Blood flow dynamics and shear stress characteristics: minimizing risk of blood trauma in blood pumps

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Summary

In Extracorporeal membrane oxygenation (ECMO), the patient's blood is pumped through a circuit composed of a blood pump, oxygenator, tubing, cannulae, and connectors exposing the blood to highly unsteady flow fields. Large eddy simulation (LES) was used to study the flow characteristics of a diagonal ECMO blood pump. By studying the flow structures and separating the shear stress characteristics into elongational and off-diagonal components, increased understanding of the flow structures and their potential effect on blood trauma was obtained. These studies could lead to improvements of pump design and reduce ECMO treatment complication risk.

Introduction

ECMO is a last resort treatment for critically ill patients in need of lung and/or heart support. The blood flow dynamics developing in the different ECMO circuit components are characterized by all known potential coagulation initiators: high shear, prolonged residence times and artificial surfaces. To avoid flow-induced coagulation activation and hemolysis, the stress exerted on the red blood cells, platelets and von Willebrand factor (vWf) needs to remain at near physiological levels, i.e. < 12 Pa [1]. Often a scalar form of the stress tensor is applied when assessing the effect of shear on individual blood components. For example. it is known that vWf may unfold from its naturally coiled state to an extended strand revealing its binding and cleavage sites at shear rates greater than 5000 s^{-1}. However, the existence of elongational flow may lower this shear rate threshold [2], pinpointing that that a scalar stress representation may be insufficient.

Methods

This study numerically investigated DP3 (Xenios AG., Heilbronn, Germany), a diagonal blood pump used in ECMO. The computed-aided design (CAD) geometry used in the simulations was acquired through micro computed tomography [3]. LES was applied to resolve the flow field. The account for impeller rotation, a sliding mesh motion with 1440 time steps per pump revolution (rpm) was applied. A constant viscosity of 0.0036 Pas and constant density of 1059 kg/m3 were used. The computational grid consisted of 32M cells. Three different pump speeds were studied: 5000, 6250 and 8000 rpm and two flow different rates: 1 and 4 L/min.

Results and Discussion

Throughout the pump, the flow was found to be either transitional or turbulent. The results showed three main flow structures coupled with highly unsteady stress characteristics: 1) a backflow at the pump inlet due to boundary layer separation at the impeller blades resulting in vortex roll-up over the impeller moving towards the pump inlet; 2) rotating flow cells under the impeller potentially affecting impeller stability, and 3) Taylor-Couette like structures in the pump outlet region.

Focusing on the stress characteristics, a combination of shearing and elongating flow areas was identified. The impeller and outlet of the pumps clearly showed that the necessary conditions for vWf unfolding existed, Figure 1. From 5 to 16% of the total pump volume exhibited these conditions. At the lower flow rate, the height of the problematic area for the off diagonal shear rate increased with the increasing height of the inlet recirculation.

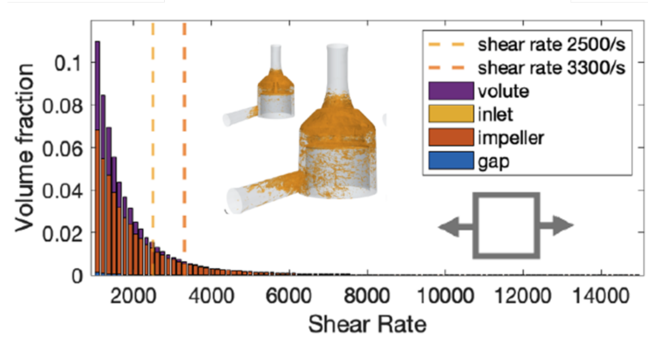

Figure 1: Elongational shear rate with lines marking 2500 s^{-1} and 3300 s^{-1}. The orange areas in pump geometry shows all regions having elongational shear rate above 2500 s^{-1}.

Conclusions

This study emphasizes the importance of evaluating the elongational and the off-diagonal components of the shear rate separately to identify areas of unwanted flow conditions. This increases our understanding concerning impact of pump design on individual blood components.

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References

[1] Chan et al. (2022). *J Biomech*, **130**:110898
[2] Casa and Ku (2017). *Ann Rev Biomed Eng*, **5**: 415-433.
[3] Gross-Hardt et al. (2019). *Critical Care,* **23**(1)