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

S. Conrad[1]

[1]Louisiana State University Health Sciences Center, Shreveport, LA, USA

Abstract

Venovenous extracorporeal life support (VV-ECLS) provides gas exchange support for severe lung failure by using an extracorporeal circuit consisting of a blood pump and an artificial membrane lung. Blood is withdrawn from a cannula placed into the inferior vena cava, and returned from the circuit into the superior vena cava, adding oxygen to and removing carbon dioxide from the venous blood. Since both cannulas are in the central venous system, some of the oxygenated blood returned to the venous system is aspirated by the drainage cannula, resulting in recirculation of oxygenated blood and reducing the effectiveness of ECLS. This project aims to systematically study recirculation and the factors contributing to it such as cannula position, ECLS blood flow rates and cardiac parameters to better predict and potentially minimize it.

A multiphysics model of the right atrium (RA) and the vena cavae was constructed that included FSI, CFD and mass transport components. The RA geometry was obtained by 3D surface reconstruction from slices from a contrast CT of the chest using InVesalius (Renato Archer Information Technology Center, Campinas SP, Brazil). The surface mesh was smoothed, resampled, and shelled with a 2mm offset using MeshLab (ISTI-CNR, Pisa, Italy), exported to STL, and imported into COMSOL® v5.3 to create the solid geometry consisting of a vascular and atrial walls and an interior blood domain. Cannulas in the vena cavae were created using COMSOL® geometry features.

Linear solid mechanics FSI physics was included, with the solid component represented by the atrial wall (Young's modulus 0.2 MPa) and the fluid component represented by blood with solid-fluid interface at the inner atrial wall. Convection/diffusion physics was added to represent oxygen content of blood (as oxygen saturation). Mass transport was dominated by convection. Boundary conditions included atrial inflow and tricuspid outflow specified as velocity profiles obtained from echocardiographic studies to simulate normal right atrial chamber contraction, relaxation and tricuspid valve opening. Recirculation fraction was computed using the formula (SdO_2 - SvO_2)/(SrO_2 - SvO_2) where subscripts represent d = drainage, r = reinfusion, and v = mixed venous saturations. SvO_2 was calculated from the vena cavae saturations weighted by the respective flow.

The geometry was meshed with approximately 500,000 elements. Fluid flow was solved with the Navier-Stokes equations, and fluid-structure interaction using the solid mechanics FSI physics interface. Mass transport was coupled to velocity. The direct, fully-coupled MUMPS solver was used. One cardiac cycle was solved to establish initial

conditions for the following cardiac cycle, which used for calculations. Flow and oxygen transport are one-way coupled, so fluid flow was solved first then oxygen transport was solved.

The model simulated atrial function appropriately. Volume and pressure curves of the right atrium matched physiologic conditions, and flow patterns reflected atrial contraction and relaxation. Test solutions supported the feasibility of recirculation fraction calculation. The model will be used for a systematic study of recirculation under a variety of clinical operating conditions.