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Computational Fluid Dynamics in Cardiac Surgery and Perfusion: A Review

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Abstract:	Cardiovascular diseases persist as a leading cause of mortality and morbidity, despite significant advances in diagnostic and surgical approaches. Computational Fluid Dynamics (CFD) represents a branch of fluid mechanics widely used in industrial engineering but is increasingly applied to the cardiovascular system. This review delves into the transformative potential for simulating cardiac surgery procedures and perfusion systems, providing an in-depth examination of the state-of-the-art in cardiovascular CFD modeling. The study first describes the rationale for CFD modeling and later focuses on the latest advances in heart valve surgery, transcatheter heart valve replacement, aortic aneurysms, and extracorporeal membrane oxygenation. The review underscores the role of CFD in better understanding physiopathology and its clinical relevance, as well as the profound impact of hemodynamic stimuli on patient outcomes. By integrating computational methods with advanced imaging techniques, CFD establishes a quantitative framework for understanding the intricacies of the cardiac field, providing valuable insights into disease progression and treatment strategies. As technology advances, the evolving synergy between computational simulations and clinical interventions is poised to revolutionize cardiovascular care. This collaboration sets the stage for more personalized and effective therapeutic strategies. With its potential to enhance our understanding of cardiac pathologies, CFD stands as a promising tool for improving patient outcomes in the dynamic landscape of cardiovascular medicine.

Computational Fluid Dynamics in Cardiac Surgery and Perfusion: A Review

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Abstract

Cardiovascular diseases persist as a leading cause of mortality and morbidity, despite significant advances in diagnostic and surgical approaches. Computational Fluid Dynamics (CFD) represents a branch of fluid mechanics widely used in industrial engineering but is increasingly applied to the cardiovascular system. This review delves into the transformative potential for simulating cardiac surgery procedures and perfusion systems, providing an in-depth examination of the state-of-the-art in cardiovascular CFD modeling. The study first describes the rationale for CFD modeling and later focuses on the latest advances in heart valve surgery, transcatheter heart valve replacement, aortic aneurysms, and extracorporeal membrane oxygenation. The review underscores the role of CFD in better understanding physiopathology and its clinical relevance, as well as the profound impact of hemodynamic stimuli on patient outcomes. By integrating computational methods with advanced imaging techniques, CFD establishes a quantitative framework for understanding the intricacies of the cardiac field, providing valuable insights into disease progression and treatment strategies. As technology advances, the evolving synergy between computational simulations and clinical interventions is poised to revolutionize cardiovascular care. This collaboration sets the stage for more personalized and effective therapeutic strategies. With its potential to enhance our understanding of cardiac pathologies, CFD stands as a promising tool for improving patient outcomes in the dynamic landscape of cardiovascular medicine.

Keywords: computational fluid dynamics, heart valve, aortic aneurysm; ECMO

Introduction

Computational Fluid Dynamics (CFD) is a powerful and widely-used simulation technique in the cardiovascular field for studying the behavior of fluids and their interaction with solids, particularly in cases of Fluid-Structure Interaction (FSI). This technique provides the means to couple the fluid and structural domains [1, 2].

CFD involves the use of numerical methods and algorithms to solve the governing equations of fluid flow, such as the Navier-Stokes equations, to predict and analyze the behavior of fluid flowing in a vessel or the heart [3]. The numerical technique discussed represents a vital aspect of fluid mechanics, offering profound insights into the intricate hemodynamics present in both normal and pathological conditions. In CFD simulations, several key components are involved. These include accurately representing the geometry of the region of interest, creating the computational domain (referred to as the mesh), defining boundary conditions to specify flow parameters, determining blood properties as either Newtonian or non-Newtonian fluids, selecting an appropriate numerical solver, and finally, executing the solution and post-processing of numerical results. Each of these elements plays a crucial role in enabling comprehensive analysis and understanding of fluid behavior within biological systems. In patient-specific simulation, the starting point for obtaining the anatomy of interest involves the segmentation of the vessel or the heart. Segmentation involves converting medical images into virtual anatomic models, specifying the actual boundaries of the region of interest for which CFD calculations can be performed [4]. The virtual model is discretized into a mesh, comprising a finite number of small elements or cells covering the entire domain. This mesh serves as the framework for numerical solution of the governing equations of fluid flow [5]. Boundary conditions are then defined, specifying the physiological behavior of the fluid and solid at the boundaries of the problem domain. These boundary conditions are essential for solving the mathematical representation of the physics, encompassing inflow and outflow velocities, wall conditions, and interactions with solid structures. [6] The CFD software solver resolves governing equations using numerical methods. This entails iterating through the mesh, calculating flow properties (velocity, pressure, temperature) at each cell based on defined boundary conditions. Numerical solutions are obtained by solving algebraic equations derived from discretizing governing equations whilst convergence criteria dictate the solution's sufficient accuracy. Post-processing follows, analyzing and visualizing results such as pressure field, flow velocity and shear stress [7].

Compared to lumped-parameter models, CFD offers a more detailed and comprehensive approach by investigating the three-dimensional nature of the vessel and allowing for a finer resolution of fluid dynamics within the cardiovascular system. This capability permits the examination of intricate flow patterns and their impact on cardiac function and pathology. However, it's important to note that a significant limitation of CFD is the assumption of rigid wall boundaries. Despite this limitation, CFD simulations provide predictive capabilities, enabling clinicians to assess the hemodynamic effects of various interventions and pathological conditions before they manifest clinically. This predictive aspect facilitates the exploration of different scenarios and treatment strategies, potentially optimizing patient outcomes, in contrast to clinical measurement methods like 4D flow MRI, which offer valuable real-time data on blood flow velocities and patterns *in-vivo*.

Verification and validation are emerging as essential steps to ensure the credibility of the simulation results. In this regard, the ASME V&V 40 guidelines, developed by the American Society of Mechanical Engineers, provide a framework for the verification and validation of CFD simulations in biomedical applications [8]. Verification refers to assessing the accuracy and consistency of the numerical methods, verifying that the simulation results converge to a true solution. "Validation assesses the accuracy of a simulation by comparing obtained results to accepted theoretical solutions or experimental data, such as 4D flow MRI, involving comparisons with advanced imaging techniques. It ensures that the simulation accurately represents the modeled real-world scenario [4, 9]. Beyond validation and verification, in-silico clinical trials offer a valuable approach to alleviate the burdens associated with traditional clinical trials for drugs and biomedical devices, characterized by high costs and the risk of failure [10]. In-silico clinical trials apply computational modeling to evaluate device performance using a 'virtual cohort' of patients, representing realistic anatomical and physiological variability within the targeted patient population. They serve as a complement to real-world clinical trials rather than a replacement [11, 12].

This paper aims to present the state-of-the-art in cardiovascular CFD, with a focus on heart valve surgery, transcatheter valve replacement, extracorporeal membrane oxygenation (ECMO), and cardiac procedures. The objective is to provide insights into understanding cardiovascular diseases, which are leading causes of death and morbidity worldwide. Hemodynamic stimuli exert remarkable effects on the function and structure of the cardiovascular system, impacting autoregulation, heart valve function, and brain perfusion. These effects play a crucial role in determining the long-term prognosis outcome for patients.

The left heart

CFD has played a pivotal role in understanding the pathogenesis of heart valve diseases. However, research interest has predominantly focused on the aortic and mitral valves, with limited literature available for the tricuspid and pulmonary valves.

Biological heart valves (BHV) exhibit high adaptation in patients and demonstrate velocity profiles similar to physiological ones but have a finite lifespan. Hellmeier et al. [13] proposed a method to estimate clinically relevant hemodynamic aortic valve parameters in patients undergoing surgical aortic valve replacement with BHV, utilizing preoperative MRI data. Simulations on virtually modeled valve replacement geometries were conducted to obtain key hemodynamic parameters, including flow velocities and pressure gradients across the BHV. Other studies have attempted to assess thrombogenic and calcification risks in BHVs by correlating these risks with fluid dynamic parameters, such as orifice area, cardiac output, and others [14]. Mechanical Heart Valves (MHV) exhibit longevity, but they may necessitate lifelong anticoagulation therapy and can induce fluid dynamic alterations. Utilizing CFD simulations, this study explores blood flow through bileaflet MHV with concomitant obstruction in the left ventricle outflow tract. The aim is to quantify the impact of the subaortic obstruction on flow patterns and investigate the performance of bileaflet MHVs using Doppler parameters [15, 16].

In the context of surgical options for valve replacement, the David procedure stands out, enabling replacement of the aortic root while preserving the native aortic valve through a reimplantation procedure. CFD plays a crucial role in the aortic valve reimplantation phase during the David procedure. Through numerical simulations, the fluid dynamics of the reimplanted valve can be analyzed by blood flow patterns, pressure distribution, and skin stresses. This analysis can assist surgeons in optimizing the position and orientation of the reimplanted valve, thereby improving post-operative hemodynamic and minimizing the need for re-operations [17].

Transcatheter interventions have revolutionized the treatment of valve diseases. Transcatheter aortic valve replacement (TAVR) involves deploying a prosthetic valve through a catheter, negating the need for open-heart surgery. Nonetheless, TAVI is associated with peri-procedural complications such as paravalvular leakage (PVL), cardiac conduction problems, stroke, and vascular issues. There are therefore several computational studies on the importance of thrombogenic risk in TAVR. Basri et al. [18] implemented an FSI simulation technique to explore the interrelationships between PVL and the severity of leaflet calcification, particularly regarding geometric orifice area openings in relation to hemodynamic flow along a patient-specific aorta model. The simulations demonstrated that the smallest percentage of geometric orifice area opening resulted in the highest likelihood of PVL. This condition increased recirculatory flow proximally to the inner wall of the ascending aorta and generated lower backflow velocity streamlines through the side area of the PVL region. Anam et al. [19] demonstrated the potential of computational techniques to analyze post TAVR-related PVL complications in patient-specific bicuspid aortic valves, assess the risk of PVL induced thrombogenicity, and compare self-expandable device performances in the same patient anatomies. The computational models were also validated using clinical data, establishing a proof of concept for a computational framework for patient-specific modeling of TAVR in bicuspid patients, as this population was initially excluded from clinical trials. Recently, Prisco et al. [20] demonstrate that mathematical modeling using CFD can predict the location and accurately quantify the PVL. They show that PVL decreases as the space occupying the PVL area increased, demonstrating that the native aortic valve contributes to reducing regurgitation and preventing PVL. Further development of this approach could be beneficial in predicting the development of post-procedural PVL, ultimately improving patient selection, choosing the best prosthetic valve, and preparing for post-procedural interventions.

Another high-risk complication of TAVR is conduction abnormalities, including atrioventricular block. These abnormalities can occur due to temporary or permanent contact injury to the atrioventricular conduction tissue [21]. CFD simulations provide insights into the altered flow patterns that may contribute to conduction abnormalities, aiding in predicting and addressing these complications. Recently, Hamdan et al. [22] tested the hypothesis that membranous septum length, as determined by CT, serves as a powerful pre-procedural anatomical predictor of conduction disturbances complicating TAVR.

TAVR-in-TAVR procedure involves implanting a transcatheter heart valve within the existing biological one. Fluid dynamics analysis were carried out to assess the risk of coronary obstruction after TAVR-in-TAVR [23]. Scuoppo and collaborators [24] have performed computational analysis to estimate the risk of device obstruction on the resulting coronary flow after TAVR-in-TAVR for different deployment strategies. Findings demonstrated that high implantation depth and device undersize of the second transcatheter device could significantly reduce coronary flow to 20% of its estimated level before TAVR. Bioprostheses have also been used for transcatheter mitral valve replacement by adapting devices originally designed to treat the diseased aortic valve. A computational study virtually simulated the transcatheter mitral valve replacement and then investigate the hemodynamic and structural mechanics of LVOT obstruction [25]. These findings are relevant to reduce the gap in the knowledge of TMVR when the bioprosthesis is used off-label for mitral valve diseases [26]. As technology continues to advance, a deeper understanding of these dynamics will further refine treatment strategies and improve patient outcomes [27].

Left Atrial Appendage

The left atrial appendage (LAA) is a complex hooked structure of the left atrium which exhibits considerable variability in size, shape, and volume, with prevalent morphological classifications [28]. This anatomical variety plays a pivotal role in thrombus formation and stroke risk, particularly in patients with atrial fibrillation [29]. The different morphologies contribute to variations in flow velocity, and the presence of atrial fibrillation exacerbates these effects, leading to increased blood stagnation and clot formation [30].

Recent CFD analyses, such as those conducted by Corti et al., shed light on the heightened risk of thrombosis in patients with atrial fibrillation, determining specific areas of stasis near the LAA. Novel indicators like "age stasis," proposed by the authors, contribute to identifying regions prone to clot formation [31]. Other studies, including the work by Duenas-Pamplona and collaborators [32], introduced a thrombosis predicting index as M4, i.e. the fourth moment of the fluid age distribution, demonstrating its superior efficacy in predicting stasis compared to other indicators. Simulations of percutaneous LAA occlusion procedures anticipated positive outcomes and highlighted the potential of CFD in assessing intervention effectiveness. These simulations indicated a significant reduction in vortices, suggesting improved blood washout after LAA occlusion and a lowered risk of clot formation [33, 34]. Investigations on LAA position within the left atrium indicated that the location, particularly near pulmonary veins, influences flow distribution and thrombosis risk [35, 36].

As a result, these investigations contributed to a deeper understanding of atrial fibrillation phenomena and enabled the calculation of previously inaccessible blood stasis-related parameters, such as residence time, vorticity, and shear stress. Factors such as high volume, low blood flow velocity, and a two-lobe-appendage configuration are identified as more likely contributors to blood stasis [37].

Moreover, the distal part of the LAA is reported as the most common region for blood stasis due to the lowest velocity magnitude. Slow flow in the LAA increases blood viscosity, altering secondary swirling flows, and intensifying blood stasis [28, 38].

The Right Heart

The right ventricle (RV), often dubbed the "forgotten ventricle," is a crucial component of the heart's circulatory system. RV failure induced by sustained pressure overload significantly contributes to morbidity and mortality in various cardiopulmonary disorders [39]. The primary focus of CFD studies on the pulmonary valve is the investigation of hemodynamics in patients with Tetralogy of FallotIf repaired, the absence of a functioning pulmonary valve often leads to pulmonary regurgitation and progressive enlargement of the right ventricular outflow tract [40]. Loke et al. [41] employed cardiac magnetic resonance imaging to segment the right ventricles (RV) of individuals with repaired Tetralogy of Fallot. They developed a computational framework capable of generating intracardiac flow simulations in patients with the aforementioned condition. This approach aimed to predict the impact of pulmonary valve replacement in patients with repaired Tetralogy of Fallot and enhance clinical decision-making based on MRI-guided indications.

Computational flow analysis was also used to suggest the optimal size of stents and conduit before performing the surgical operation, evaluating how sizes can influence the success of the procedure. Specifically, Sonntag et al. [42] conducted research to investigate the impact of oversizing a pulmonary conduit in pediatric patients on hemodynamics. Their findings indicated that oversizing the conduit resulted in an elevation of wall shear stress, potentially negating the advantages associated with having a nominally larger orifice area. Diana et al. [43] developed and validated a flow model of the right atrium, incorporating realistic geometry and transient physiological boundary conditions. Their study underscored the importance of utilizing an anatomically accurate right atrium model when investigating catheter performance and its interaction with the hemodynamic environment. The findings suggested that careful attention to the correct placement of the catheter tip within the RA is essential for achieving improved recirculation percentages and reduced shear stress values.

Tricuspid regurgitation (TR) stands out as one of the prevalent heart valve diseases. Traditionally, surgery has been the established treatment for TR, despite its association with elevated morbidity, mortality rates, and prolonged hospital stays [44]. Recent advancements have introduced transcatheter tricuspid valve therapies as a viable alternative for treating failed tricuspid valves. This is facilitated by the development of bioprostheses featuring specific design elements tailored to accommodate the tricuspid valve anatomy, as highlighted by Romeo et al. [45]. In the study of Parker et al. [46], a patient-averaged model was generated from images of four volunteers. Results demonstrated that an implicit large eddy simulation approach, coupled with a bounded-central difference convection scheme and a wall-adapting local eddy-viscosity subgrid-scale model, yielded the most accurate results in predicting the dynamics of the right atrium and tricuspid valve. Crascì et al. [47] conducted a study to quantify both the structural and hemodynamic performance of the transcatheter bicaval valves system (ie, the TricValve). They showcased the potential of computational tools in enhancing our comprehension of the biomechanical aspects of structural tricuspid valve interventions.

Aortic aneurysm (ATAA)

An ascending thoracic aortic aneurysm (ATAA) is defined as a permanent, localized dilation of the ascending aorta resulting from a degenerative weakening process in the aortic wall. This complex and potentially life-threatening condition is often associated with various predisposing risk factors, including age, hypertension, bicuspid aortic valve, Marfan syndrome, and family history [48].

The progressive increase in aneurysm diameter is consistently associated with a concurrent increment of stress exerted on the aortic wall and weakening of the aortic layers. This correlation poses a significant clinical concern as it amplifies the risk of severe events, such as aortic rupture, and aortic dissection, with an estimated incidence of 4.5 per 100 000 persons [49, 50]. Using both cardiac MRI [51] and CFDs [52], studies speculated on the mechanistic link between altered flow shear stress and aortic wall weakening. ATAA progressions was demonstrated to occur near region of high wall shear stress and disturbed flow patterns [53, 54]. Prolonged exposure to specific abnormal flow patterns may induce remodeling of the aortic wall structure, thus leading to wall degradation and a fatal risk of aortic dissection or rupture [55].

Bicuspid patients and ATAA exhibited a notably higher risk of rupture compared to those with tricuspid aortic valve morphologies [56]. Pasta and collaborators [57] emphasized the influence of abnormal flow patterns and material discontinuity at the aortic layer interface in the occurrence of aortic dissection. Their findings reveal that the presence of a bicuspid valve and material discontinuity can lead to hemodynamic disturbances on the aortic wall, increasing the risk of aortic dissection. Jayendiran and collaborators [58] underscored the significance of eccentric flow within the aortic root, highlighting its pivotal role in inducing hemodynamic alterations independent of the aortic valve phenotype. Findings revealed that within turbulent regions, there is an increased risk of atherogenic particles accumulating on the endothelial surface. Salmasi et al. [59] further suggested a strict association between elevated fluid shear stress values obtained and tissue-derived mechanical and microstructural properties of the degraded aneurysmal wall structure using CFD and segmental analysis.

Though aneurysm diameter remains a conventional criterion for intervention, additional markers and parameters are essential for diagnosing and monitoring ATAA to prevent complications. This has driven the research of many investigators to establish new biological and hemodynamical markers capable of predicting aneurysm progression and detecting its risk of rupture or dissection early [60]. Perinajovà and collaborators [61] explored the influence of oxygen and nitric oxide in ATAA using CFD, revealing differences between healthy and pathological tissue in nitric oxide concentrations. They emphasized how irregular blood flow patterns could lead to hypoxia, acting as a potential precursor to TAA pathogenesis. Similarly, Pasta and collaborators [52] investigated the association of shear stress and aortic strain with circulating biomarkers, including matrix metalloproteinases, tissue inhibitors of metalloproteinase and the exosomal level of microRNA in ascending aortic aneurysms of patients with bicuspid or tricuspid aortic valves. The findings provided direct evidence that local alterations of shear stress exerted on the aneurysm wall could lead to changes in the aortic structure, ultimately predicting adverse vascular remodeling through mechano-transduction.

The evolving landscape of ATAA research has seen the emergence of novel classification schemes, distinguishing between different phenotypes of aortic shape dilations. These classifications aimed to enhance the risk stratification of patients with ATAAs [60]. Recently, statistical shape modeling combined with computational flow simulations highlighted the variability in shear stress distribution among different aneurysm shapes. In the study of Capellini et al. [54], patient-specific computational flow analyses based on radial basis morphing techniques were employed to simulate the growth pattern of ascending aortic aneurysms and evaluate shear stress at various follow-up period. They found a remarkable hemodynamic changes at the 60% of the bulge progression and an impingement of the flow toward the bulge as shown by the analysis of the normalized flow eccentricity index.

To accurately reproduce in-vivo flow patterns, CFD modeling must employ realistic inflow boundary conditions. The unique combination of 4D flow MRI and CFD is a capable tool to contribute to this goal. Nonetheless, the limited availability of in-vivo velocity measurements often compels researchers to rely on idealized boundary conditions. The study conducted by Saitta and colleagues [62] aimed to generate and thoroughly characterize a large dataset of synthetic 4D aortic velocity profiles sampled on a 2D cross-section along the ascending aorta, mirroring features found in clinical cohorts of patients with ATAAs.

Extracorporeal Device Modeling

Extracorporeal membrane oxygenation (ECMO) is a life-saving organ support effectively used in the treatment of patients with severe respiratory failure, with or without heart failure [63]. For extracorporeal gas exchange, vascular access is needed, and this is accomplished with one or more cannulae placed in major vessels. However, blood is exposed to non-physiological conditions where blood component damage/activation induce increased risks for hemolysis, thrombosis, embolism, and bleeding [64]. In this context, computational flow analysis can be used to provide in-depth hemodynamic assessments in patients undergoing ECMO.

Since several cannulation strategies for ECMO exist, the flow field in cannulated vessels shows features resembling some canonical flow scenarios. In the case of drainage configuration, cannulae with side holes (e.g., with a lighthouse tip (single stage)) exhibit a jet in crossflow type of behavior, characterized by strong shear layers in the drainage area [65]. In the return cannula flow, using a blunt cannula, a confined jet surrounded by a co-flow develops, as shown by Lemétayer et al. [66].

The blood pump is a vital part of an ECMO system and the main source of blood damage. The blood pump used in an ECMO system is typically a centrifugal pump, which rotates quickly to create a large pressure difference and overcome resistance from the body, tubing, and oxygenator to increase blood flow [67]. Furthermore, in the context of blood pumps, mechanical stresses brought on by the non-physiological flow field are primarily responsible for blood damage and platelet activation. [68]. Consequently, a thorough understanding of the fluid mechanics associated with the components is vital to assess the phenomena related to undesired hemodynamic effects. Li et al. [69] utilized computational flow analysis to evaluate the effect of volute design factors, such as spiral start position, volute tongue radius, volute inlet height, volute size, diffuser pipe angle and volute shape, on hemodynamic performance and hemocompatibility of the centrifugal blood pump. Han et al. [70] presented the development of a novel pediatric pump-lung (PPL) for ECMO through a combination of CFD design optimization and in-vitro experimentation. The pediatric pump-lung was designed based on the CFD analysis of hydrodynamics and hemolysis in the pump and the gas transfer performance of the oxygenator. Therefore, CFD-based modeling can be an effective tool for predicting the flow field, pressure distribution, and oxygen transfer in the design of new ECMO systems.

Thrombosis is among the most common side effects linked to extracorporeal oxygenation. According to reports, thrombosis rates in patients receiving ECMO support can range from 18 to 85% [71]. When severe oxygenator thrombosis occurs, there is a risk of decreased gas exchange efficiency and increased blood flow resistance, potentially endangering the patient's life. For this reason, CFD modeling was used to evaluate the effect of oxygenator design features on the surrounding hemodynamic environment. Bozzi et al. [72] investigated the performance of two magnetic levitating centrifugal pumps, designed for ECMO applications, differing in the impeller design. They evaluated local and global hemodynamics using simulations, coupling Eulerian and Lagrangian techniques. In particular, the Lagrangian approach enabled the calculation of idealized platelet trajectories and their stress histories. These were used to estimate platelet sensitization and activation, ultimately assessing the thrombogenic potential of the pumps. Fu et al. [73] employed computational flow analysis to investigate how different oxygenator structures affect their hemodynamic surroundings and analyze the relationship between hemodynamic parameters and thrombosis risk within the oxygenator. Five different oxygenator models were compared, and the parameters of accumulated residence time and coagulation factor concentrations were proposed to evaluate thrombosis risk. These studies can contribute to the design of an oxygenator to enhance hemodynamic surroundings and lower the risk of thrombosis.

To further enhance our understanding of blood flow dynamics, experimental techniques such as particle image velocimetry were used in conjunction with computational flow modeling. Particle velocimetry provides a visual representation of fluid flow by tracking the movement of tracer particles within the blood. Integrating experimental data into flow simulations allows for a more accurate depiction of flow patterns, aiding in the identification of recirculation zones, vortices, and areas of stagnant flow that may contribute to thrombotic events. In this setting, Fiusco et al. [66] characterized the flow structure dynamics during different flow rates and positions for a return lighthouse tip cannula. Moreover, the effect of different flow conditions and the impact on blood damage levels (quantified by hemolytic index) was assessed. The study was carried out using CFD simulations and then the numerical results were validated by experimental data obtained from particle image velocimetry measurements.

Computational flow analysis is also widely used to evaluate the hemodynamic effects of ECMO on cardiovascular system. The hemodynamic performances of various types of ECMO are different from each other, which maybe the key reasons for the differences in the outcomes and complications. Therefore, for peripherical ECMO, the lower-extremity ischemia is a complication that must be considered [74]. The type, support level, and duration of ECMO should also be carefully regulated according to the patients' condition, as they are the important factors related to vascular complications [75, 76].

Conclusions, limitations and future perspectives

After presenting the rationale behind CFD simulations, this review aimed to describe the most important findings of blood flow simulations in the setting of cardiac surgery and perfusion. Within this framework, CFD simulations yield valuable results for clinicians, aiding in treatment planning and risk assessment by providing insights into fluid dynamic parameters such as blood pressure and velocity field. By integrating engineering principles with medical concepts, CFD can contribute to refining and optimizing both surgical intervention and ECMO technologies, thereby improving patient outcomes and mitigating associated risks. However, CFD simulations encounter limitations including the need for technical expertise, computational efforts, knowledge of boundary conditions, as well as a regulatory process, and lack of systematic validation against *in-vivo* data. Addressing these limitations requires the development of robust validation methodologies to enhance the credibility of computational models in future studies.

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Computational Fluid Modeling in Cardiac Surgery and Perfusion: A Review

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