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Hemodynamic performance limits of the neonatal Double-Lumen cannula

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Abstract

Venovenous extracorporeal membrane oxygenation (VV-ECMO) is the preferred surgical intervention for patients suffering from severe cardiorespiratory failure, also encountered in SARS-CoV-2 management. The key component of VV-ECMO is the double-lumen cannula (DLC) that enables single-site access. The biofluid dynamics of this compact device is particularly challenging for neonatal patients due to high Reynolds numbers, tricuspid valve location and right-atrium hemodynamics. In this paper we present detailed findings of our comparative analysis of the right-atrial hemodynamics and salient design features of the 13Fr Avalon Elite DLC (as the clinically preferred neonatal cannula) with the alternate Origen DLC design, using experimentally validated computational fluid dynamics. Highly accurate 3D-reconstructions of both devices were obtained through an integrated optical coherence tomography and micro-CT imaging approach. Both cannula configurations displayed complex flow structures inside the atrium, superimposed over predominant recirculation regimes. We found that the Avalon DLC performed significantly better than the Origen alternative, by capturing 80% and 94% of venous blood from the inferior and superior vena cavae, respectively and infusing the oxygenated blood with an efficiency of more than 85%. The micro-scale geometric design features of the Avalon DLC that are associated with superior hemodynamics were investigated through 14 parametric cannula configurations. These simulations showed that the strategic placement of drainage holes, the smooth infusion blood stream diverter and efficient distribution of the venous blood capturing area between the vena cavae are associated with robust blood flow performance. Nevertheless, our parametric results indicate that there is still room for further device optimization beyond the performance measurements for both Avalon and Origen DLC in this study. In particular, the performance envelope of malpositioned cannula and off-design conditions require additional blood flow simulations for analysis.

1. Introduction

Extracorporeal membrane oxygenation (ECMO) is a life-sustaining therapy that has saved numerous lives since it was first successfully development in 1970 (Baffes et al., 1970), with high survival rate (Peek et al., 2009) for patients suffering from severe cardiorespiratory failure. Blood perfusion during ECMO therapy is typically achieved by either venoarterial (VA) or venovenous (VV) access. VV-ECMO is the currently preferred intervention in neonatal population due to its superior outcomes compared to conventional ventilator therapy (Palmér et al., 2016) and the lower risk of serious acute complications as encountered in VA-ECMO (Koerner et al., 2019).

Double lumen cannula (DLC), which has been shown to play a pivotal role in advancing VV-ECMO therapy, is basically a single catheter with two separated channels. One channel is responsible for the infusion of oxygenated blood and the other channel functions to drain venous blood from the right atrium. Utilizing DLC during VV-ECMO provides single-site surgical access, resulting in better patient mobilization and rehabilitation, lower recirculation levels (Klein et al., 1985) and lower risk of infection, bleeding, thrombosis and sepsis rates (Hamilton and Foxcroft, 2007). During
VV-ECMO, DLC is inserted percutaneously in the right internal jugular vein and is advanced into the right atrium under ultrasound guidance. Infusion lumen in the DLC directs the oxygenated blood flow to the tricuspid valve while drainage lumen is responsible for the suction of the venous return blood. The overall efficiency of the VV-ECMO therapy is firmly tied to DLC performance due to the simultaneous operation of both infusion and drainage channels inside the compact atrium, which is characterized by complex hemodynamics that can potentially result in the mixing of different blood streams.

Despite the significant advantages that VV-DLC provides, it can also lead to high levels of recirculation (Chacon and Shillcutt, 2017). Recirculation fraction is defined as the fraction of blood from the infusion port that does not enter the pulmonary circulation, which is immediately drained through the drainage side before being systematically circulated. Extensive research has shown that DLC design (Rasooli et al., 2020) and positioning (Clements et al., 2008; Jamil et al., 2020; Wang et al., 2008; Xie et al., 2016) [9, 10], the volume of the atrium (Jamil et al., 2020) and ECMO flow rate (Sreenan et al., 2000; van Heijst et al., 2001), are the key factors that have a significant impact on recirculation levels. Our recent computational study revealed high recirculation fraction for Origen DLC even with correct caval positioning (Muhammad et al., 2018) which underscores the significance of DLC design parameters. Adequate perfusion of DLC in VV-ECMO requires drainage of venous blood from the right atrium to the ECMO circuit and delivery of oxygenated blood to the tricuspid valve for systemic circulation. Neonatal population present a unique challenge for the DLC assisted VV-ECMO therapy as the smaller physiology entails smaller DLC sizes to be considered. Hence, the interplay between limited space and small DLC sizes can lead to complicated and potentially different hemodynamic challenges. Significant research effort has been directed at addressing the design considerations and has been realized in the form of various DLC designs that are being utilized in routine clinical practice.

Our primary aim in this study was to determine the current performance levels of two clinically approved and widely used cannulas: Origen and Avalon DLC. Most importantly, we set out to quantify the potential performance improvement of both cannulas through extensive parametric hemodynamic analysis of their key design features. This involved meticulously scrutinizing the DLC design principles under the purview of providing adequate venous unloading and oxygenated blood delivery. Conventional device characterization relies on in vivo bench testing or in vivo monitoring; however, in this study, we used our recently developed combined experimental and patient-specific computational fluid dynamics (CFD) strategy (Muhammad et al., 2018). This enabled us to thoroughly investigate the impact of different design parameters on the final device characteristics of recirculation fraction and blood damage. In the first phase of our study, we were able to identify and compare the relevant key design features of commercial cannulas using the CFD-based analysis of existing DLCs. We then parameterized these design features in the second phase of this study to extend the design rationale and to develop and test novel DLC prototypes that satisfy the design considerations while also providing better performance in hemodynamic parameters compared to the existing ones.

2. Methodology

2.1. Image-based 3D device reconstruction

Two 13 French (Fr) DLC devices (both Avalon and Origen) were selected for this study as recommended by our collaborating neonatal intensivists and newborn intensive care unit (NICU) clinicians. Both devices were scanned using micro-CT with an extremely fine resolution (~150 μm) and image data was segmented in slicer software to obtain the 3D reconstruction (Çakmak et al., 2020). To resolve the exact geometry of the infusion and drainage holes, DLCs were scanned under optical coherence tomography (OCT) reaching less than 2 μm resolution. Fig. 1 summarizes the details of this 3D reconstruction approach.

2.2. Patient-specific right-atrial anatomy

The 3D reconstruction of the right atrium (RA) geometry of a neonate (weight = 3 kg, height = 50 cm, body surface area = 0.2 m²) having normal venous return was acquired from MRI scans through approved IRB. The DLC models were oriented in the RA model in situ to replicate the confined in vivo atrial hemodynamics (Fig. 2). We evaluated the atrial hemodynamic performance of new parametric design features (Table 1), subjected to the identical methodology and performance metrics used for the two commercially-available designs.

Numerical simulations were carried out in FLUENT solving steady RANS turbulent and 2nd order SIMPLE algorithm. Boundary conditions were identical to our earlier study (Muhammad et al., 2018). To summarize briefly, for the infusion channel (120 ml/kg/min), two hydraulic diameter extension inlet flowrate as plug flow (due to the short entrance length of ECMO circuit) was assigned for IVC/SVC (50/50 split of neonatal total cardiac output), nine hydraulic diameter extension and pressure outlet was specified for the tricuspid valve annulus and the outflow condition was considered for the drainage channel. A mesh independence study similar to our earlier study (Muhammad et al., 2018) was performed and a high-quality polyhedral mesh was prepared, which consisted of 0.685 million cells.

Evaluation parameters, such as recirculation fraction (as in Jamil et al., 2020), superior vena cava (SVC) and inferior vena cava (IVC) blood capture efficiencies, were calculated by post-processing the computational results. We defined the SVC and IVC blood capture efficiencies as the fraction of the total venous blood taken from the respective conduits, which are dependent on the design and drainage mechanism of the DLC. Common clinical practices were used to minimize recirculation fraction as much as possible (ideally below 20% (Locker et al., 2003)). In addition, other hemodynamic parameters such as shear stress, hemolysis and residence times were also computed.

2.3. CFD solver validation

Following the protocols for standard mesh sensitivity and CFD verification tests, we tested our solver against the FDA nozzle benchmark test (Supplementary Fig. 1). Next, we validated our jet-direction computations by connecting the DLC infusion port to a pump running water-glycerin blood analog fluid and then captured the images of free jet via high-speed camera on benchtop. Finally, we conducted particle image velocimetry (PIV) measurements at the operating Reynolds (Re) number of 1845. The details of this experimental approach are available in the literature [9] and briefly stated as follows. A closed loop flow loop is employed where the DLC was placed in a tank the size of 25 × 30 × 50 cm. Water was used as working fluid and seeded with silver coated spherical glass particles. A laser sheet the thickness of less than 1 mm was placed congruent with the mid-plane of the cannula. Time-resolved planar PIV was performed at a frame rate of 200 Hz.
3. Results

3.1. Experimental validation

The numerical results of jet direction demonstrated excellent agreement with the bench experimental tests, as shown Fig. 3, where the numerical and free-jet bench-top experimental results are superimposed. More specifically, Fig. 3 compares the PIV-measured and CFD-predicted velocity fields. A semi-instantaneous PIV velocity profile is also presented to show the turbulent flow characteristics and justify our CFD turbulent solver.

3.2. Internal flow, velocity and wall shear stress

The two DLC designs demonstrated similar velocity patterns as displayed in Fig. 4 (top). While the jet directions were similar, the IVC drainage flow of the Avalon design allowed more freedom for its jet wake development. Furthermore, the Avalon jet wake region was significantly longer and allowed better gradual expansion than Origen. The peripheral IVC side hole arrangement also resulted in a more balanced flow compared to Origen. Although the flow percentage through the drainage hole sets can vary, the flow through individual holes of the same sets was balanced. It was observed that the highest wall shear stress (WSS) zone was located at the infusion conduit across all the designs, although lower values of WSS were evident for the Avalon DLC (Fig. 4 - bottom). Similarly, the drainage holes closest to the drainage outlet resulted in high WSS hotspots. The internal flow quality of the drainage pathway in Avalon was slightly better than Origen as indicated by the corresponding WSS distributions.

3.3. Right atrial flow characteristics

As depicted in Fig. 5, both of the commercially-available cannula designs generated the characteristic flow circulation inside the right atrium. In the Avalon DLC, an additional secondary flow circulation was induced due to its IVC side-hole flow. From a device design perspective, flow residence time characteristics of both designs were significantly different and worth discussing. The infusion jet wake region of the Avalon design exits the atrial flow domain significantly faster than the Origen. This jet-core region is associated with high blood flow rate which results in efficient infusion. However, the remaining few flow streams that cannot exit from the tricuspid annulus caused significantly higher blood residence times compared to the Origen design. It is important to note that these few remaining flow streams have the potential to increase thrombogenicity, but this also depends on positioning for both designs, the recirculation fractions varied significantly. For the Origen DLC, the recirculation fraction was 38% compared to only 15% for the Avalon. Furthermore, IVC efficiency of the Avalon DLC was 80% compared to 40% for the Origen. SVC efficiency was measured at 94% for both Avalon and Origen DLC designs.

3.4. Parametric cannula configurations

Table 1 lists all of the new design parameters that were analyzed in this study, including drainage hole numbers, hole size, hole arrangement, cannula tip size and SVC pathway separation from IVC drainage. By comparing the computational data presented in Section 3.3 with the new design parameters listed in Table 1, it is evident that these new designs were able to deliver higher SVC efficiency and lower recirculation fraction levels compared to the clinically-approved cannulae. Our results show that the optimal arrangement of tip holes can provide up to 70% IVC capture efficiency (Table 1: Design 8), which is identified to be the most challenging performance parameter for the neonatal cannulae. Likewise, the tip hole location is found to have a much more significant impact on the IVC performance when compared to the
Our findings also show that IVC capture efficiency is significantly influenced by the orientation of the DLC cannula relative to the right atrium. Unfortunately, in actual clinical scenarios, the optimal positioning of the DLC is rarely possible. Therefore, configurations that are less sensitive to cannula positioning are desired.

One possible novel configuration that can address the aforementioned problem is inspired from turbo-jet engine inlets (Fig. 6). The fuselage-shaped tip insert attached to the conical diffuser allows for improved IVC flow capture independent of the main external atrial flow direction due to its unique “flow attachment” function regardless of the inflow direction (see also Supplementary Fig. 2). In this design, a more uniform infusion jet flow is achieved due to the precise orientation of the IH towards the tricuspid valve annulus, the smooth internal cannula pathway and extremely efficient IVC and SVC capture (Fig. 6). The recirculation fraction, and IVC and SVC efficiencies for this novel design were calculated to be 13%, 84% and 100%, respectively.

4. Discussion

We computationally evaluated two clinically-approved DLCs with the Avalon and Origen designs and our findings show that the Avalon DLC is clinically preferred to the Origen DLC in terms of providing more effective hemodynamic support for neonatal VV-ECMO therapy. Our comprehensive CFD analyses using an inverse-design approach reveal the RA hemodynamics of the Avalon DLC in situ for the first time in the literature. A series of parametric simulations indicate that the Avalon design has more optimal performance in terms of recirculation, and IVC and SVC blood capture efficiencies. Importantly for patients with cardiorespiratory failure, this study enabled us to identify the main features of DLC design that are critical for more effective surgical procedures with the potential for even more optimal DLC designs in the future.

4.1. Avalon and Origen DLC performance inside the atrium

In the Avalon DLC, venous blood drainage is achieved through its tip and drainage holes DH1-11, where DH1-3 are intended to remove blood from the SVC while the tip and remaining sections of the cannula drain the blood from IVC. For DH 1–3, the shape of the drainage lumen restricts their size and circumferential location as it allows holes to be placed in only half of the circumference. Nonetheless, it does provide an equally-distributed flow through these holes, as they are located at the same distance from the suction side, which results in lower wall shear stress values.

In relation to the Origen DLC, three equal-sized drainage holes (DH1-DH3) are arranged in a straight line, which results in unequal flow through the holes. For equal-sized holes DH1–3, the tendency is for the maximum flow to pass through the initial DH1 and then decreases steadily for the other holes located distally. It should also be noted that although DH1-3 allows for sufficient drainage for both DLCs in normal conditions, this arrangement can make the Origen DLC vulnerable to complete blockage of IVC blood drainage when there is any malposition of these holes. A full circumferential arrangement, such as DH4-7 and DH8-11, is more suitable to ensure a balanced blood flow and avoid blockages.

The Avalon DLC also provides more sufficient redundancy of SVC drainage than the Origen DLC. In the event that the tip or any of the holes DH4-11 are blocked, IVC blood can still be drained via the other holes or the tip in the Avalon design. In comparison, a single tip is responsible for IVC blood drainage in the Origen design and there is no alternative mechanism to drain the venous blood from the IVC if the tip is blocked. Similarly for SVC drainage, the Avalon DLC is less likely to be blocked than the Origen DLC due to the circumferential arrangement of DH 1–3, which are located on the same side in the Avalon design and therefore provide better redundancy.

In addition to the drainage mechanics of DLC design, infusion jet characteristics also play a dominant role in shaping atrial hemody-
namics. However, realizing the optimal jet infusion characteristics is challenging as there are many dependent factors to take into account. The size and shape of the infusion lumen are extremely important on the basis they control the infusion velocities and WSS (Rasooli et al., 2020). In the multi-hole design of the Origen DLC, the infusion lumen is relatively small which entails higher WSS values. In comparison, the larger size of the infusion lumen in the Avalon DLC show lower values of WSS. These characteristics are critical in determining the maximum ECMO flow rate that can be achieved with acceptable blood damage.

The guiding mechanism of the jet also plays an important role as it dictates jet energy dissipation, expansion characteristics and jet direction capabilities. The jet expansion cross-sectional area in the Origen DLC is not optimal and the bulk flow in the infusion lumen encounters a rapid directional change. Furthermore, it is also important to note that the suboptimal jet direction mechanism in the Origen DLC prevents efficient utilization of the jet area.

In more practical terms, this means that the Origen DLC has a higher exit area but only a fraction of it is efficiently utilized at exit. In comparison, the Avalon DLC embodies better jet direction strategy, allowing for smooth transition and expansion inside the atrium. However, slight flow disturbances can nevertheless be observed near the infusion holes.

For the Avalon DLC, three drainage holes are located in the SVC while the rest of the eight holes and tip are located in the IVC. This is a good design strategy since the three holes with high suction pressure are able to capture the SVC blood while the eight holes and the tip provide a larger suction surface area that makes up for the decrease in suction pressure towards the proximal end. Fig. 7 shows the distribution of blood capturing area on the drainage side for Avalon DLC, with only 15% of the blood capturing area dedicated to SVC and the other 85% of the area intended for drainage of blood from the IVC. The larger tip (45% of the total blood capturing area) provides efficient suction efficiency by making up

### Table 1
Design matrix for the novel DLC design configurations. For each design configuration, the tabulated key performance parameters of (i) Recirculation (Recir.), (ii) Superior Vena Cava (SVC) and (iii) Inferior Vena Cava capture efficiency values were computed by post-processing the CFD solutions. The clinical applicability of each design configuration is also evaluated in the last column.

| #   | Design drawing | Design features                                      | Recir. | SVC eff. | IVC eff. |
|-----|----------------|------------------------------------------------------|--------|----------|----------|
| 1   |                | Single hole (lengthwise)                             | 35     | 100      | 54       |
| 2   |                | Two holes (lengthwise)                               | 32     | 100      | 51       |
| 3   |                | Two holes closer to tip                              | 32     | 100      | 51       |
| 4   |                | Expanded tip                                         | 26     | 100      | 61       |
| 5   |                | 4 holes (arranged circumferentially)                 | 28     | 100      | 55       |
| 6   |                | Smaller inlet size                                   | 26     | 100      | 58       |
| 7   |                | Triple lumen                                         | 25     | 100      | 60       |
| 8   |                | 4 holes (circumferentially)                          | 15     | 96       | 69       |
| 9   |                | 4 small holes (circumferentially)                    | 23     | 100      | 61       |
| 10  |                | 4 holes (lengthwise)                                 | 22     | 100      | 62       |
| 11  |                | 8 holes (lengthwise)                                 | 12     | 96       | 51       |
| 12  |                | 8 holes further apart (lengthwise)                   | 23     | 100      | 59       |
| 13  |                | Larger 3rd lumen with 8 holes further apart (lengthwise) | 25     | 100      | 60       |
for the reduced suction pressure. In addition, the longer distance between the infusion jet and drainage holes discourages recirculation.

The relatively poor performance of the Origen DLC can be attributed to design features that do not conform to RA anatomy. In the ideal caval position, the drainage holes are located inside the atrium while the tip is positioned at the cavo-atrial junction. However, the Origen design arrangement not only allows the venous blood from the SVC to pool in the atrium but also increases the risk of blood shunting from the infusion hole to the drainage holes, making it less effective for suction.

Fig. 3. Comparison of the infusion jet direction for the bench experiment (Top Left) and computational fluid dynamics (CFD) simulation over-plotted with experimental camera image (Top Right). Bottom Row: Comparison of flow fields measured via particle image velocimetry (left) and computed with the CFD solver (right) for the neonatal Origen DLC cannula. In order to illustrate the unsteadiness in experimental flow fields an instantaneous velocity field is provided on purpose, while CFD provides time-averaged results. Time-averaged PIV is in good agreement with CFD as reported elsewhere (Rasooli et al., 2020).

Fig. 4. Comparison of velocity magnitude on a cut-plane for Avalon (top) and Origen DLC (bottom). Higher velocities are observed in the infusion port and the drainage hole proximal to the drainage port. Comparison of wall shear stress (WSS) distribution on the Avalon (top) and Origen DLC (bottom). A region of high wall shear stress (WSS) is observed adjacent to the infusion port exit. The aspiration hole closer to the drainage port experiences the highest WSS on the venous side of blood flow. Tr: Tricuspid Valve, IVC: Inferior Vena Cava, SVC: Superior Vena Cava.
which are located almost in the wake of the infusion jet. Moreover, the three large-sized drainage holes claim almost all of the suction side pressure and provide little stimulus to draw blood from the tip section, which results in very poor IVC blood capture efficiency. Fig. 7 highlights the key differences in suction area distribution between the Avalon and Origen DLC respectively. While most of the drainage exit orifice area in the Avalon DLC is reserved only for the SVC and IVC, the available drainage area in the Origen DLC is distributed to capture blood from the SVC, IVC and the atrium. In fact, the blood capturing surface area of the Origen is design in such a biased way that blood drains from the SVC, IVC and the atrium preferentially. The smaller distances between the infusion hole and the drainage holes provides a strong stimulus for the proximal atrium chamber flow to move towards the drainage holes, which then in turn can increase further recirculation.

4.2. Novel DLC design configurations and performance

As we discovered in this study, the geometric optimization of DLC design requires a comprehensive evaluation of DLC functionality in the actual right atrium. While it is possible to examine DLC functionality in idealized cuboidal domains to provide geometry-dependent jet characteristics and balanced flow distributions, this research approach will not guarantee optimal performance when the device is placed inside the right atrium. The functional requirements of an effective DLC involve the drainage of venous blood from the SVC and IVC and the infusion of oxygenated blood to the tricuspid valve. The precise nature of this cardiorespiratory function necessitates that the design characteristics of the DLC, such as the number and location of holes, are synchronized with the surrounding physiological conditions.

In developing more optimal novel DLC configurations, we were committed to overcoming the apparent shortcomings of the two commercially-available DLC designs examined in this study. Therefore, several novel design configurations explored to test the limits of DLC performance are listed in Table 1. One of the main features

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**Fig. 5.** Flow streamlines for correct position of Origen DLC and Avalon DLC. Color represents the three-dimensional blood residence time distribution plotted on flow streamlines. Higher red regions signify longer residence times making them more susceptible to blood clotting and thrombogenicity. Tr: Tricuspid Valve, IVC: Inferior Vena Cava, SVC: Superior Vena Cava. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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**Fig. 6.** Flow streamlines for one of the new designs (Table 1: Design 4) compared with the novel “flow-capturing cannula” concept (right column). An insert, indicated with an arrow, facilitates flow attachment and improves IVC drainage efficiency independent of its canula position relative to IVC flow. Top Row: Only the flow streamlines emerging through the infusion hole are plotted for both designs. Bottom Row: Corresponding IVC drainage is plotted. The innovative flow capturing design represents a novel approach where infusion lumen is located co-axially to facilitate better infusion flow guidance while drainage holes are arranged circumferentially for efficient venous blood capture from the SVC (flow streamlines originating from the SVC are omitted as they were similar for both designs) IVC: Inferior vena cava, SVC: Superior vena cava, Tr: Tricuspid valve annulus.
of these configurations is a more efficient jet infusion guiding mechanism. This was achieved by using the co-axial arrangement of the infusion lumen inside the drainage lumen instead of the side-by-side arrangement used in the Avalon or Origen DLC. This novel co-axial arrangement was found to possess multiple functional design advantages. It was able to more efficiently guide the infusion jet with a longer guidance length. It also resulted in minimal losses and smoother expansion of the infusion jet into the atrium. More importantly, the new DLC designs achieved much better jet direction performance with more efficient utilization of the infusion hole area. The superior characteristics of new DLC designs can be attributed to longer guidance lengths and minimum area change of the infusion hole. Based on our results it can be deduced that geometric features can manipulate jet characteristics and simpler mechanisms of jet control is more efficient and possible. These complexities may cause instabilities in terms of flow control and can limit maximum ECMO flow rate possible.

Another salient feature of these novel design configurations is that the outer lumen that makes up the outer body of the cannula allows for full coverage of the circumference where equal-sized drainage holes can be placed for balanced drainage flow. It is also possible to vary the size of the holes depending on the requirements. Moreover, such a circumferential arrangement of holes is less liable for anatomic obstruction due to the surrounding environment. Even if there is an obstruction to any one of the holes, the rest of the holes can make up for that deficiency.

Moreover, the in-situ arrangement for these configurations is when the drainage holes are placed in the SVC while the longer distance between the infusion and drainage holes ensures minimal mixing of venous and oxygenated blood, hence less recirculation. Among all our design configurations and the commercial ones examined in this study, the design with a fuselage-shaped insert attached to the cannula tip was found to significantly enhance the cannula performance in terms of recirculation fraction, and IVC and SVC blood capture efficiencies.

However, we also acknowledge that these performance indices correspond to current atrial anatomy and significant changes should be expected for varied surrounding anatomy or off-design conditions, such as anatomic obstruction and malposition. Further in depth and randomized studies are warranted. Methodological limitations are discussed in Ref. (Jamil et al., 2020).

5. Conclusions

This study provides a functional explanation of the prevailing complications of the DLC use in VV-ECMO. A thorough CFD analysis of two existing designs revealed deficiencies in their functional design and overall performance in the atrium. Our findings clearly show that the superior performance of the Avalon DLC (replicated geometry) can be linked to its more effective design features, yet Avalon DLC had short-comings Compared to the Origen DLC (replicated geometry), the superior performance of the Avalon DLC can be attributed to more efficient distribution of the drainage surface area, the size and location of the drainage holes, and the efficient guiding mechanism of the infusion jet. Problems associated with recirculation and poor SVC/IVC efficiencies in the Origen DLC can be traced back to obvious design shortcomings, such as imbalanced drainage flow inside the DLC itself and in situ positions that apparently do not conform to the surrounding anatomy. Yet despite the encouraging performance of the Avalon design features, we identified certain key aspects in our 11 novel design configurations that can be modified to further improve DLC functionality. Our findings indicate that these features will expand the performance envelope of DLC off-design for malposition scenarios; however, we also acknowledge that further in-vitro studies are required to confirm this concept.

CRediT authorship contribution statement

Reza Rasooli: Conceptualization, Data curation, Writing, Discussions, Methodology, Validation.
Muhammad Jamil: Original draft preparation, Discussions, Methodology, Validation.
Mohammad Rezaeimoghaddam: Writing, Discussions, Methodology, Validation.
Yahya Yıldız: Conceptualization, Methodology, Clinical Insight, Writing.
Ece Salihoglu: Conceptualization, Methodology, Clinical Insight, Writing.
Kerem Pekkan: Supervision, Conceptualization, Writing, Reviewing, Editing and Funding acquisition.

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Conflict of interest

Authors have no relations with the companies and have no conflicts of interest. Geometries are not from the actual design drawings but reconstructed with best tools available.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.afjem.2018.07.005.
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