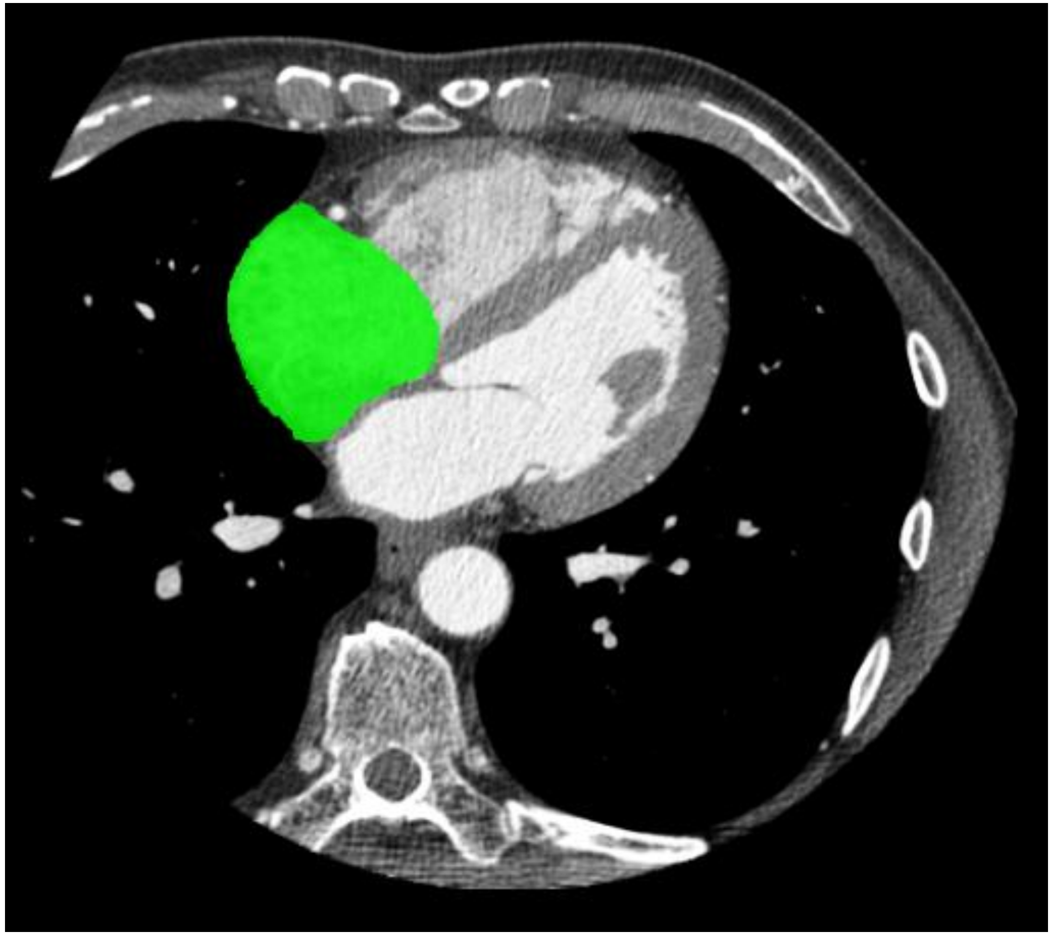
- Cannula design
- Cannula placement
- Relative flow rates

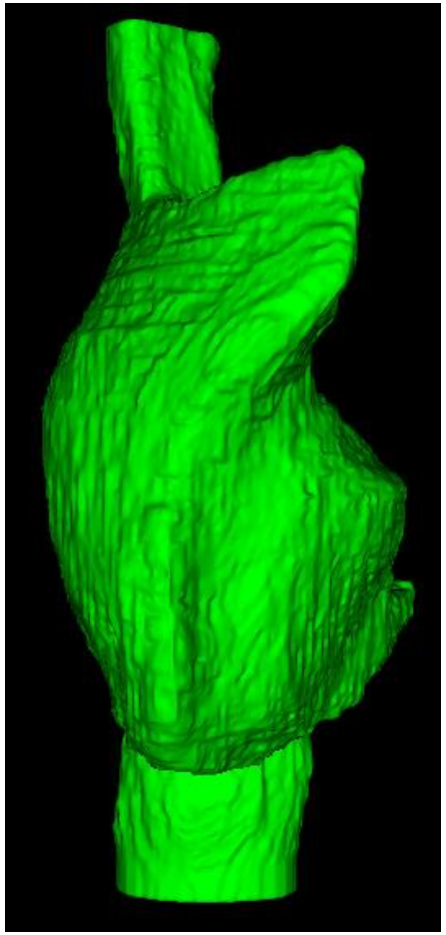
Objective – develop a multiphysics model of blood flow and recirculation to systematically study these factors

Design considerations



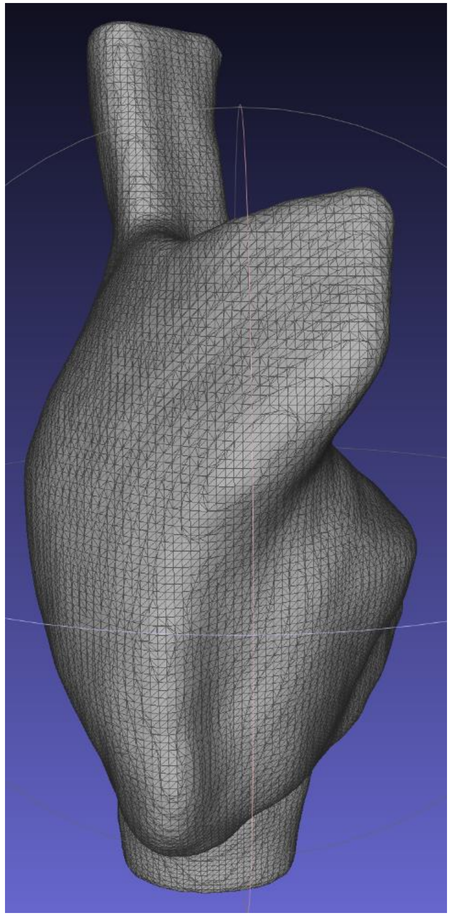
Solid geometry construction

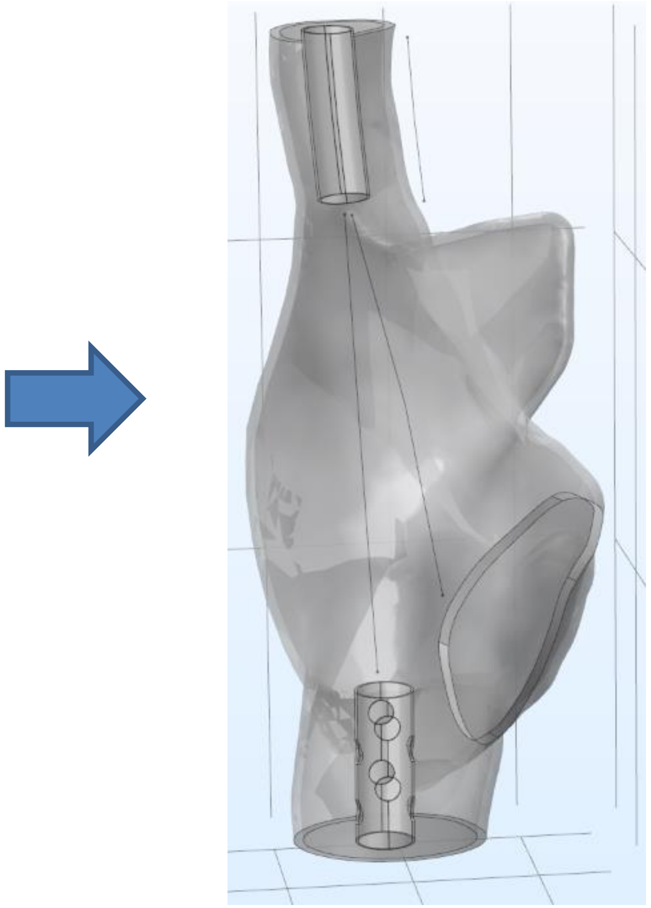




The right atrial geometry was obtained by 3D surface reconstruction of slices from a contrast CT of the chest using InVesalius (Renato Archer IT Center, Campinas, Brazil).

Geometry shelling and import

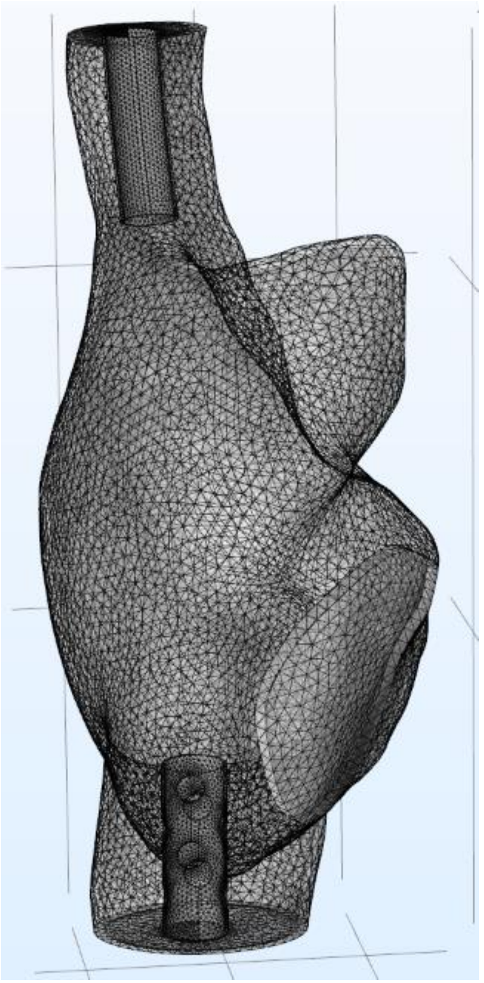




The surface mesh was smoothed, resampled, and shelled with a 2 mm offset using MeshLab (ISTI-CNR, Pisa, Italy), exported to STL, and imported into COMSOL® v5.3 to create the solid geometry consisting of vascular and atrial walls with an interior blood domain.

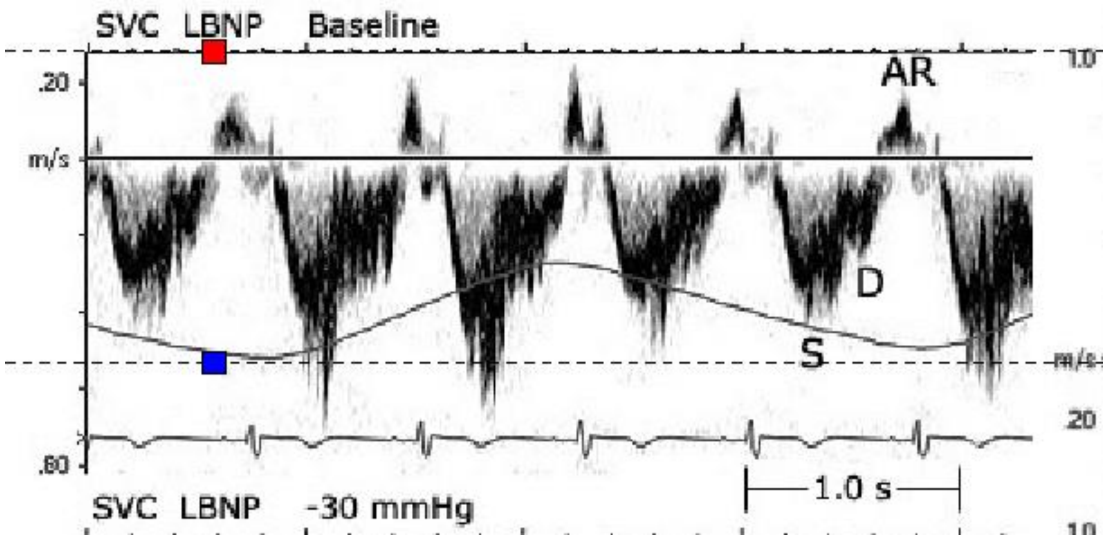
The tricuspid valve (TV) orifice and cannulas in the vena cavae were added using COMSOL® geometry features.

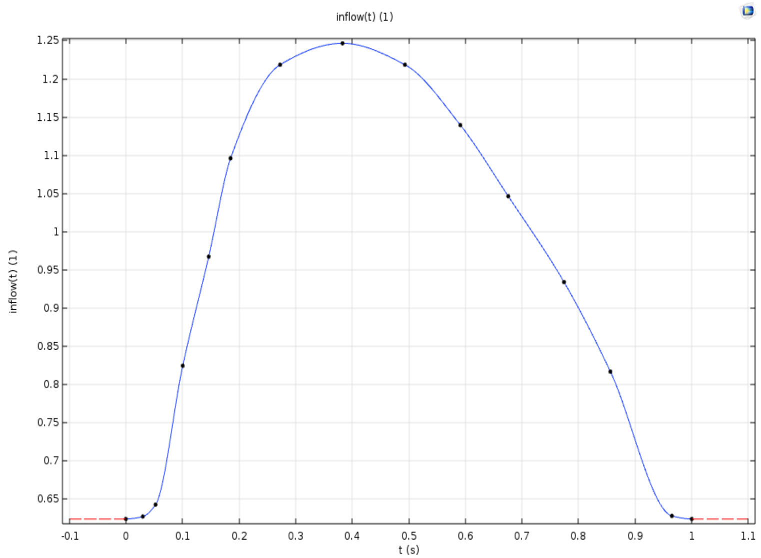
Meshing



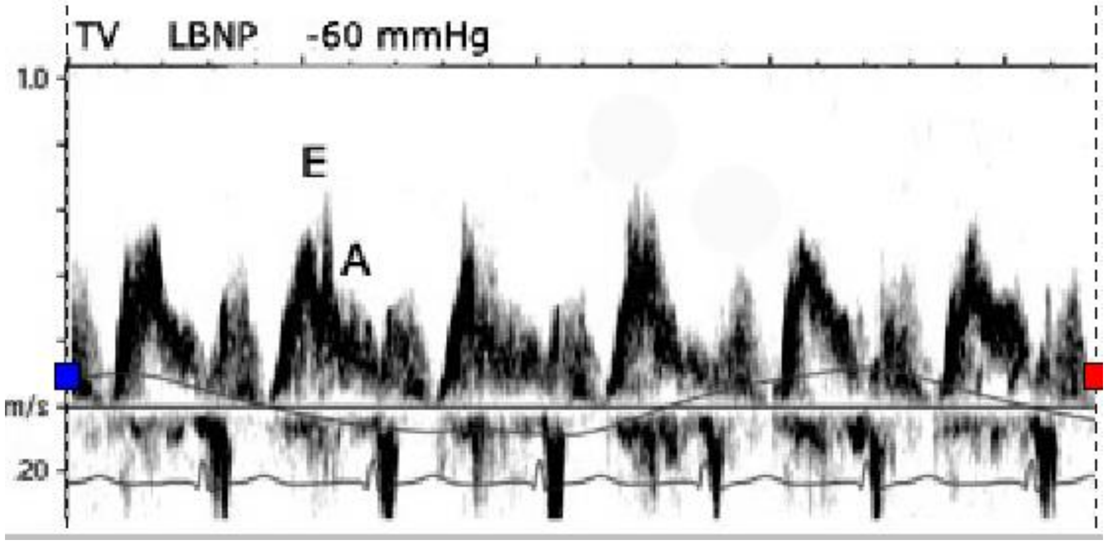
The geometry was meshed with approximately 500,000 tetrahedral elements sized appropriate to localized flow velocity.

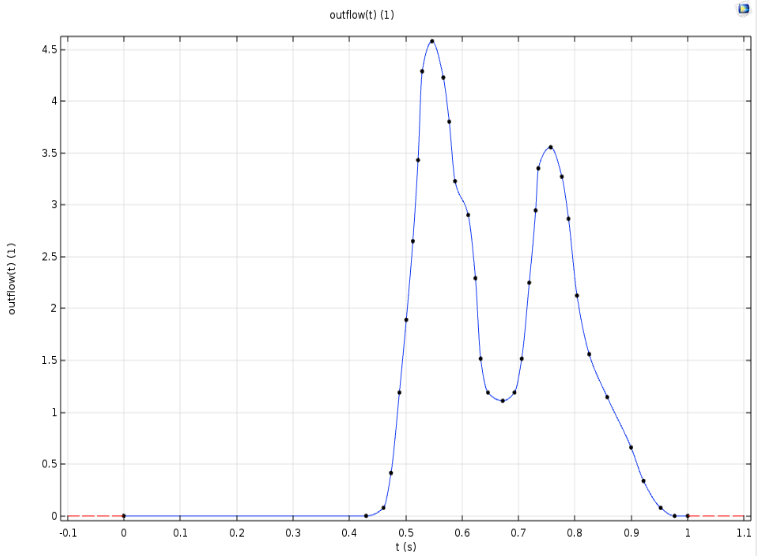
Boundary conditions – SVC/IVC inflow and TV outflow





Laminar inflow inlet condition





Velocity outlet condition with parabolic profile using Poisson equation

FSI interface material properties

Parameter	*Value*	*Units*
Blood density	1000	kg/m^3
Blood dynamic viscosity	0.003	Pa·s
Atrial wall density	1060	kg/m^3
Atrial wall Young’s modulus	0.2	MPa
Atrial wall Poisson ratio	0.45	-

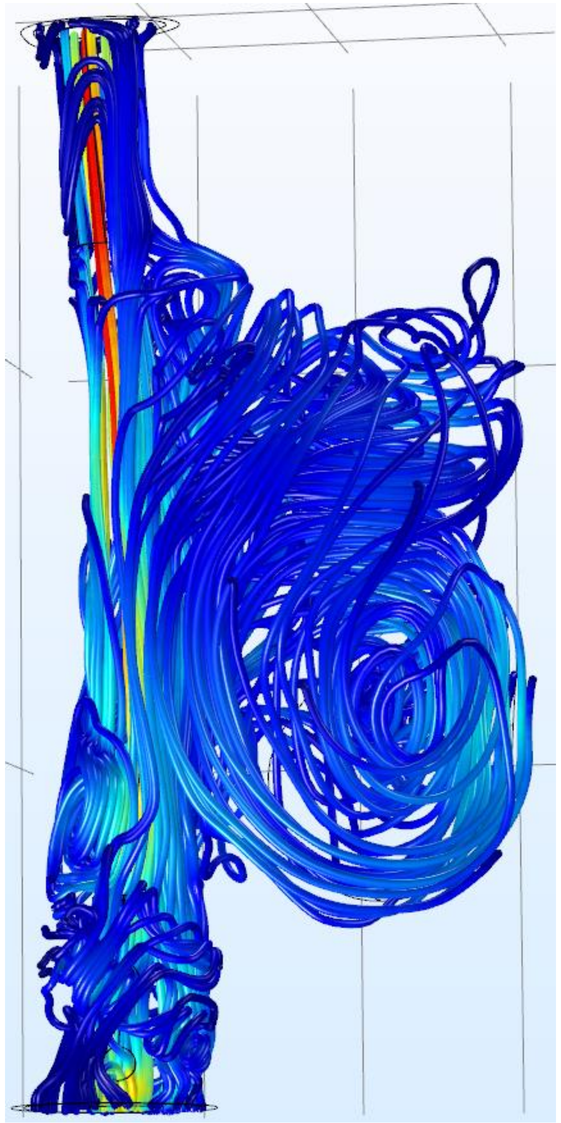
Solution

- Fully coupled direct solver
- MUMPS linear system solver
- $2x10^6$ DOF
- BDF time-stepping
- Time intervals limited to constrain CFL number:

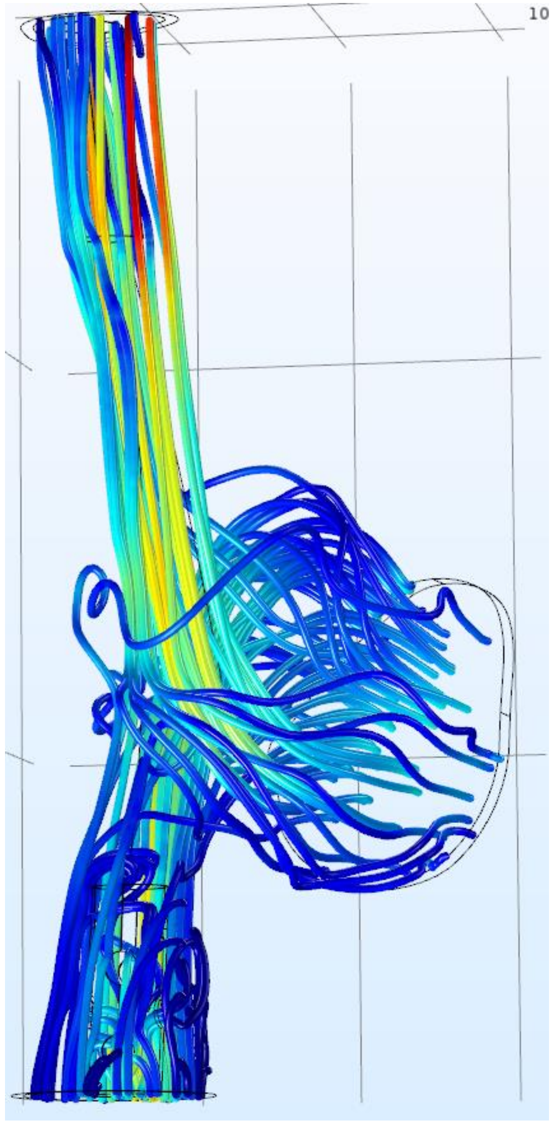
$$\frac{u\Delta t}{\Delta x} \leq 1$$

Velocity streamline patterns

Ventricular systole
(tricuspid valve closed)

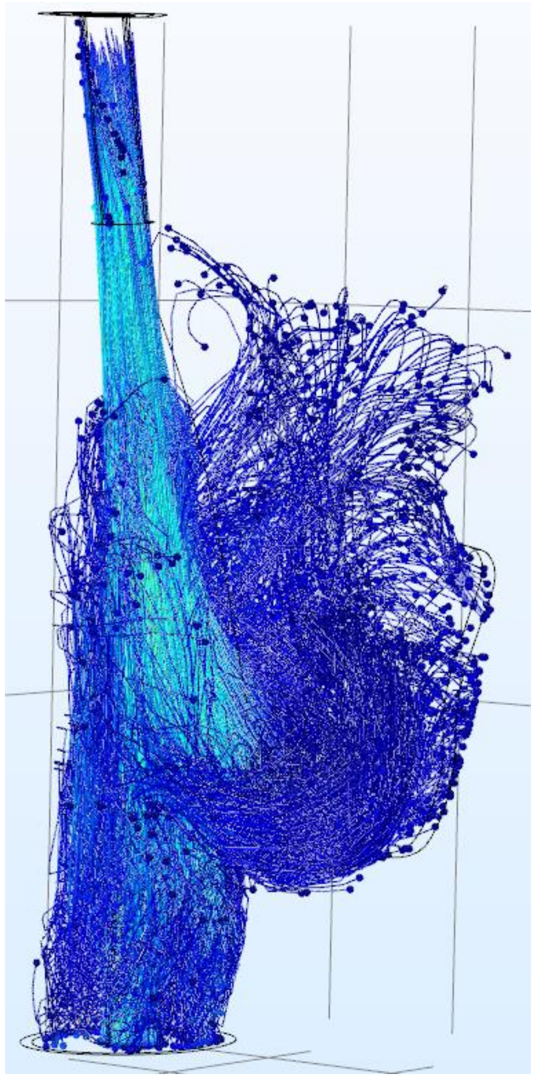


Ventricular diastole
(tricuspid valve open)



Calculation of recirculation

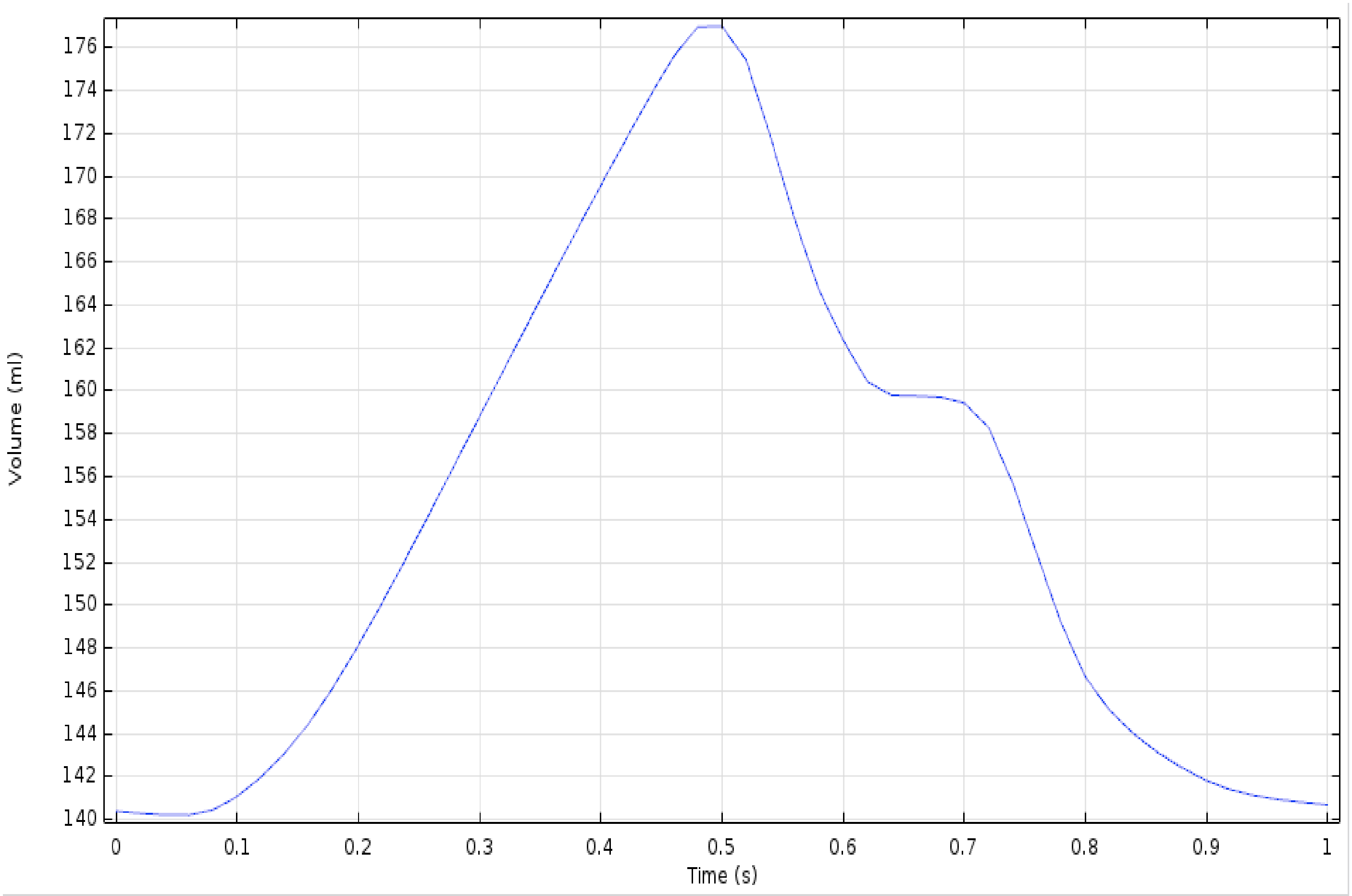
- Particle tracing used to represent oxygenated blood in the reinfusion cannula
- High Péclet number (10^7 – 10^8) precluded use of the convection-diffusion equation for oxygen transport
- 2000 massless particles injected into the reinfusion cannula
- Exit boundaries at tricuspid valve and drainage cannula
- Particle counter placed at the drainage cannula
- Recirculation determined as the transmission probability through the drainage cannula



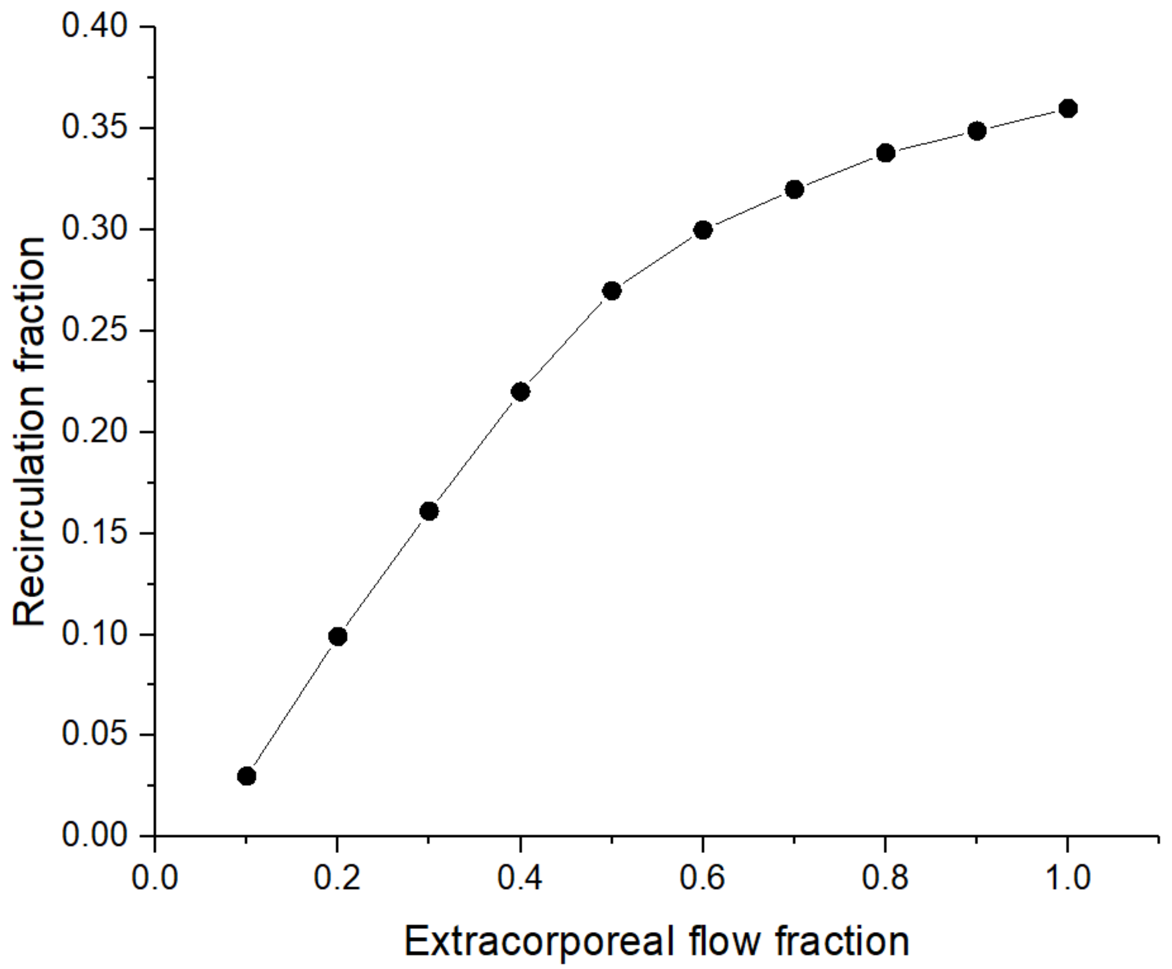
Results – atrial filling over cardiac cycle

CO: 3 L·min^{-1}
HR: 60 min^{-1}

Deformation plot



Results – recirculation as a function of circuit flow



- Cardiac output 5 L/min
- Extracorporeal flow varied 0.5 to 5 L/min
  - Extracorporeal flow fraction 0.1 to 1.0

$$EFF = \frac{Q_{ECLS}}{CO}$$

  - Data consistent with reported recirculation rates under similar conditions

Summary

- A model of extracorporeal circulation to incorporate CT-based patient anatomy
- FSI coupled with physiologic boundary conditions provided a realistic geometric domain for fluid flow studies
- Particle tracing permitted the calculation of recirculation in the face of extremely high Péclet numbers

Acknowledgments

- John Dunec
- Siva Sashank Tholeti
- Angela Straccia