Online Supplement

Appendix – Flow Anatomy of the TCPC Pathways

Following is a series of plates detailing the flow fields for each patient geometry studied. The flow conditions are labeled as follows: “MRI” for the baseline flow condition measured by MRI through-plane velocity mapping, “EX-2” for the total caval flow of 2x baseline exercise condition, and “EX-3” for the 3x baseline exercise condition. All plots are for the MRI-measured pulmonary flow splits.

There are three types of plots presented:

Streamline plots show the tangents to the velocity vectors for flow through the TCPC. As these are steady-state simulations, they can be viewed as the path of a blood cell originating from a given place on the boundary of the caval vessels as it travels through the TCPC. IVC streamlines are color coded in red and orange, right SVC in blue and green, and left SVC in purple and pink. Azygous vein flow exists in one model, Chop20, and is color coded with light blue and green.

Pressure surface contour plots color encode hydrostatic pressure at the geometry surface. All scales shown are in mmHg and go from a high pressure encoded in red of 0 mmHg, to a negative low pressure encoded in blue in order to graphically display the pressure drop distribution through the geometry. Arrows in any of these plots correspond to the blood flow direction.

Finally, the power dissipation plots color encode volumetric power dissipation in units of mW/dm³. Some plots are shown for a plane through the geometry superimposed on the complete geometry. These plots also show the velocity vectors for that plane. Other geometries are better illustrated with surface dissipation plots, since for some models with less flow collision, most dissipation occurs at the vessel walls.

We believe these plates add significant value to the research presented here, allowing visualization of a wide variety of patient geometries at different physiologic flow conditions representing rest and different levels of exercise. They effectively illustrate the variety of flow patterns in TCPC geometries and their effect on power dissipation.

Despite the variety of geometries presented, themes recur: 1) IVC baffle and LPA narrowings that dissipate little power at baseline flows may be sources of significant power loss at increased flows, 2) flow collision between SVC and IVC flows can be a significant source of power loss and usually increases significantly with increasing power loss, 3) increased skewing of the IVC flow toward the LPA wall in exercise flow conditions results in higher power loss. These phenomena underscore the importance of studying exercise flows in order to fully characterize the TCPC geometry.
PLATE 1 Intra-cardiac TCPC with diffuse LPA hypoplasia, CHOP*18. Flow through all three main RPA branches are also simulated and displayed here due to their proximity to the TCPC (A) SVC flow prefers the RPA upper lobe (B) A posterior view illustrates how the IVC flow is distributed in the connection to both lungs (good hepatic flow mixing). (C) IVC flow dominates the posterior TCPC wall and recirculates into the SVC at exercise. (D) Dissipation source shed from the baffle wall due to jet-like IVC flow. (E) Complex RPA flow between IVC-SVC generating internal hydrodynamic dissipation. (F) Moderate LPA stenosis pressure drop.
PLATE 2 Intra-atrial with azygous vein continuation, CHOP20. (A) Recirculation due to sudden area change close to the IVC inlet. (B) Azygous inflow dominates the connection proximal to the RPA. (C) It also opposes the hepatic vein baffle (hvb) inflow, deflecting it anteriorly. (D) SVC flow finds its way deep into the hvb anastomosis at the highest CO. (E) High pressure drop at the hvb narrowing. (F) Pressure increase due to stagnating hvb inflow. (G) Dissipation source along the SVC-hvb shear layer. (H) Dissipation source due to squeezed hvb stream and azygous shear layers.
PLATE 3 Bilateral SVC with a large cambered intra-atrial conduit and end-to-side anastomosis proximal to the LSVC, CHOP22. (A) RSVC preferentially streams to RPA at all conditions. (B) Relatively stagnant region only IVC flow. (C) Considerable mixing of LSVC with IVC at the pouch. (D) Large recirculation region of LSVC pouch is more pronounced (contributed by increased IVC flow) at exercise. (E) IVC flow penetrates into LSVC – even at the resting condition. (F) At rest connection pressure is more uniform but at exercise gradients become more apparent. (G) Dissipation source type-I, squeezed IVC flow at the posterior wall. (H) Dissipation source type-II, complex shear layers of LSVC-IVC mixing.
PLATE 4 A typical intra-cardiac TCPC with mild LPA hypoplasia, CHOP25. (A) SVC prefers RPA, similar to CHOP18. (B) Model has a small pouch posterior to IVC (not shown) helps to distribute IVC blood uniformly. (C) Line of reattachment, very high recirculation of the IVC blood (D) Relatively uniform pressure distribution in the connection at low cardiac outputs. (E) An almost 90 degree bend in LPA, contributing to pressure drop. (F) High internal hydrodynamic dissipation source due to emerging IVC flow.
PLATE 5 Intra-cardiac TCPC, CHOP30. (A) IVC flow diverted anteriorly. (B) Small recirculation region at LPA due to irregularities. (C) IVC flow penetrates into SVC, making a posterior turn. (D) Dissipation source originating from the shear layer between colliding IVC and SVC flows. (E) Jet-like IVC flow due to sudden area increase sheds a concentrated dissipative sheet. (F) Quieter flow at the resting condition with minimal internal hydrodynamic power loss.
PLATE 6 Intra-atrial IVC baffle with mild narrowing, mild proximal LPA stenosis, CHOP31. (A) IVC flow with increasing penetrance into SVC with increasing flow rate. (B) Increasing pressure drop at IVC and LPA. (C) Dissipation source caused by shear layer from colliding SVC and IVC flow – minimal at rest, significant at exercise conditions. (D) Dissipation source due to IVC pinching, also mild at rest but significant at exercise. (E) Dissipation source due to LPA narrowing partially seen in this plane.
PLATE 7 Bilateral SVC’s with straight IVC baffle anastomosis proximal to RSVC, CHOP32. (A) IVC flow stagnates and bifurcates into two swirls. (B) L-R SVC preferential to L-R PA’s respectively; slight mixing occurs at high CO, see I. (C) Surface dissipation source at RPA due to squeezed flow towards cephalic direction. (D) Dissipation source due to IVC stream that goes to LPA without circulating. (E) Dissipation source due to circulating IVC flow. (F) Dissipation source due to area change. (J) Sudden pressure drop just downstream of LPA and RPA, associated with turning (G to I) Looking from posterior, illustrates levels of bilateral SVC flow mixing and stagnation.
PLATE 8 Extra-cardiac TCPC with an unusual large caval offset, CHOP33. (A) Severe stenosis causing very high pressure drop which increase drastically with exercise (~20x at EX-3) In no other model is the increase in pressure drop that severe. (B) Stenosis between the cavae restricts IVC flow, largely separating the two flows. (C) IVC blood goes posterior and swirls before going through the stenosis towards the LPA. (D) SVC flow is almost exclusively directed to the LPA. (D,E) SVC flow shifted even more towards LPA with the increasing IVC flow during leg exercise. (F) Recirculation due to turning flow upstream of stenosis, becomes chaotic at the highest CO condition. (G) As observed in other models, IVC still prefers to go deep into the SVC and recirculates before going to the LPA - lesser in the resting condition. (H) Increasing dissipation sources from rest to exercise.
PLATE 9 TCPC (intra-cardiac) with LPA diameter considerably larger than the RPA, CHOP34. (A) Recirculation due to sudden area change close to the IVC inlet. (B) Azygous inflow dominates the connection proximal to the RPA. (C) It also opposes the IVC inflow deflecting it towards the anterior. (D) SVC flow finds its way deep in to the IVC anastomosis at the highest CO. (E) Pressure drop at the IVC narrowing. (F) Pressure increase due to stagnating IVC inflow. (G) Dissipation source along the SVC-IVC shear layer. (H) Dissipation source due to squeezed IVC stream and azygous shear layers.
PLATE 10 Intra-cardiac TCPC with larger LPA than RPA, CHOP37. (A) Sharp SVC-IVC flow interface which is more diffuse with exercise (B) SVC flow prefers right lung, only at EX-2 there is slight flow towards the left lung (C) Another view looking from RPA shows the recirculating IVC flow in the pouch region; shape of recirculation changes from rest to exercise (D) Pressure drop at RPA. (E) Typical dissipation sources on the PA vessel walls due to squeezed flow in that region. (F) Internal sources of dissipation along an arbitrary cut.