

Article

The Influence of Different ECMO Cannulation Site and Blood Perfusion Conditions on the Aortic Hemodynamics: A Computational Fluid Dynamic Model

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Abstract: Extracorporeal Membrane Oxygenation (ECMO) is a medical device used to support patients with severe cardiac and/or respiratory failure. It is being used more frequently to offer percutaneous mechanical circulatory support, even though the intricate interactions between ECMO and the failing heart, as well as its impact on hemodynamics and perfusion, are not yet fully understood. Within the two main types of ECMO support (the veno-venous ECMO (VV-ECMO), which is used to support only the lungs) and the veno-arterial ECMO (VA-ECMO), which is used to support the lungs and heart), consideration is given solely to the second approach. Indeed, this study focuses on the impact of different ECMO cannulation site and blood perfusion conditions on the aortic hemodynamics and organ perfusion in VA-ECMO. Using computed tomography (CT) images, we reconstructed specific aortic models based on clinical cannula configurations and placements. A detailed cannula-aorta integration model was developed to simulate the VA-ECMO blood supply environment. Employing computational fluid dynamics (CFD), we analyzed how varying ECMO perfusion levels and ECMO cannulation sites affect flow characteristics. This study provides insights into optimizing ECMO therapy by understanding its effects on blood flow and potential damage to blood and organs.

Keywords: computational fluid dynamics; extracorporeal membrane oxygenation; aortic hemodynamics



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1. Introduction

Extracorporeal Membrane Oxygenation (ECMO) is widely used as an advanced medical device with the aim to provide critical support for patients experiencing severe cardiac and/or respiratory failure [1,2]. Its application has increased notably in recent years, enhancing the chances of survival for patients with severe and life-threatening conditions [3]. ECMO systems generally fall into two categories: veno-venous ECMO (VV-ECMO), which exclusively supports pulmonary function, and veno-arterial ECMO (VA-ECMO), which provides comprehensive support for both the lungs and the heart [4]. Although ECMO is increasingly utilized, the complex interactions between the device and a failing heart, along with its impacts on hemodynamics and organ perfusion, remain areas of concern [5]. When VA-ECMO is deployed, it delivers oxygenated blood directly into the arterial system, bypassing the failing heart and lungs [6]. However, this creates the potential for severe complications, such as Harlequin syndrome (also known as “north-south syndrome” or “dual circulation”) [7–10].

This syndrome arises when there is a mismatch between the native cardiac output and the retrograde ECMO flow, leading to inhomogeneous aortic flow patterns. The upper body (supplied by the left ventricle) and the lower body (supplied by the ECMO circuit) may receive blood with vastly different oxygenation levels. This can lead to complications

such as pulmonary congestion, left ventricular distension, and end-organ hypoxemia, all of which contribute significantly to morbidity and mortality in ECMO patients.

The femoral artery is commonly used for rapid vascular access in adult VA-ECMO. However, this approach carries notable risks, including femoral artery occlusion, distal limb ischemia, reperfusion injury leading to compartment syndrome, retroperitoneal hemorrhage, thrombosis, embolization, and, critically, brain and myocardial ischemia due to inadequate upper body perfusion. These risks are particularly elevated in patients with severe peripheral vascular disease, which may serve as a relative contraindication to femoral artery cannulation. Subclavian artery cannulation offers a promising alternative, helping to maintain cerebral and cardiac blood flow while reducing the complications linked to femoral artery cannulation.

Understanding the hemodynamic changes that occur during VA-ECMO is crucial for optimizing patient outcomes. Clinicians often face challenges in balancing ECMO flow with native heart function to prevent complications such as organ ischemia, increased afterload, or systemic hypoperfusion. This makes the study of aortic flow dynamics, particularly through mathematical modeling [11] and computational fluid dynamics (CFD), vitally important.

Computational Fluid Dynamics models are a powerful tool in the cardiovascular realm [12–17] and, specifically, in ECMO therapy [17–19], providing valuable insights into fluid dynamics, optimizing device settings and configurations, and ultimately improving patient outcomes through better understanding and management of the complex interactions between ECMO systems and the human body.

Indeed, the CFD modeling has the power to provide a detailed simulation of blood flow dynamics within the ECMO circuit and the specific patient's vasculature. It is essential for understanding how the ECMO device (type, position, orientation) influences blood flow and how it interacts with the patient's anatomy. CFD models can simulate various cannula placements and configurations, that are critical points in ECMO therapy, to determine their impact on hemodynamics. This helps in optimizing cannula positioning to ensure effective blood flow, reduce complications, and improve patient outcomes. In addition, CFD models allow for the optimization of ECMO settings to minimize adverse effects on blood by evaluating parameters like wall shear stress (WSS) and oscillatory shear index (OSI) that are crucial in evaluating potential blood damage and the risk of thrombus formation or hemolysis.

State-of-the-art contributions made a previous attempt to investigate blood flow behavior in VA-ECMO cannulation [18–23].

Xi et al. [22] employed a CFD method in peripheral VA-ECMO cannulation to study the impact of varying perfusion conditions—specifically, different cardiac output volumes and ECMO perfusion levels—on flow characteristics such as velocity and pressure gradient. GU et al. [23] examined the differences in aortic hemodynamics between central VA-ECMO and peripheral VA-ECMO, discovering that lower extremity perfusion levels were significantly reduced in peripheral VA-ECMO compared to central ECMO. However, these studies simplified the aortic model or used an idealized version, which diverges from clinical reality and does not account for many important organ perfusions within the aorta.

The aim of our study is to specifically investigate the VA-ECMO approach, focusing on how variations in ECMO cannulation sites (femoral vs. subclavian) and blood perfusion conditions influence aortic hemodynamics and organ perfusion.

By analyzing how cannulation sites and ECMO flow rates affect aortic and organ perfusion, we aim to provide insights that could improve the precision of ECMO management and reduce the risk of adverse clinical outcomes.

By examining these factors, the research aims to enhance understanding of how different ECMO configurations impact blood flow dynamics and organ function, potentially improving clinical outcomes for patients undergoing VA-ECMO therapy. Mathematical models and computational fluid dynamics approaches play an important role in understanding and optimizing an ECMO system, with a particular focus in improving flow

dynamics, ensuring appropriate flow rates, reducing areas of low velocity or stagnation, and managing pressure gradients to minimize complications like thrombosis or afterload on the heart. The model helps predict where improvements in flow or adjustments in cannulation might better support patient outcomes. Thus, this investigation is directly linked to real-world clinical challenges, and its findings could lead to better-informed decisions during ECMO therapy, ultimately improving patient survival rates and reducing complications associated with this life-saving yet high-risk procedure.

2. Materials and Methods

2.1. Anatomical Model

A three-dimensional, patient-specific model of the aorta, obtained from a series of DICOM (Digital Imaging and Communications in Medicine) images (in vivo contrast-enhanced axial CT scan), was used. CT images were performed on a healthy female (21 years old [24]). The resulting surface geometry (Figure 1) was improved for CFD analysis and converted into an appropriate format to be imported in COMSOL Multiphysics® (version 6.1) software [25], used for fluid dynamic simulation.



Figure 1. Tridimensional model of aorta and branches.

The model of the aorta includes four sections: the ascending aorta, the aortic arch, the thoracic aorta, and the abdominal aorta. The 4 branch vessels of the aortic arch (identified in our study as superior trunk) are the right subclavian artery (RSCA), right common carotid artery (RCCA), left common carotid artery (LCCA) and left subclavian artery (LSCA) (Figure 2). The aorta model was reconstructed including also the left gastric artery (LGA), hepatic artery (HA), splenic artery (SA), superior mesenteric artery (SMA), right renal artery (RRA), left renal artery (LRA), inferior mesenteric artery (IMA), left internal iliac artery (LIIA), right iliac artery extension (RIAE), left profunda artery (LPA), and left femoral artery (LFA), shown in Figure 2.

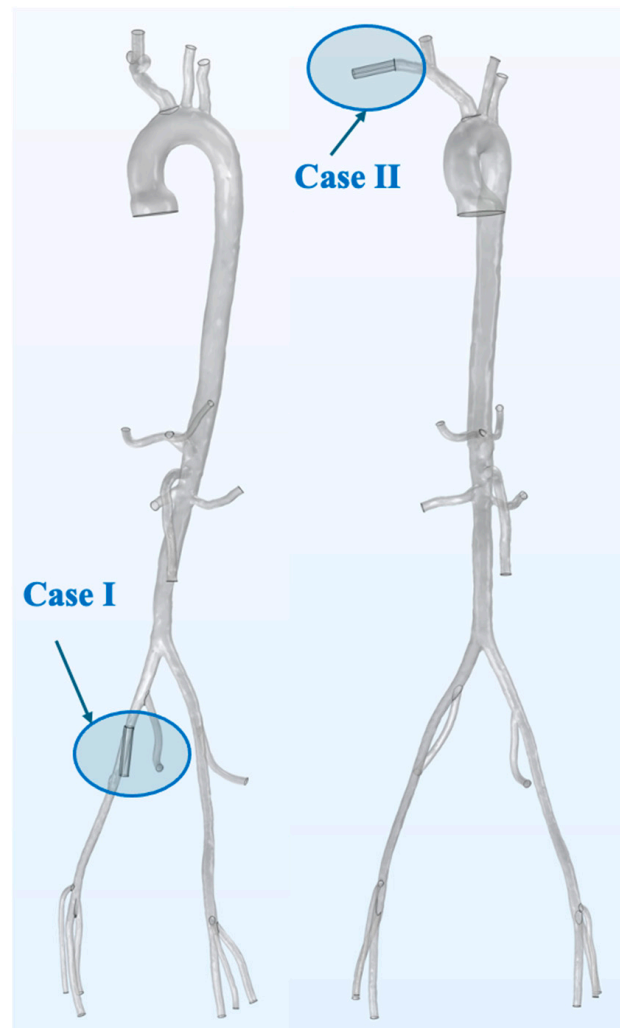


Figure 2. VA-ECMO cannulations sites.

A simplified arterial cannula with 18 Fr (6.0 mm diameter) size was modeled and inserted in two different positions according to the clinical routine placement of VA-ECMO cannulations [4]. Thus, two models are considered, as follows:

- Case I, with arterial cannula positioned in femoral site (Figure 2);
- Case II, with arterial cannula positioned in subclavian site (Figure 2).

2.2. Mathematical Model, Boundary Conditions, and Simulation Details

To simulate the blood motion, the 3D incompressible Navier–Stokes equations were considered, as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho (\partial \mathbf{u} / \partial t) + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{F} \quad (2)$$

where $\mathbf{u}$ indicates the fluid velocity vector, $\nabla \mathbf{u}$ is the tensor derivative of the velocity vector $\mathbf{u}$, p represents the pressure, μ is the dynamic viscosity, ρ is the density of blood, $\mathbf{I}$ is the identity matrix, and $\mathbf{F}$ is the volume force field.

It is important to note that, because the patient was in a supine position during the surgical procedure, the force of gravity (term $\mathbf{F}$) was omitted from the computational study. Thus, the simplified equation to simulate the blood motion is as follows:

$$\rho (\partial \mathbf{u} / \partial t) + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (3)$$

Blood is assumed to have a Newtonian behavior, a conventional assumption for flows in vessels as large as the aorta [26]. The laminar model was adopted to simulate the blood flow motion. Blood density ρ was assumed to be equal to 1060 kg/m^3 , while the dynamic viscosity μ was $0.0035 \text{ Pa} \cdot \text{s}$.

In most previous CFD studies, blood was simplified as a Newtonian fluid, even though its behavior is not truly Newtonian. As flow velocity and shear strain rates increase, blood viscosity decreases [27,28]. However, in low-flow regions, viscosity is higher than typically accounted for, and non-Newtonian models could better represent these variations in blood viscosity. Prior studies have simulated blood flow across various vessels, highlighting differences in pressure and wall shear stress (WSS) estimates when using Newtonian versus non-Newtonian models [29–31]. In our study, focused on a large vessel, we chose to approximate blood as a Newtonian fluid for simplicity.

For both cases, we hypothesized that no flow came out from the aortic valve (total support condition: all the blood flow rate in aorta is supplied by ECMO). Thus, the blood was delivered only through the arterial cannula, and the aorta was modeled with a zero-velocity input.

To evaluate the hemodynamics in the aorta vessel, two steady-state simulations were performed, as follows:

- (a) Case I: Arterial Cannula in femoral site;
- (b) Case II: Arterial Cannula in subclavian site.

Each case was analyzed considering different conditions of flow rates in VA-ECMO cannula. Specifically, several values of constant flow rate (2.00/3.00 and 4.00 L/min) were set as the inlet boundary condition for the VA-ECMO cannula. A pressure outlet boundary condition of 70 mmHg was applied at all the exits. Considering that this study investigates how variations in ECMO cannulation sites (femoral vs. subclavian) and blood perfusion conditions influence aortic hemodynamics and organ perfusion, the assumption of identical boundary conditions for both simulations was chosen. For the computational fluid dynamics simulation, the aorta and the VA-ECMO cannula walls were assumed to be inflexible, and no-slip boundary conditions were applied.

In this study, COMSOL 6.1 (Comsol Inc., Burlington, MA, USA), a finite element analysis solver for various physics and engineering applications [25] was used.

To analyze mesh quality and performance in COMSOL 6.1, several key metrics were evaluated, including minimum element quality, element volume ratio, and maximum growth rate. For both cases (I and II), optimal mesh parameters were selected to balance mesh quality, computation time, and solution accuracy. The convergence error achieved was around 10^{-6} , indicating that the solutions are highly accurate. This careful tuning of mesh parameters ensures that the numerical results are reliable while maintaining efficient computational performance.

The meshes comprised tetrahedral elements totaling 219,288 elements for case I and 209,937 elements for case II, with a minimum element quality of 0.0020739 for case I and 0.004269 for case II, an average element quality of 0.6794 for case I and 0.6657 for case II, and an element volume ratio of 1.468×10^{-5} for case I and 2.623×10^{-7} for case II (Figure 3).

While increased refinement typically leads to more accurate results, it also significantly impacts computational load and times due to mesh quality. Therefore, it is essential to

establish a sufficiently fine mesh beyond which further refinement yields diminishing returns. In this analysis, lower computational times were prioritized, as an excessively refined solution was not necessary. To solve the Navier–Stokes equations, some choices were made, as follows: the Pardiso solver with a pivoting perturbation of 1.0×10^{-13} , the P1–P1 finite element method for spatial discretization, and linear elements for both velocity components and the pressure field. The computations were performed on an Intel (Santa Clara, CA, USA) Xeon 2.10 GHz processor with 192 GB of RAM.

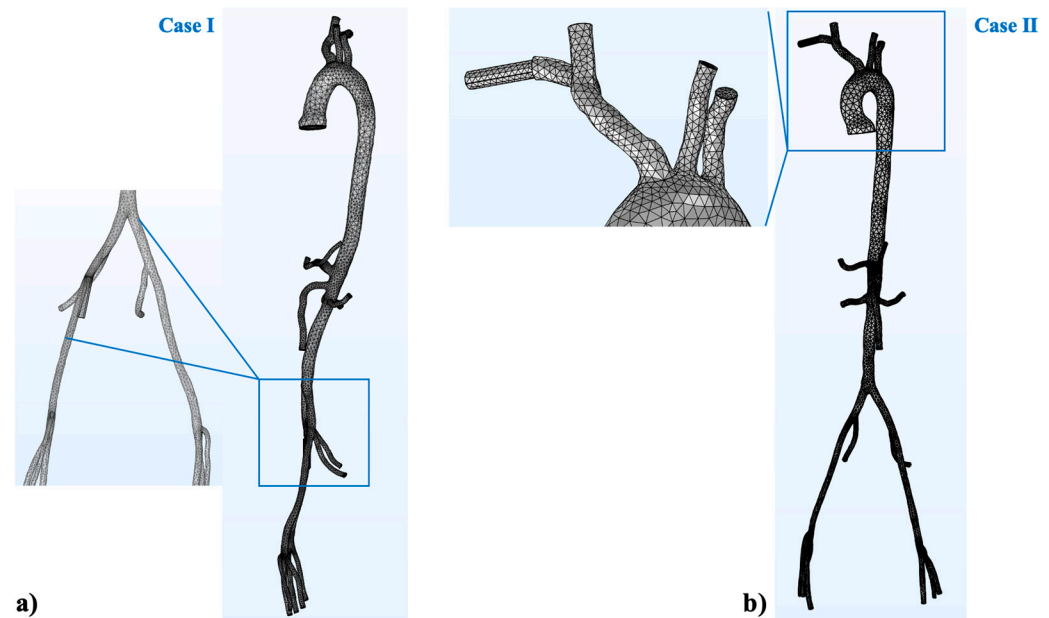


Figure 3. Mesh in case I (arterial cannula in femoral site (a)) and in case II (arterial cannula in femoral site (b)).

3. Results

The hemodynamic modifications (flow distribution and velocity pattern) were evaluated in case I and case II also considering, for each case, several values of constant flow rate (2.00/3.00 and 4.00 L/min) set as the inlet boundary condition for the VA-ECMO cannula.

The flow distribution in all vessels for the two analyzed cases and for the different values of VA-ECMO cannula inlet flow rates are evaluated.

More specifically, the velocity field in terms of streamlines in epiaortic vessels (superior trunk) for the case I and II and for the three values of VA-ECMO cannula inlet flow rate (2.00/3.00 and 4.00 L/min) are shown in Figure 4. In the upper part of the aorta, the flow is lower in the case of femoral cannulation; in the case of subclavian artery cannulation, the flow towards the upper part of the body increases with the increase in the flow rate. It should be remembered that in the vessel occupied by the cannula there is an additional cannula to provide the correct perfusion.

Similarly, the velocity flow distributions in terms of streamlines in thoracic vessels (inferior trunk) for the case I and II and for the three values of VA-ECMO cannula inlet flow rate (2.00/3.00 and 4.00 L/min) are illustrated in Figure 5. Analyzing the flows in the lower part of the trunk, it is possible to note how the flows are lower in the case of subclavian cannulation. This could lead to ischemic phenomena in the lower limbs or other types of problems related to poor blood supply.

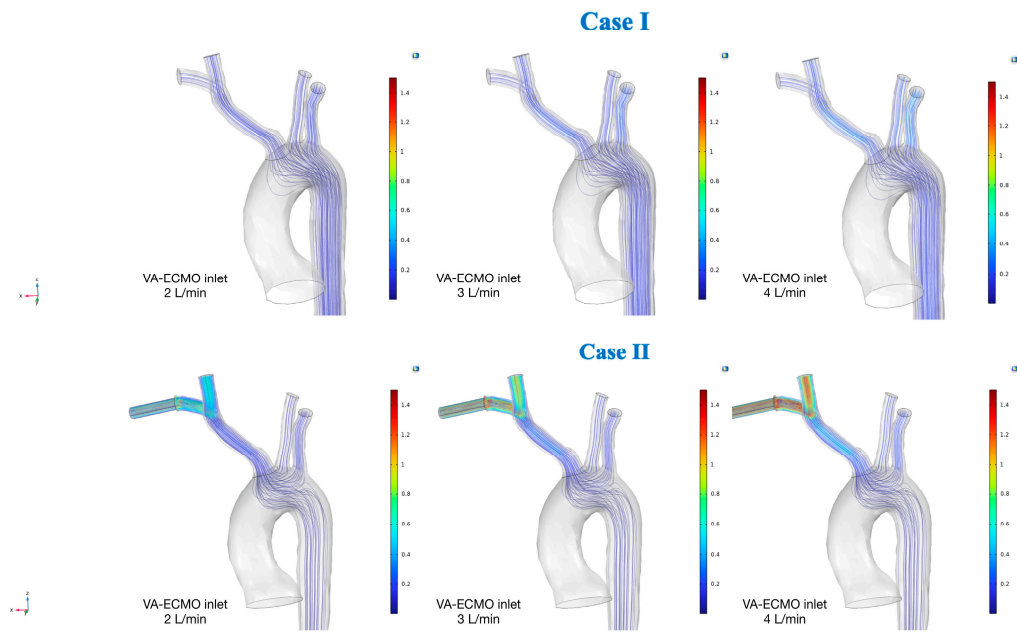


Figure 4. Velocity field (streamlines) (m/s) in cannula and epi-aortic branches in case I (arterial cannula in femoral site) and in case II (arterial cannula in subclavian site) for the three values of VA-ECMO cannula inlet flow rate (2.00/3.00 and 4.00 L/min).

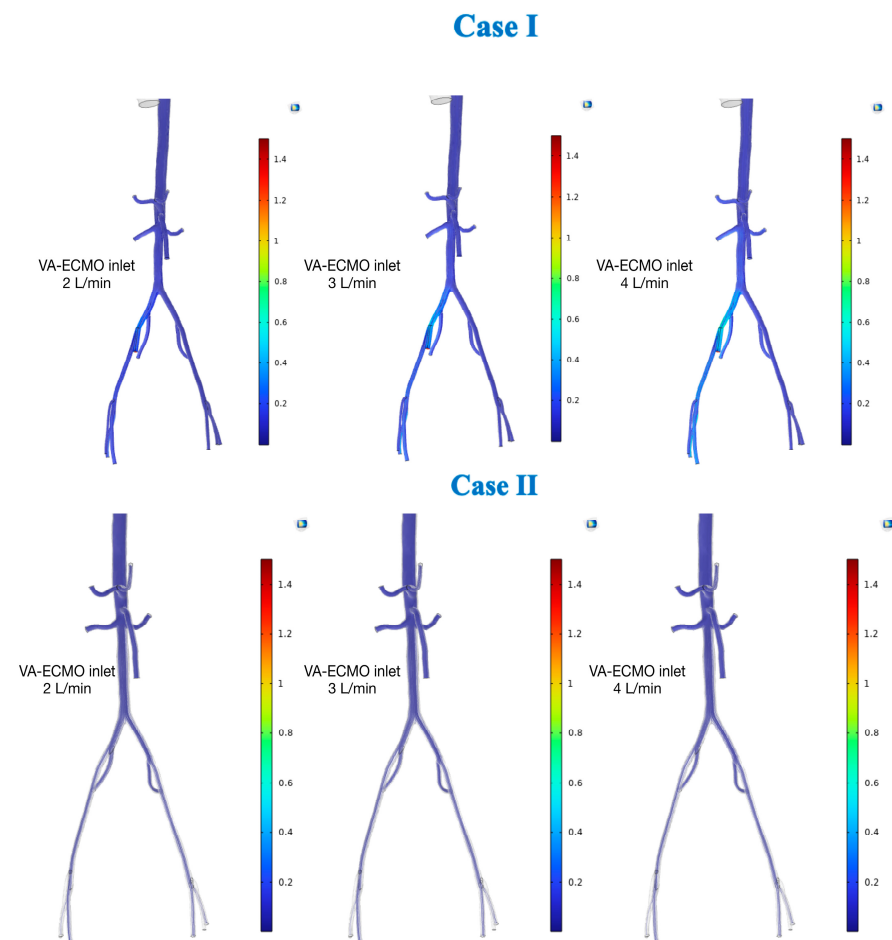


Figure 5. Velocity field (streamlines) (m/s) in cannula and thoracic branches in case I (arterial cannula in femoral site) and in case II (arterial cannula in subclavian site) for the three values of VA-ECMO cannula inlet flow rate (2.00/3.00 and 4.00 L/min).

In addition, mean flow rates in superior and inferior trunk between case I and case II and for the three values of VA-ECMO cannula inlet flow rate (2.00/3.00 and 4.00 L/min) are evaluated and shown in Table 1.

Table 1. Comparison of mean flow rates in superior and inferior trunk between case I and case II and for different values of VA-ECMO cannula inlet flow rate.

Vessel	Case I (Femoral Site)			Case II (Subclavian Site)		
	Cannula Inlet			Cannula Inlet		
	(2.00 L/min)	(3.00 L/min)	(4.00 L/min)	(2.00 L/min)	(3.00 L/min)	(4.00 L/min)
	Mean Flow (L/min)	Mean Flow (L/min)	Mean Flow (L/min)	Mean Flow (L/min)	Mean Flow (L/min)	Mean Flow (L/min)
Superior Trunk	0.7019	1.0530	1.4041	1.2332	1.8507	2.4688
Inferior Trunk	1.3165	1.9746	2.6326	0.1546	0.2321	0.3099

Perfusion of the upper part of the trunk is certainly greater in the case of subclavian cannulation. It should also be considered that an additional cannula helps to perfuse the most sacrificed vessels.

For both cases, we hypothesized that no flow came out from the aortic valve (total support condition: all the blood flow rate in aorta is supplied by ECMO). Thus, the blood was delivered only through the arterial cannula, and the aorta was modeled with a zero-velocity input. To give information on aortic hemodynamics in the presence of left ventricular flow, in addition to the flow rate in the cannula, we performed an additional simulation. More specifically, for both cases (Case I femoral site and Case II subclavian site), the conditions were as follows:

- Flow rate of 3.00 L/min was set as the inlet boundary condition for the VA-ECMO cannula;
- Flow rate of 1.00 L/min (small left ventricular contribution) was set as the inlet boundary condition for the ascending aorta;
- A pressure outlet boundary of 70 mmHg was applied at all the exits.

Thus, compared to the simulations in which only the condition of 3.00 L/min was set as the inlet boundary for the VA-ECMO cannula, we added the condition of flow rate of 1.00 L/min (small left ventricular contribution) as the inlet boundary condition for the ascending aorta. Table 2 shows the results of this simulation.

Table 2. Comparison of mean flow rates in superior and inferior trunk between case I and case II and for same values of VA-ECMO cannula inlet flow rate (3.00 L/min) and with the additional condition of flow rate of 1.00 L/min (small left ventricular contribution) as the inlet boundary condition for the ascending aorta.

Vessel	Case I (Femoral Site)		Case II (Subclavian Site)	
	Cannula Inlet	Asc. Aorta Inlet	Cannula Inlet	Asc. Aorta Inlet
	(3.00 L/min)	(1.00 L/min)	(3.00 L/min)	(1.00 L/min)
	Mean Flow (L/min)		Mean Flow (L/min)	
Superior Trunk	1.7807		2.5227	
Inferior Trunk	2.2561		0.5228	

As results, in Case I (femoral site), the flow through the superior trunk was 1.7807 L/min, while the inferior trunk received 2.2561 L/min. In contrast, for Case II (subclavian site), the superior trunk experienced a higher flow rate of 2.5227 L/min, while the inferior trunk saw a significantly lower flow of 0.5228 L/min.

4. Discussion

This study aimed to investigate the effects of different ECMO cannulation sites and varying blood perfusion conditions on aortic hemodynamics and organ perfusion using computational fluid dynamics (CFD). The use of extracorporeal membrane oxygenation (ECMO) [3,5], particularly veno-arterial ECMO (VA-ECMO), has become increasingly prevalent in supporting patients with severe respiratory and cardiac failure [6–10]. However, its impact on blood flow dynamics and organ perfusion remains an area of concern [5]. Indeed, the effort of the clinical and scientific community is moving towards greater understanding of the hemodynamic alterations that occur during VA-ECMO to improve patient outcomes. Clinicians often encounter challenges in harmonizing ECMO flow with the patient's native cardiac function to avoid complications such as organ ischemia, elevated afterload, or systemic hypoperfusion. As a result, the investigation of aortic flow dynamics, particularly through mathematical modeling [11] and computational fluid dynamics (CFD), becomes critically important.

Recent advancements have sought to investigate blood flow behavior during VA-ECMO cannulation [18–23]. Xi et al. [22] used a CFD approach to model only peripheral VA-ECMO cannulation, examining the effects of different cardiac output volumes and ECMO perfusion levels on flow characteristics like velocity and pressure gradients. The authors demonstrated that peripheral VA-ECMO with varying levels of cardiac output and ECMO perfusion significantly affects aortic flow dynamics.

Gu et al. [23] studied aortic hemodynamics in both central and peripheral VA-ECMO configurations, finding that peripheral VA-ECMO resulted in significantly reduced lower extremity perfusion compared to central ECMO. However, these studies relied on simplified or idealized aortic models, which deviate from clinical reality and overlook important organ-specific perfusion patterns within the aorta. Compared to these previous studies, we analyzed aortic hemodynamics in both central and peripheral VA-ECMO configurations with several cannulation perfusion levels and in a patient-specific model.

Our findings provide valuable insights into the intricate hemodynamic interactions in the aorta during VA-ECMO support. The CFD simulations revealed that both cannulation site and perfusion levels significantly influence aortic flow patterns and organ perfusion. Specifically, differences in cannulation positions led to distinct variations in flow distribution, which are critical for minimizing blood damage and optimizing oxygen delivery to vital organs. Our model demonstrated that suboptimal cannulation positioning can result in uneven perfusion, potentially compromising cerebral and myocardial blood flow. This is particularly concerning for patients with preexisting cardiovascular conditions, where maintaining adequate perfusion is crucial. Based on data of this type, the surgeon can adjust the various flow rates.

Using an additional simulation, we explored the two different VA-ECMO cannulation sites (femoral and subclavian) and assessed how the inclusion of a small left ventricular flow (1.00 L/min) affects the aortic hemodynamics when the ECMO is supplying most of the circulatory support (3.00 L/min). The goal was to understand the distribution of flow between the superior and inferior trunks of the aorta under these conditions.

In Case I (femoral site), the flow through the superior trunk was 1.7807 L/min, while the inferior trunk received 2.2561 L/min. In contrast, for Case II (subclavian site), the superior trunk experienced a higher flow rate of 2.5227 L/min, while the inferior trunk saw a significantly lower flow of 0.5228 L/min.

These results suggest a significant difference in how blood flow is distributed between the superior and inferior aorta depending on the cannulation site. The subclavian site seems to favor increased flow to the superior trunk, likely due to the anatomical proximity of the cannula to this region and the reduced need to route blood flow further downstream. On the other hand, the femoral site supports a more balanced distribution, with a higher flow rate to the inferior trunk.

This difference can be attributed to the hemodynamic impact of the cannulation location on the overall vascular resistance and the interaction between the ECMO flow

and the small left ventricular contribution. The small left ventricular flow (1.00 L/min) is expected to provide a modest contribution to the aortic flow, but the presence of ECMO support strongly influences how the flow is directed through the arterial tree.

The value of CFD in this context lies in its ability to model typical flow patterns and pressures associated with various cannulation strategies, which can inform protocols and best practices. By understanding how different cannulation sites influence blood distribution to critical organs (such as the brain and kidneys), clinicians can make more informed decisions that help mitigate complications like upper body hypoperfusion or lower limb ischemia. CFD simulations also allow for exploring how different flow rates affect aortic hemodynamics, which can guide post-ECMO adjustments in clinical practice to optimize organ perfusion and reduce risks of complications.

In essence, while CFD simulations cannot replace the need for rapid decision making in emergency ECMO deployment, they provide a valuable foundation for establishing generalized, evidence-based protocols that improve outcomes across a range of emergency scenarios.

Moreover, the study highlights the importance of monitoring ECMO perfusion levels closely. The results indicate that higher ECMO flow rates, while ensuring sufficient circulatory support, can lead to increased shear stress, raising concerns about potential blood trauma and hemolysis. Conversely, lower perfusion rates may lead to insufficient organ perfusion, particularly in the brain and heart. Striking the right balance between these two extremes is essential for improving patient outcomes.

Our findings align with existing literature that underscores the complexity of ECMO management and the need for further research into optimizing ECMO settings. Studies by others have indicated similar challenges in achieving optimal hemodynamic support without causing adverse effects on blood flow patterns. However, our study advances the understanding of how different cannulation strategies directly impact these outcomes, offering practical guidelines for clinical ECMO management. Indeed, important considerations can be made on the implications of subclavian vs. femoral cannulation on organ perfusion. Concerning subclavian cannulation, our study confirmed that it provides better perfusion to the upper body, including the brain, which is advantageous for preventing cerebral ischemia. However, it might compromise blood flow to the lower body, leading to risks of ischemia in the lower limbs or abdominal organs. This approach may thus be more suitable for patients where brain and upper body perfusion is the primary concern, such as those with significant cardiac dysfunction or risk of stroke. Femoral cannulation offers better blood supply to the lower body but at the potential expense of upper body perfusion, including blood flow to the brain. This could lead to upper body hypoperfusion if the patient's native cardiac output is insufficient. Femoral cannulation may be preferable in patients where perfusion to the abdominal organs and lower extremities is the priority, such as in trauma cases or in those with pre-existing vascular issues in the lower body.

Clinical significance of the patterns indicates a trade-off between upper and lower body perfusion based on cannulation site. Clinicians need to balance the risk of ischemia in different regions, selecting the cannulation site based on patient-specific factors, such as the presence of peripheral vascular disease, risk of cerebral ischemia, or critical organ perfusion needs. For instance, in patients requiring brain protection and high cerebral perfusion, subclavian cannulation might be prioritized. On the other hand, patients with a risk of lower limb ischemia or who need strong perfusion to the abdominal organs might benefit more from femoral cannulation.

These insights guide the selection of VA-ECMO cannulation sites to optimize patient outcomes and minimize the risk of organ ischemia depending on the clinical scenario.

There are some limitations to this study. First, while the CFD models provide detailed insights into flow characteristics, they are inherently limited by the assumptions made regarding blood properties, vessel wall elasticity, and other physiological factors that were not accounted for in this simulation.

The limitation of the Newtonian fluid deserves particular attention. Indeed, from a macroscopic point of view, the blood has a non-Newtonian behavior [32], but for large vessels it can be modeled as an incompressible and Newtonian fluid [26], with a viscosity of 0.0035 Pa·s [33]. As a non-Newtonian fluid, its viscosity changes depending on the shear rate. At higher shear rates (like those near vessel walls or during rapid blood flow), blood behaves more like a Newtonian fluid with stable viscosity. However, at low shear rates, which occur in areas of slower blood flow or near stasis (such as in large arteries or areas with complex flow patterns), blood viscosity increases as red blood cells aggregate. Flow velocities and pressure gradients in low-shear regions might be inaccurately predicted. A Newtonian assumption might make the model better suited to high-shear regions (e.g., near the cannula and high-velocity regions), but it could reduce accuracy in areas where blood flows more slowly.

The rigid-wall assumption in this model presents a significant limitation, particularly in patients with altered aortic compliance, such as those with hypertension. In clinical settings, this could lead to an underestimation of adverse effects on blood flow dynamics, particularly in how ECMO therapy influences organ perfusion. Future models should incorporate aortic elasticity to better simulate real-world conditions and to improve the accuracy of hemodynamic predictions, allowing for more precise optimization of VA-ECMO cannulation strategies in diverse patient populations.

Another limitation concerns the single-patient analysis that was conducted in this study. Using data from a single patient limits the generalizability of the findings. Differences in anatomy and physiology across patients mean that broader trends might be missed, and specific predictions may not apply to others with different profiles. For broader application, incorporating multiple patient anatomies and performing sensitivity analyses would help validate and generalize the study's findings, making the model a more reliable tool for clinical guidance in ECMO cannulation strategies.

Additionally, the study focuses on VA-ECMO, and the findings may not be entirely applicable to veno-venous ECMO (VV-ECMO) or other forms of mechanical circulatory support. Future studies could explore these aspects to provide a more comprehensive understanding of ECMO's hemodynamic effects across different patient populations and conditions.

5. Conclusions

This study demonstrates that the aortic hemodynamics and organ perfusion in VA-ECMO are significantly influenced by cannulation site and ECMO perfusion settings. By employing computational fluid dynamics (CFD) on patient-specific aortic models reconstructed from CT images, we evaluated the complex flow dynamics associated with various cannulation configurations. Our findings highlight the potential to optimize VA-ECMO therapy through tailored cannulation strategies, thereby improving blood flow distribution and minimizing risks to organs. This work provides a foundational understanding that may guide clinicians in selecting ECMO parameters that maximize therapeutic efficacy while reducing hemodynamic complications, potentially improving outcomes for patients with severe cardiac and respiratory failure. In conclusion, this study reports that both the ECMO cannulation site and perfusion level significantly affect aortic hemodynamics and organ perfusion during VA-ECMO. These findings highlight the importance of individualized cannulation strategies and careful monitoring of perfusion levels to optimize ECMO therapy. The insights gained from this work can guide clinicians in refining ECMO protocols, ultimately improving patient outcomes in critical care settings. Further studies incorporating a broader patient dataset and non-Newtonian blood flow models are warranted to validate and generalize these findings.

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G.F.; project administration, G.F.; funding acquisition, G.F. All authors have read and agreed to the published version of the manuscript.

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