Artificial Organs

Patient-Specific Atrial Hemodynamics of a Double Lumen Neonatal Cannula in Correct Caval Position

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Abstract: Clinical success of pediatric veno-venous (VV) extracorporeal membrane oxygenation (ECMO) is associated with the double lumen cannula cardiovascular device design as well as its anatomic orientation in the atrium. The positions of cannula ports with respect to the vena cavae and the tricuspid valve are believed to play a significant role on device hemodynamics. Despite various improvements in ECMO catheters, especially for the neonatal and congenital heart patients, it is still challenging to select a catalogue size that would fit to most patients optimally. In effect, the local unfavorable blood flow characteristics of the cannula would translate to an overall loss of efficiency of the ECMO circuit. In this study, the complex flow regime of a neonatal double lumen cannula, positioned in a patient-specific right atrium, is presented for the first time in literature. A pulsatile computational fluid dynamics (CFD) solver that is validated for cardiovascular device flow regimes was used to perform the detailed flow, oxygenated blood transport, and site-specific blood damage analysis using an integrated cannula and right atrium model. A standard 13Fr double lumen cannula was scanned using micro-CT, reconstructed and simulated under physiologic flow conditions. User defined scalar transport equations allowed the quantification of the mixing and convection of oxygenated and deoxygenated blood as well as blood residence times and hemolysis build-up. Site-specific CFD analysis provided key insight into the hemodynamic challenges encountered in cannula design and the associated intra-atrial flow patterns. Due to neonatal flow conditions, an ultra high velocity infusion jet emanated from the infusion port and created a zone of major recirculation in the atrium. This flow regime influenced the delivery of the oxygenated blood to the tricuspid valve. Elevated velocities and complex gradients resulted in higher wall shear stresses (WSS) particularly at the infusion port having the highest value followed by the aspiration hole closest to the drainage port. Our results show that, in a cannula that is perfectly oriented in the atrium, almost 38% of the oxygenated blood is lost to the atrial circulation while only half of the blood from inferior vena cava (IVC) can reach to the tricuspid valve. As such, approximately 6% of venous blood from superior vena cava (SVC) can be delivered to tricuspid. High values of hemolysis index were observed with blood damage encountered around infusion hole (0.025%). These results warrant further improvements in the cannula design to achieve optimal performance of ECMO and better patient outcomes. **Key Words:** Extracorporeal membrane oxygenation—Double lumen neonatal cannula—Blood residence time—Hemolysis index—Computational fluid dynamics.

Veno-venous (VV) double-lumen cannulation is desirable during extracorporeal membrane oxygenation (ECMO) for neonatal patients with severe respiratory failure (1). VV ECMO is associated with a high survival rate and low profile of complications. For neonatal patients with indications such as congenital diaphragmatic hernia (CDH), meconium aspiration syndrome (MAS), and persistent pulmonary hypertension of the newborn (PPHN), the use of ECMO has been increasing steadily in

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the last few decades (2,3). Neonatal patients, which constitute a subgroup, present the highest use of ECMO accounting for 40% of all ECMO cases (4). Although significant improvement in the ECMO technology has led to higher survival rates and better patient care, its widened use demands continuous improvement in the existing technology and its application for challenging subgroups such as neonates where appropriate oxygenation and size constraint become paramount.

The VV ECMO utilizes a double lumen cannula which obviates the need of using two separate cannulations as it allows single site access with additional important advantages such as improved patient mobilization, physical rehabilitation and allows pulmonary extubation. The cannula is one of the key components of the ECMO circuit. In terms of the blood flow in neonates, it can pose a paradoxical design challenge for the blood supply as it is solely responsible both for the delivery of the oxygenated blood and the extraction of desaturated blood from the patient in a very compact blood-wetted component. Thus, it is hypothesized that this component would have significant impact on the ECMO performance. Previous studies have focused on the performance of cannula mainly in terms of recirculation and oxygenation through in vivo experiments. For example, Rais-Bahrami et al. reported improved oxygenation and reduced recirculation in OriGen cannula in lambs (5). Qiu et al. investigated the hemodynamic evaluation of the bicaval dual lumen cannula where different sized Avalon cannulas were analyzed in vitro and their flow ranges were studied using human blood (6). Said et al. tested the newly developed VR13 cannula against the existing design in sheep and reported elevated levels of recirculation at high flow rates (7). In this study for the first-time in literature to our knowledge, the detailed hemodynamic performance evaluation of a standard double lumen cannula positioned in a patient-specific right atrium is presented. The atrial hemodynamics induced by the double lumen cannula received limited attention in literature, in spite of the fact that it is the basis of overall ECMO performance and holds paramount importance in the neonatal intensive care. In addition to its use as a medical device design tool to improve cannula performance (8), computational fluid dynamics (CFD) provides an alternative simulation platform providing a priori information about hemodynamic performance and valuable foresight into various situations encountered in clinical practice. Therefore, the objective of this study is to first develop a comprehensive CFD model that will address the complex double lumen cannula flow regimes and provide detailed hemodynamic performance evaluation using hemodynamic indices. Hemodynamic performance indices include, the cannula design, flow patterns, blood residence times, local and global blood damage as well as infusion and drainage efficacy of the cannula.

MATERIALS AND METHODS

A clinically approved 3D model of the standard double lumen cannula (13Fr Origen Biomedical, Austin, TX, USA) was scanned using micro-CT with a resolution of 150 microns (NewTom 5G scanner, QR Verona, Verona, Italy). Due to its ability to resolve structural features as small as a few micrometers in size, micro-CT is more advantageous than the conventional CT. 3D reconstruction of the right atrium including the tricuspid valve, superior vena cava (SVC) and inferior vena cava (IVC) was obtained from the IRB approved MRI data of a neonatal patient (age 3 months, height 50 cm, BSA 0.2 m^2) having normal atrial and venous anatomy, that was segmented using 3D Slicer software. Cannula was positioned in the 3D reconstructed right atrium using an anatomical editing tool in consultation with a neonatal intensive care unit cardiologist (1) (Fig. 1). The resulting

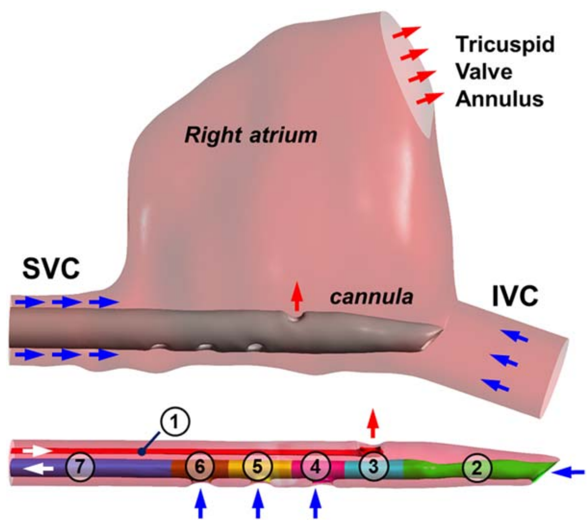

FIG. 1. Micro-CT scan of a 13Fr neonatal cannula oriented in normal position relative to a patient-specific right atrium anatomical reconstruction. SVC: Superior vena cava, IVC: Inferior vena cava. Bottom Figure shows the expanded view of the cannula where colored blood volumes indicate different site-specific analysis domains of the device. Each color refers to different flow domains represented by inflow and outflow arrow directions. Where ①: infusion duct, ②: cannula tip, ③: distal tip, ④: hole 1, ⑤: hole 2, ⑥: hole 3 and ⑦: drainage outlet. [Color figure can be viewed at wileyonlinelibrary.com]

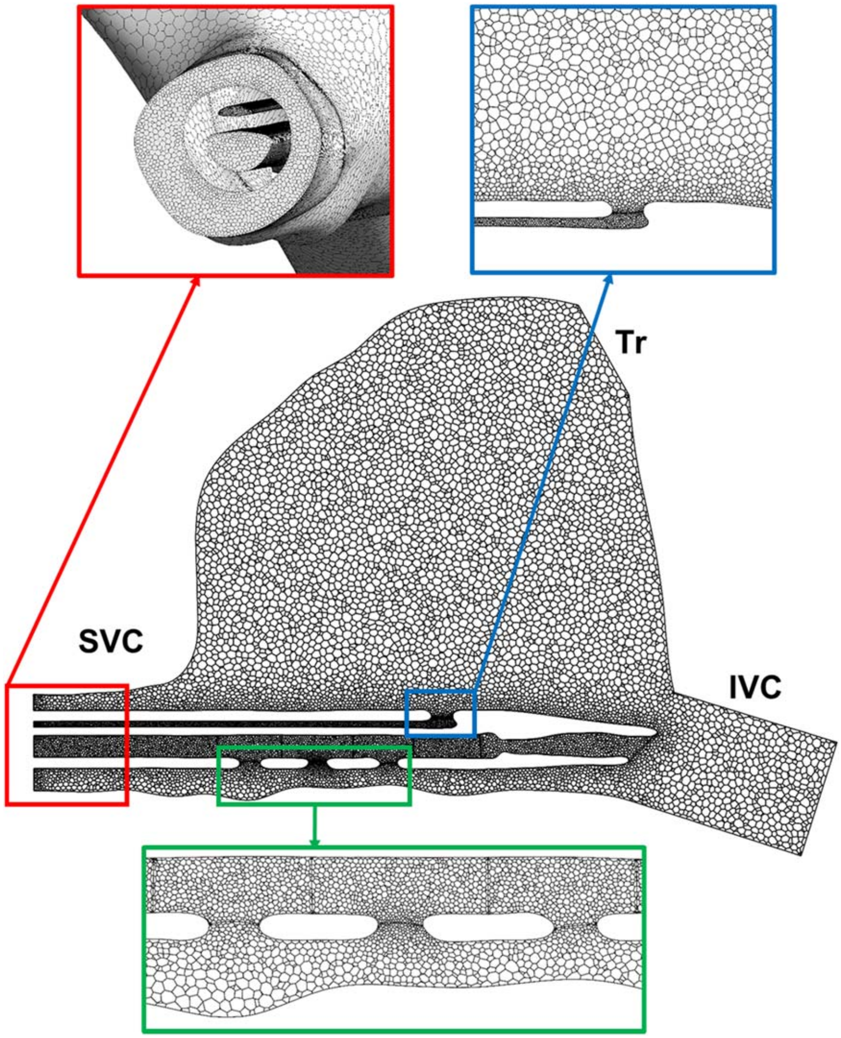

FIG. 2. Cut-plane snapshots from the computational multi-domain mesh used in the flow simulation. Top left inset (red square) shows the expanded end view of the cannula positioned inside the superior vena cava (SVC). Top right inset (blue square) shows the expanded view of the mesh where infusion jet would expand in the atrial volume before entering the tricuspid valve. Bottom inset (green square) shows the expanded view of the mesh around the three aspiration holes. [Color figure can be viewed at wileyonlinelibrary.com]

configuration replicates a perfectly positioned normal clinical configuration where the infusion hole points directly to the tricuspid valve annulus, while the cannula tip rests proximal to the inferior cavoatrial junction. Furthermore, the minimum clearance between the cannula and SVC was no less than 1.5 mm at any point.

In order to quantify the detailed local performance metrics of constitutive cannula regions, the blood volume is divided in to several zones as shown in Fig. 1 where each color represents a separate volumetric analysis zone. Oxygenated blood from the ECMO circuit enters the infusion zone (Zone 1 in Fig. 1) while venous blood is sent to the external ECMO via Zones 2 through 7.

Multiple computational grid generation strategies were tested for this complex model and finally a high-quality multi-zonal tetrahedral/polyhedral mesh was adopted which is generated using Ansys Workbench meshing toolbox (ANSYS Inc, Canonsburg, PA, USA). A nonuniform mesh resolution was kept to resolve the high flow gradients in the local regions of high velocity while minimizing the computational cost. Three meshes consisting of 0.4 million, 0.685 million, and 1.2 million polyhedral cells, respectively, were prepared and were named coarse, medium, and fine referring to their degree of refinement for grid convergence analysis. The medium mesh was selected for the simulations as it offered computational efficiency and resulted in less than 3% absolute error in velocity magnitude. Resorting to polyhedral meshes resulted in almost 3–5 times lower cell count as compared to unstructured tetrahedral mesh and improved mesh quality metrics leading to better convergence (Figure 2). The CFD solver is experimentally validated via the scaled-up rapid-prototype model of the double-lumen cannula using particle image velocimetry as well as through the FDA nozzle case (9). These results are not included in this manuscript for brevity but will be communicated in a future publication.

Blood was defined as incompressible Newtonian fluid having viscosity and density of 0.0035 Pa s and 1060 kg/m^3, respectively. Boundary conditions for pathologically low blood flow were applied at cannula infusion port as plugged flow, for example, 120 mL/kg/min as it lies in the same range for the patients recommended for ECMO therapy (10,11). Outflow boundary conditions with equal weighting were applied at the tricuspid outlet and drainage outlet. In order to obtain the flow inside the atrium, the three-dimensional Navier-Stokes equations were solved in Fluent (Ansys Inc., Canonsburg, PA) with a pressure-based solver and the pressure-velocity coupling algorithm is set as Semi-Implicit Method for Pressure-Linked Equations (SIMPLE). The solver was essentially same as in our earlier studies (8), which is experimentally validated in transitional cardiovascular flows. Due to the complexity of flow regimes, a second-order discretization of pressure and momentum terms is found to be necessary to eliminate numerical diffusion introduced by the discretization.

Power law approach of Giersiepen et al. was used to model blood damage and was implemented in Fluent as passive scalar equation as reported previously (12). Similarly the governing transport equation of blood residence time is also included as custom user-defined function. Likewise, three additional advection-diffusion equations were defined for each inlet, that is, SVC, IVC and infusion port, respectively, to track the desaturated blood introduced from these venous inlets individually. Through this approach the percent contribution of each inlet toward the either of the two outlets, that is, tricuspid outlet and drainage outlet can be quantified. The general form of these five additional convection-diffusion transport equations are as follows;

$$^{\partial C_i}/_{\partial t} + \vec{u}.\nabla C_i - D\Delta C_i = \text{Si} \quad (1)$$

where $\vec{u}$ is the velocity vector, C_i is concentration of passive-scalar (blood damage, hemolysis, etc.), D represents the diffusion coefficient and Si represents the source term. Three scalars namely C_1, C_2, and C_3 were defined for infusion, superior vena cava, and inferior vena cava inlets, respectively. Concentration of C_i was considered 1 at the respective inlet and zero for other inlets and flux of the corresponding passive scalar was specified to be zero at the walls and outlets. For scalars corresponding to inlet ports, self-diffusion coefficient of water was used (13). These scalars provide metrics that are needed to quantify the flow derangements inside the cannula-atrium system.

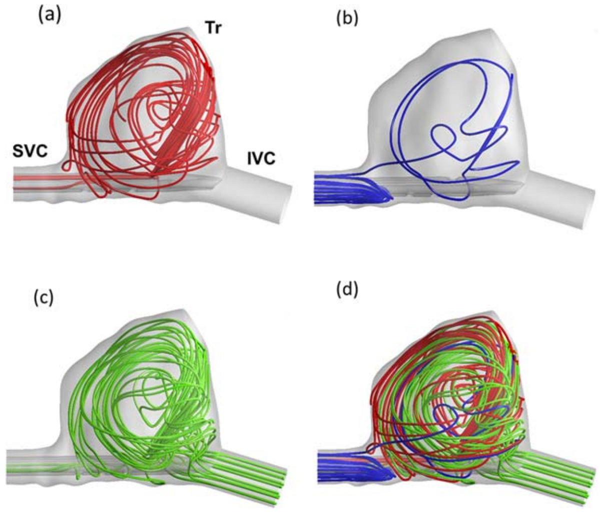

FIG. 3. Velocity streamlines inside the atrium at flow rate of 120 mL/min/kg. Streamlines are color coded to show their origin from different inlets. *Green*: IVC inflow, *Blue*: SVC inflow, *Red*: Infusion port inflow. In figure d, all colored streamlines are superimposed to display entire time-averaged complex flow that contributes to large atrial circulation. [Color figure can be viewed at wileyonlinelibrary.com]

RESULTS

Atrial flow characteristics and patterns

In Fig. 3, the time-averaged flow streamlines inside the atrium are plotted. It is evident that an extremely complex flow field persists in atrium owing to the interplay between the venous blood influx and the oxygenated blood from the ECMO circuit via the cannula. Oxygen deficient blood from the body pools in the right atrium from SVC and IVC respectively, and is drained to the ECMO circuit via aspiration holes and cannula tip. Ideally, the oxygenated blood from the ECMO circuit enters the atrium via infusion port and is directed toward the tricuspid valve, which is subsequently pushed to the pulmonary circulation. In this regime the blood coming out of infusion port has the highest velocity (4.35 m/s) compared to blood influx from SVC and IVC, thus, possessing the highest momentum and is predominantly responsible for shaping the atrial blood dynamics.

The most significant finding is that the jet from the infusion port expands in the atrium and a recirculation zone is created in the atrium before being

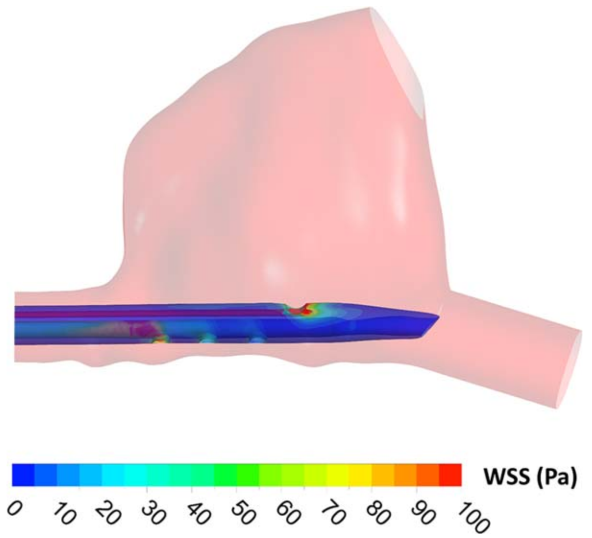

FIG. 4. Wall shear stress distribution on the cannula, a region of high shear stress is observed adjacent to the infusion port exit. Aspiration hole closer to the drainage port experiences the highest WSS on the venous side of blood flow. [Color figure can be viewed at wileyonlinelibrary.com]

swept away through the tricuspid annulus. It can also be seen from Fig. 3a that some of the oxygenated blood from the infusion port is drained via the aspiration holes.

Venous blood from SVC goes to ECMO circuit through the aspiration holes while rest of the blood feeds the recirculation zone generated by the infusion jet. Most of the blood flows through the hole proximal to the drainage port and the flow decreases gradually in the subsequent infusion holes and the cannula tip.

Interestingly, a significant percentage of blood from the IVC recirculates in the atrium and is later washed out through the tricuspid valve. Due to the respective proximity of the cannula tip and the recirculation zone created by the infusion jet, incoming deoxygenated blood from the IVC interacts with the recirculation zone and in the process deoxygenated blood is drained via tricuspid valve.

Wall shear stress and blood damage

Figure 4a shows the shear stress profile in the cannula body. It is evident from Table 1 that blood is subjected to extremely high shear stress in the infusion port with its magnitude at least one order of magnitude higher than any other part in the atrium. Double-lumen canula shear stress levels are least one time higher than the ones reported for other medical devices such as ventricular assist devices (VAD) and aortic cannulae (8,14). The infusion jet also registers a zone of high WSS on the cannula body near the infusion hole. Moreover, relatively high WSS is observed at the drainage port and aspiration holes. It is also worth noting that higher WSS is encountered in the regions proximal to drainage port.

Figure 5a presents the residence time distribution of blood in the atrium. Higher residence time is attributed to the recirculation and also makes blood more susceptible to thrombosis. Moreover, higher residence time is also significant since blood damage is a function of residence time and shear stress. Figure 5b presents the distribution of hemolysis index as the oxygenated blood enters the right atrium. Highest blood damage is observed in the region where the jet expands in the atrium.

Quantitative efficacy analysis of the cannula-atrial system

As highlighted earlier, user-defined scalar equations were defined in Fluent (Ansys Inc.) to quantitatively analyze the composition of blood at outlets and thus determine their origin. These quantities can also allow us to compute the cannula efficacy in the atrium. Table 2 shows the numerical values of these user-defined quantities.

These indicate that almost half of the oxygenated blood from the infusion port is delivered to the tricuspid outlet reaching a split of 62%. This indicates that in the ideal condition a significant amount (38%) of blood goes out from the drainage port. While the cannula configuration collects almost the entire SVC blood (94%), only half of the IVC blood (54%) is collected at the drainage port. The rest of venous desaturated blood is shunted through the tricuspid valve. This indicates that IVC suction performance of double-lumen cannula is severely restricted.

TABLE 1. *Average wall shear stress (Pa s) values at different volume zones*

S. No.	Flow rate (mL/min/kg)	Re	Atrium	Drainage port	Infusion	Hole 1	Hole 2	Hole 3	Tip	Tip distal
1	30	463	0.2	6.6	55.9	0.8	2.3	8.0	0.4	0.2
2	60	924	0.5	17.7	155.6	2.4	7.0	23.5	0.9	0.4
3	90	1387	0.9	34.3	304.4	4.8	13.7	44.8	1.5	0.6
4	120	1849	1.4	56.9	497.4	8.0	22.5	72.0	2.1	0.8

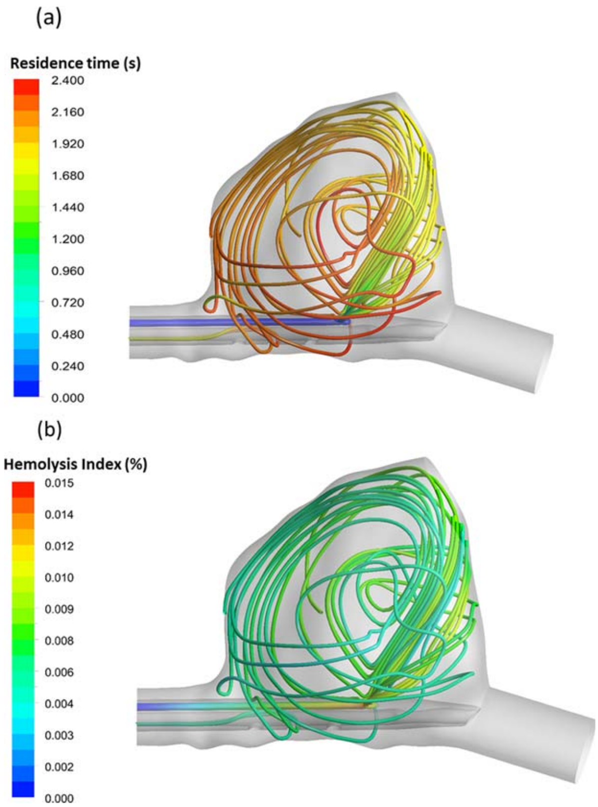

FIG. 5. (a) Residence time distribution along the streamlines inside the atrium is presented for the physiological device flow rate of 120 mL/min/kg and at jet Re 1849. As expected the residence time is higher at the regions of high recirculation, figure (b) illustrates the NIH hemolysis index distribution along the corresponding streamlines. Hemolysis index is a function of residence time and shear stress. The highest value of HI is encountered in the area near the infusion hole. [Color figure can be viewed at wileyonlinelibrary.com]

Table 3 summarized the computed compositions of passive scalars at the drainage and tricuspid outlets, respectively, in terms of species flow rate. It can be observed that, at the physiological device flow rate (120 mL/min/kg), 67% of the blood at tricuspid valve is from infusion port while 31% and 2% blood originates from the IVC and SVC, respectively. Likewise, 42% of the blood at the drainage outlet is from infusion port while 32% and 27% of the blood comes from SVC and IVC, respectively.

TABLE 3. *Results of area average of scalars at the outlets*

		Drainage outlet			Tricuspid outlet		
Flow rate (mL/min/kg)	Re	C_1	C_2	C_3	C_1	C_2	C_3
30	463	0.01	0.89	0.10	0.23	0.13	0.64
60	924	0.17	0.58	0.25	0.44	0.06	0.51
90	1387	0.34	0.41	0.26	0.58	0.03	0.39
120	1849	0.42	0.32	0.27	0.67	0.02	0.31

While almost entire SVC blood is collected by the cannula, distribution of venous blood through the three aspiration holes is severely unbalanced. It is noted that most of the blood is drained through Hole 3 (52%), which is proximal to the drainage port, while significantly less blood is captured through the structures on the venous side. Hole 2, Hole 1, and cannula tip capture 28%, 15%, and 5% of the blood on the venous side, respectively. This results in unbalanced WSS at these holes and contributes to blood damage as well.

Site-specific blood damage and residence time of blood

Average residence time for blood before it is flushed away to the external ECMO circuit through the drainage outlet is 1.56 s compared to average residence time of 1.46 s for blood going out from the tricuspid outlet.

The average flow of damaged blood through the tricuspid is significantly higher than the amount of damaged blood flowing through the drainage outlet (0.007% in tricuspid vs. 0.0046% in drainage outlet). This indicates that the bulk of the blood that is damaged goes through the tricuspid valve. As expected, the highest damage was observed near the infusion hole (0.025%).

DISCUSSION

A good cannula design should not interfere with the natural streaming of venous blood in the right-atrium. While there is limited hemodynamic information on the relatively smooth physiological 3D

TABLE 2. *Results of percentage scalar distribution at the outlets*

		C_1		C_2		C_3	
Flow rate (mL/min/kg)	Re	Drainage outlet	Tricuspid	Drainage outlet	Tricuspid	Drainage outlet	Tricuspid
30	463	5	95	88	12	14	86
60	924	28	72	91	9	33	67
90	1387	37	63	93	7	40	60
120	1849	38	62	94	6	46	54

right-atrium flow patterns (15), this study shows that the introduction of the double lumen cannula results in extremely complex flow fields. The present multi-species CFD model is the key to understand these complex device flow patterns and to improve the apparently poor cannula design. Future studies will show if better designs could be proposed to overcome the limitations highlighted in our results.

In addition to the design features, the complex flow profile in the right atrium is associated with the anatomic position of the cannula relative to the venous inlets. The correct anatomic position can be easily achieved under image guidance where tip of the cannula rests close to IVC and infusion hole is directed toward the tricuspid valve. However, for neonates, ensuring proper placement can be challenging due to the interfering factors such as mechanical ventilator support causing mediastinal shift that can lead to atrial collapse and warping of the atrium-IVC junction. Moreover, patient movement can frequently dislodge the cannula tip from the IVC and can result in atrial perforation (16). Our analysis shows that flow dynamics are very sensitive to the position of the cannula in the atrium. Any movement or ectopy would alter the "ideal" hemodynamics as illustrated in this study, influencing the ECMO efficacy subsequently. Given the poor IVC drainage function, it may be wise to introduce the cannula a little deeper in the IVC. However, any such movement would result in corresponding movement of the infusion hole making it susceptible to malposition. For the current design in particular, increasing the distance between infusion hole and the cannula tip may provide more leverage for deeper placement of cannula tip in the IVC without compromising the hemodynamic output. While contemporary cannulas from other manufacturers can also be tested similarly, we believe that as the major design layout is the same for all clinically approved cannulas, the flow structures identified in this research paper would be similar. Nevertheless, this study underlines the need to study the alternative cannula designs available in the market, which may offer better hemodynamic characteristics. It would also provide valuable insight across the fundamental cannula designs and toward the development of optimal cannula configuration. We believe that scalability plays an important role in the cannula performance as there have been reports that smaller size of the cannula is associated with higher complication rates (17). It is important to emphasize that geometrically-scaled down versions of the adult or pediatric cannulas may not be the best designs in neonatal population. There has been some clinical evidence where it has been suggested that linear scaling down of adult cannula designs may not work for neonatal populations (18).

The present study indicates that a significant percentage of oxygenated blood (38%) is recirculated and prompts suboptimal performance of a typical cannula that is approved for clinical use. High recirculation increases the blood residence time, making it more susceptible to thromboembolic events. This is particularly severe for congenital heart patients with additional anatomical complications such as an atrial septal defect or patent foramen ovale. The locations of complex atrial structures need to be taken in to account due to their potential association with the thromboembolic flow patterns. Concurrently, the venous blood from the SVC and IVC also mixes with the oxygenated blood, and results in major desaturation. On the venous side of the ECMO circuit, cannula directs the blood from the SVC to external ECMO circuit efficiently; almost 94% of the blood is collected. Whereas for IVC, approximately half of the blood (53%) goes through the tricuspid valve, which is due to the presence of recirculation zone and highlights the inability of the cannula tip to efficiently collect the venous blood from the IVC. Based on the present performance analysis, the suboptimal performance expressed by large recirculation and longer residence times would lead to loss of efficiency. Both the sub-optimal delivery of oxygenated blood and heavily desaturated blood collection can be traced to the geometric design of the cannula.

The most unfavorable characteristic of the cannula that predisposed the cannula-atrial system to high recirculation is attributed to inability of the cannula to direct all the blood through the tricuspid annulus. Apparently, the infusion port is unable to turn and redirect the extremely high momentum blood toward the tricuspid. To further study this phenomenon, we ran flow simulations at various flow rates as shown in Fig. 6. At lower flow rates ($\sim$30 mL/min/kg) most of the blood from the infusion hole goes directly to the tricuspid valve, as intended by the design, thereby delivering optimal performance. However, as the infusion flow rate is increased to 60 mL/min/kg and beyond to the even higher physiological levels the flow pattern from the infusion hole starts to deviate from the optimal flow direction, giving rise to the aforementioned recirculation in the atrium. Thus, it can be deduced that existing cannula is efficient at lower flow rates where blood momentum is small and around

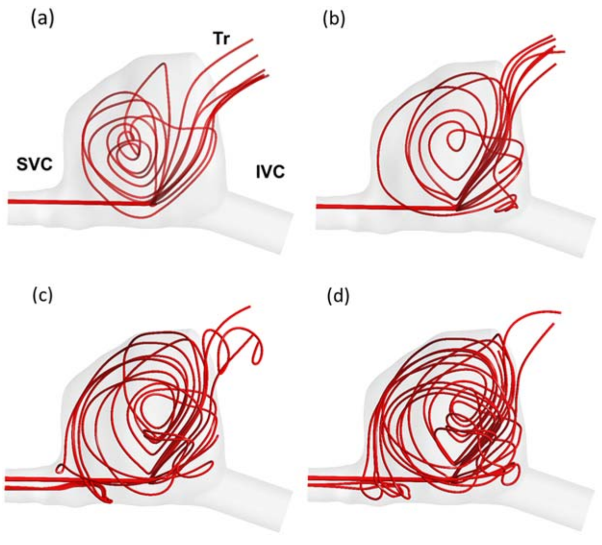

FIG. 6. Velocity streamlines showing the direction of jet from the infusion hole at different inflow velocities. (a) 30 mL/min/kg, (b) 60 mL/min/kg, (c) 90 mL/min/kg, (d) 120 mL/min/kg. The approximate angle of the infusion jet was observed to be 48, 57, 55, and 53 degrees, respectively, for figures (a–d). [Color figure can be viewed at wileyonlinelibrary.com]

30 mL/min/kg (as per our simulation) marks the tip-off point of this design beyond which this design fails to redirect the blood momentum towards the tricuspid valve. In order to incorporate different clinical operating points, major hemodynamic parameters and scalar distributions are plotted at different flow rates in Tables (1–3). From these results, it can be observed that a compromise on the infusion flow rate can result in improved blood damage, lower WSS, and better oxygenation efficiency.

Blood damage is a function of shear stress and residence time. It is evident from Fig. 4 that the oxygenated blood is subjected to extremely high shear stress as it is squeezed through the infusion port. From the perspective of blood damage, the areas of interest include infusion port and region near the Hole 3 where very high shear stress and longer residence times have been observed. Highest blood damage was observed proximal to the infusion hole where the infusion jet expanded in the atrium, due to prolonged exposure to high shear stress. This damage is at least one order of magnitude higher than the values reported for other medical devices (14).

Based on our observations regarding the flow structures, blood damage, and residence times, this study provides detailed insight on the performance of the cannula inside the atrium and hints at probable improvement areas in the cannula design for bioengineers. Although many complications of cannula conjoined with installation, operation and removal have been reported, this study focused primarily on the hemodynamic characteristics inherent to the cannula design. Our simulation results of increased blood damage, high WSS, and large recirculation seem to implicate the characteristic design of the cannula for suboptimal hemodynamic performance suggesting certain design deficiencies. In this study, CFD has been able to highlight certain suboptimal features of the existing design, which may have gone undetected by the device approval process. Cannulas are categorized in *Food and Drug Administration (FDA) designation: Manufacturer and User Device Experience* (19), under the category of "Catheter, Cannula and Tubing, Vascular, Cardiopulmonary Bypass" which monitors a large category of noncritical non-ECMO devices (16). As our study illustrated, the neonatal double lumen cannula and some other critical devices of this category may warrant design changes to go through a special expedited pathway of approval so that the suboptimal design features can be eliminated rapidly in the clinics. Thus, these findings warrant further improvements in the design of double lumen cannula to enhance its atrial hemodynamic performance and would pave the way for better patient care subsequently.

Limitations

The main limitation of the simulation involves the use of rigid walls for the patient-specific right atrium leading an over simplistic approximation of global flow characteristics. However, within the purview of our study designed for detailed evaluation of cannula inside the atrium, we believe our inferences shall remain valid as they correlate strongly to cannula geometry. Moreover, we only simulated the part of cannula inside the atrium. In reality, the length of the infusion and drainage outlet are at least more than twice the length simulated in this study. This would inevitably change the absolute total blood damage and residence time metrics. The values of blood damage and residence times reported in this study can be considered as the ones representing only a part of the ECMO circuit. The rest of the ECMO circuit, for example, oxygenator, pump, tubing, and so forth would incur additional characteristic effects on the overall ECMO performance.

A caveat exists, in the alteration of component level design nuances such as drainage mechanism, optimal placement considerations or sharp contours as it may also lead to unpredictable clinical implications at the device-system level. Future design development efforts require foresight on the design modifications as well as the ability to prospectively analyze the functional or clinical outcomes.

CONCLUSIONS

Detailed hemodynamic performance of a clinical double lumen neonatal cannula correctly positioned in the right atrium is presented for the first time in literature. Major blood structures, which should influence device design efforts, are identified including a strong recirculating blood structure and a persistent jet direction. These flow patterns are generated due to the combined action of the three major blood inflow ports. An extremely complex device flow regime prompted high blood damage indices, high residence times, and resulted in significantly desaturated blood delivery to the tricuspid valve annulus. As in clinical practice, an anatomically perfect cannula placement is seldom possible for various practical challenges, so these results can be interpreted to be on the conservative side. Due to its high momentum, the velocity flow jet from the infusion hole only delivers a proportion of the total oxygenated blood to the tricuspid annulus unlike its intended design. This deficiency revealed significant mixing of oxygenated and deoxygenated blood inside the atrium which showed precipitous decrease of cannula performance specifically at the IVC port. Extremely high WSS and unbalanced blood damage contribution is also observed in the infusion pathway. The Origen cannula investigated in this study is selected only due to its availability to the research team and should be considered as a representative "brand less" template DLC model. While other neonatal cannula options in the market can be analyzed using the proposed model, the major flow patterns and conclusions should also hold for them and to our opinion are not specific to the brand studied here. We also extended our study by considering flow variations in the context of various clinical situations and highlighted the optimal operating conditions of the existing design. In terms of optimal cannula design, regions having abnormal levels of blood damage and WSS present themselves as the potential sites of design improvement and hence can be modulated for enhanced ECMO performance.

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Conflict of Interest: The authors declare that they have no conflict of interest in this work.

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