A Multiphysics Model of O2 Transport and Recirculation During Venovenous Extracorporeal Life Support

S. A. Conrad
Louisiana State University Health Sciences Center, Shreveport, LA, USA

Introduction: Extracorporeal life support (ECLS) is a technique to provide cardiopulmonary support with an extracorporeal circuit consisting of a blood pump and artificial lung. Venovenous ECLS, used for respiratory support, typically drains blood from a cannula in the inferior vena cava and returns it to a cannula in the superior vena cava. Since both cannulas are in the venous system, some of the returned blood is drained and recirculated (Figure 1), reducing efficiency. A number of factors can influence recirculation, including flow rate and cardiac output as well as cannula design and position. To better understand these factors, a 3D multiphysics model of the vena cavae and right atrium was developed.

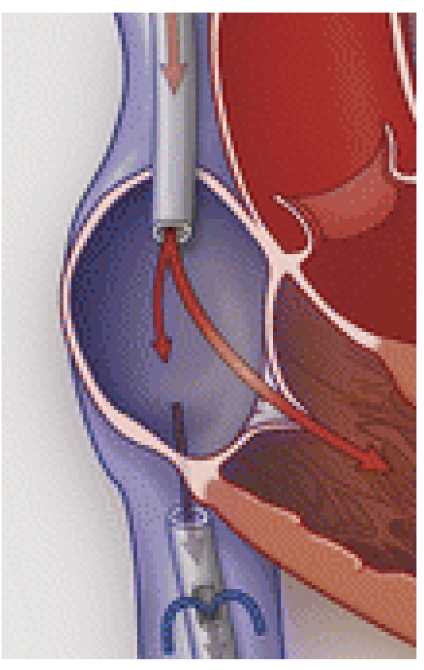

Figure 1. Cannulas and blood flow during VV ECLS

Computational Methods: A multiphysics model of the right atrium (RA) and the vena cavae was constructed that included FSI, CFD and particle tracing components. The RA geometry was obtained by 3D surface reconstruction of slices from a contrast CT of the chest using InVesalius (Renato Archer IT Center, Campinas, Brazil). 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 and an interior blood domain. The tricuspid valve (TV) orifice and cannulas in the vena cavae were added using COMSOL® geometry features.

Linear elastic solid mechanics FSI physics was included, with the solid component represented by the atrial wall, the fluid component represented by blood, and the solid-fluid interface at the inner atrial wall. Since oxygen transport was greatly dominated by convection (Péclet number approximately 10^8), particle tracing was used for calculation of recirculation. Boundary conditions included vena cavae inflow and tricuspid outflow specified as velocity profiles obtained from echocardiographic studies to simulate normal right atrial contraction, relaxation and TV opening.

The geometry was meshed with approximately 500,000 elements sized appropriate to localized flow velocity. Fluid flow was solved with the Navier-Stokes equations, and fluid-structure interaction using the solid mechanics FSI physics interface. Massless particle transport was one-way coupled to velocity. Sequential cardiac cycles were solved. Model parameters are given in Table 1.

Parameter	*Value*	*Units*
Blood density	1000	kg/m³
Blood dynamic viscosity	0.003	Pa·s
Atrial wall density	1060	kg/m³
Atrial wall Young's modulus	0.2	MPa
Atrial wall Poisson ratio	0.45	-

Table 1. Model parameters

Results: RA deformation and volume change due to systole and diastole during the cardiac cycle was well represented (Figures 2 and 3).

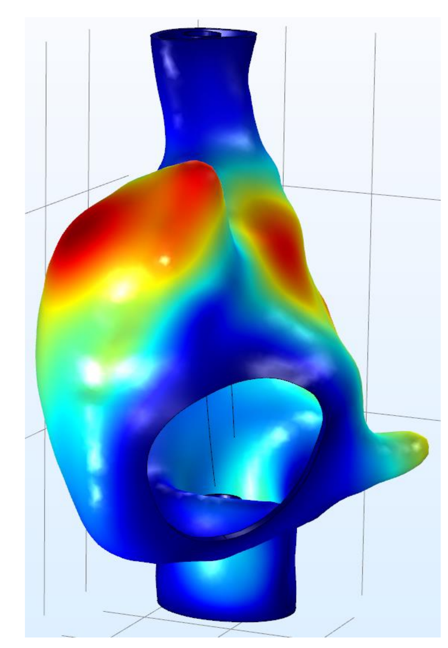

Figure 2. Atrial deformation

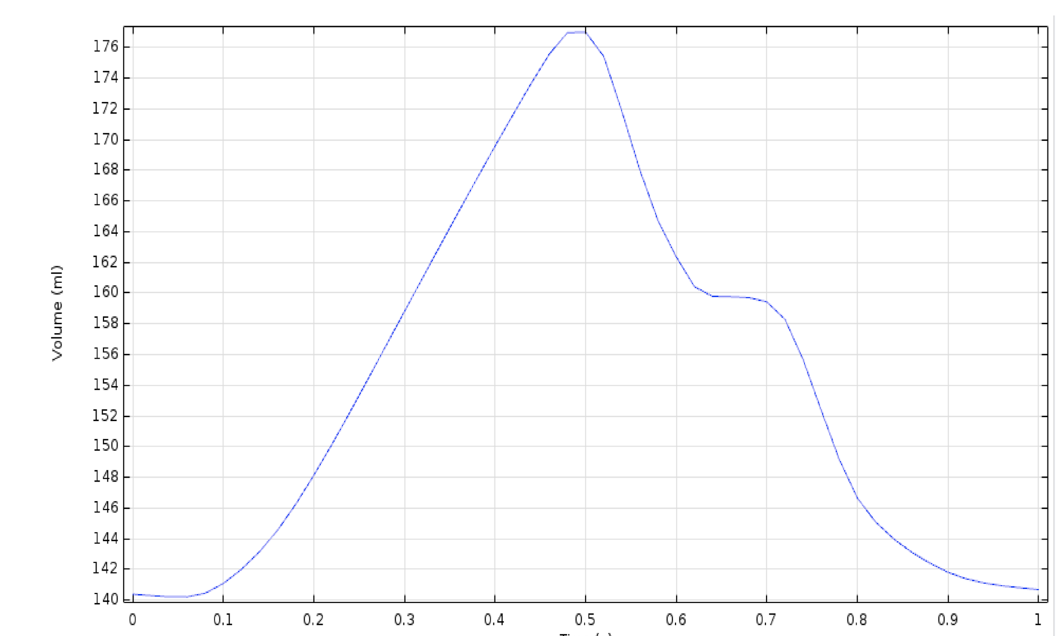

Figure 3. Atrial volume change

Flow patterns in the atrium during ECLS were found to be complex (Figure 4), and not previously described in the literature. Tracing particles for oxygen were released from the inflow cannula over one cardiac cycle (Figure 5), and a particle counter was attached to the drainage cannula outflow. Recirculation was calculated as the transmission probability at the drainage cannula outflow. As an example, at cardiac output of 5 L/min and circuit flow of 4.5 L/min, recirculation was 34.6%.

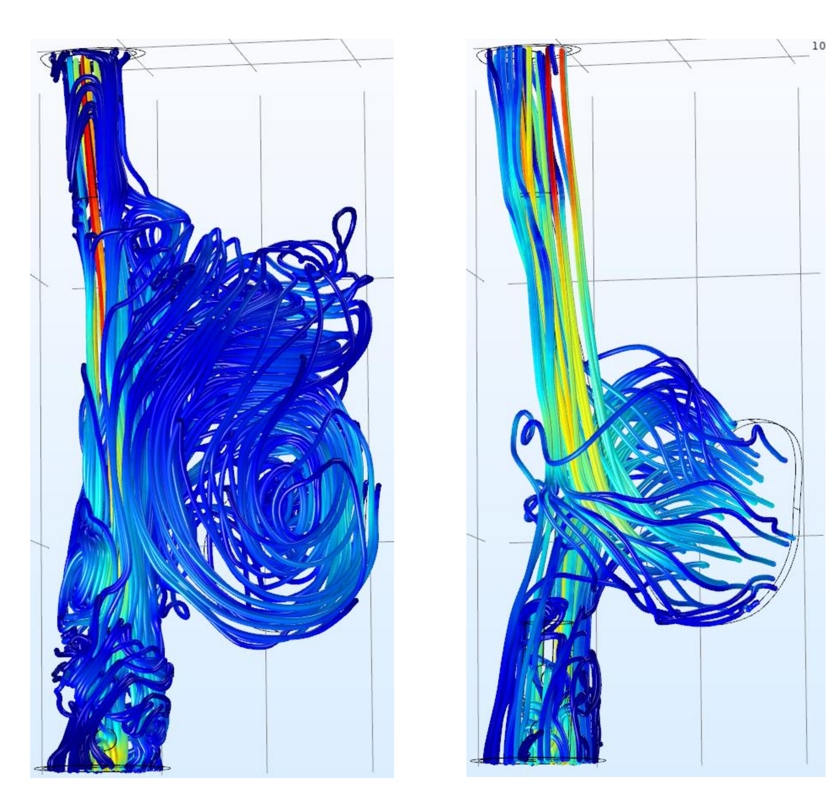

Figure 4. Velocity streamlines in ventricular systole and diastole

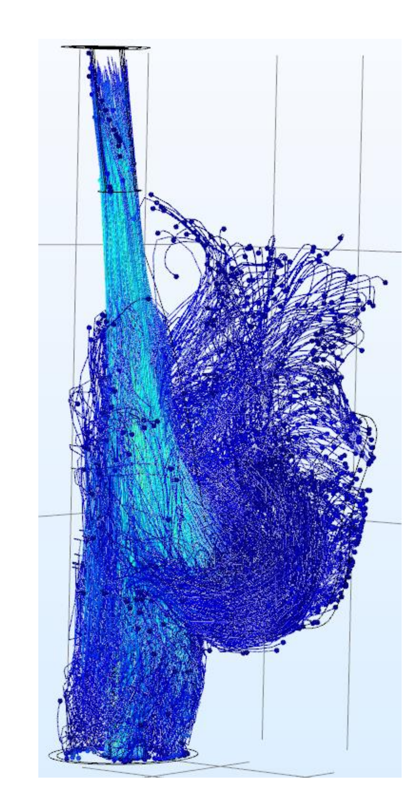

Figure 5. Particle trajectories early after release

Conclusions: This FSI model of the RA during VV ECLS appropriately represents atrial blood flow and contraction/relaxation. Particle tracing allowed calculation of recirculation fraction at very high Péclet numbers. Future studies will target configurations to optimize clinical application of VV ECLS.