Proc. Annual Meeting of the Austrian Society for
Biomedical Engineering 2021
DOI: 10.3217/978-3-85125-826-4-08

EFFECT OF ATRIAL INFLOW CONDITIONS ON VENTRICULAR FLOW PATTERN DURING LVAD SUPPORT: A SIMULATION STUDY

Ghodrati M.[1,2], Schlöglhofer T.[1,2,3], Maurer A.[1,2], Zonta F.[4], Moscato F.[1,2], Schima H.[1,2,3], Aigner P.[1,2]

[1] Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Austria
[2] Ludwig Boltzmann Institute for Cardiovascular Research, Vienna, Austria
[3] Department for Cardiac Surgery, Medical University of Vienna, Austria
[4]Institute of Fluid Dynamics and Heat Transfer, Technical University of Vienna, Austria

mojgan.ghodrati@meduniwien.ac.at

Abstract

Simulations of the ventricular flow patterns during left ventricular assist device (LVAD) support are mainly performed with straight inflow condition, neglecting the influence of the atrial vortex. In this study, the influence of the atrial inflow conditions – including rotation and asymmetric flow profiles – on the platelet behavior were investigated via Computational Fluid Dynamics (CFD) simulations.

Keywords

Left ventricular assist device, ventricular flow patterns, atrial inflow, computational fluid dynamics

Introduction

The use of LVADs as a treatment method for heart failure patients has been steadily increasing [1]. Despite the success of this treatment, there is still a high risk of thrombosis and consequently a high mortality rate from stroke [2], [3]. Therefore, there is an urgent need for intraventricular flow field investigation during LVAD support for a better understanding of the reasons for the high prevalence of thrombosis in these patients. Numerical simulations can be a useful tool for flow field analysis and for evaluation of the critical parameters at the location of depositions. However, the accuracy of the simulated flow fields is highly dependent on the defined inflow conditions [4].

Simulations of the ventricular flow patterns during LVAD support are mainly performed with perpendicular inflow conditions from the left atrium neglecting asymmetries arising due to uneven flow contribution of the pulmonary veins [5]–[7] as well as the atrial vortex. In this study, the influence of the atrial inflow conditions – including rotation and asymmetric flow profiles – on the flow patterns and the platelet behavior were investigated via numerical simulations.

Methods

The left ventricle (LV) and the pump of an LVAD patient were segmented from computed tomography (CT) images and used in this study.

The Navier-Stokes equations were solved using the finite-volume CFD solver (FLUENT, Ansys 19.1, Pennsylvania, USA). The blood was modeled as a non-Newtonian fluid with a density of 1060 kg/m3 and a dynamic viscosity of 0.0035 Pa·s. using Laminar model [8].

Three different inflow boundary conditions were considered to investigate the importance of the atrial inflow conditions; first, a simulation was performed with perpendicular velocity to the inflow (Straight, flow rate: 3.5 lit/min) to replicate the typical approach of intraventricular flow simulation. For the second simulation an additional rotational component at the inflow (Rotation: 35 rpm) was applied as a representative of the atrial vortex and a third simulation was performed with asymmetric inflow conditions (Asymmetric: 60%/40% left/right flow ratio to replicate physiologic uneven flow distribution of the pulmonary veins). The overview of boundary conditions can be seen in Fig1.

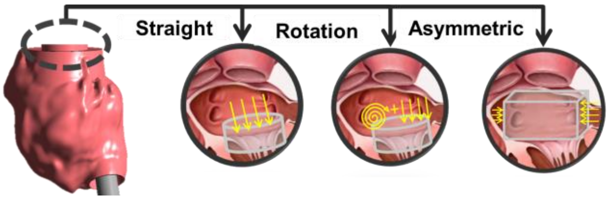

Figure 1: Patient specific LV geometry with atrial inflow conditions.

A Lagrangian approach was used to track 10 000 particles with a diameter of three micrometers. Particles were injected at the beginning of the simulation at the mitral annulus and tracked over 7s within the LV. The risk of platelet activation and aggregation was evaluated by analysis of particle trajectories inside of the LV. The Shear Stress Histories (SSH), (Eq. 1), and the Residence Times (RT) of the particles, (Eq. 2), were used as indicators for thrombogenicity [9]

$$SSH = \int_{t_0}^{t} \tau(X(t'), t')dt' \tag{1}$$

$$RT_i = T_i^{entrance} - T_i^{exit} \tag{2}$$

Published by Verlag der TU Graz
Graz University of Technology

DOI: 10.3217/978-3-85125-826-4-08

Results

Atrial inflow conditions affect the intraventricular flow patterns as well as particle trajectories significantly (Fig. 2).

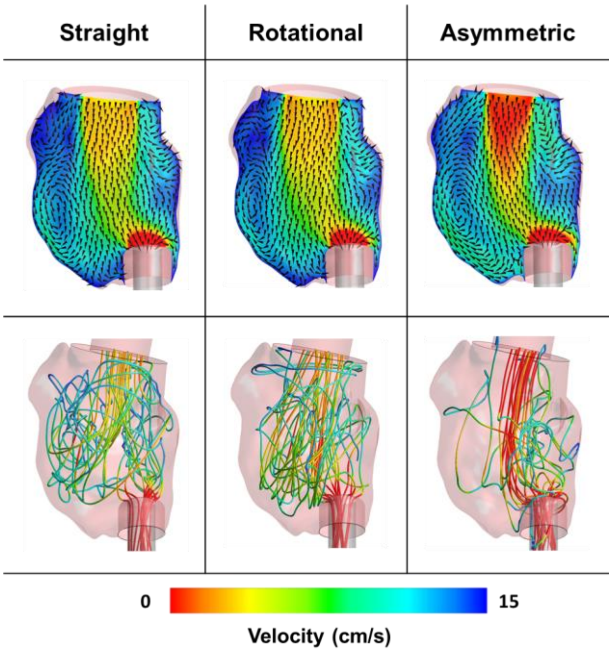

Figure 2: Top row: mean blood flow patterns at coronal plane; bottom row: Particle trajectories for straight, rotation, asymmetric inflow conditions colored with particle velocity magnitude.

Also stagnation regions was increased with rotational inflow (Straight: 13.62, Rotation: 15.83, Asymmetric: 7.33 cm^2) which can be seen in Fig. 3.

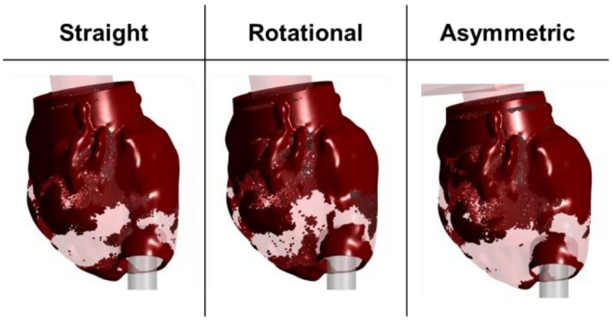

Figure 3: Iso-volume of stagnation volume defined by mean velocity magnitude < 0.5 cm/s.

The distribution of the particles in terms of RT and SSH is visualized by using box plots (Fig. 4 & Fig. 5).

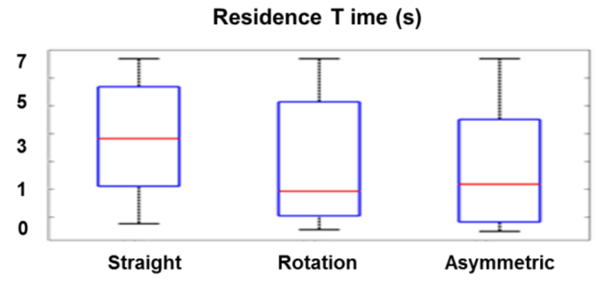

Figure 4: Box plots of particle residence time.

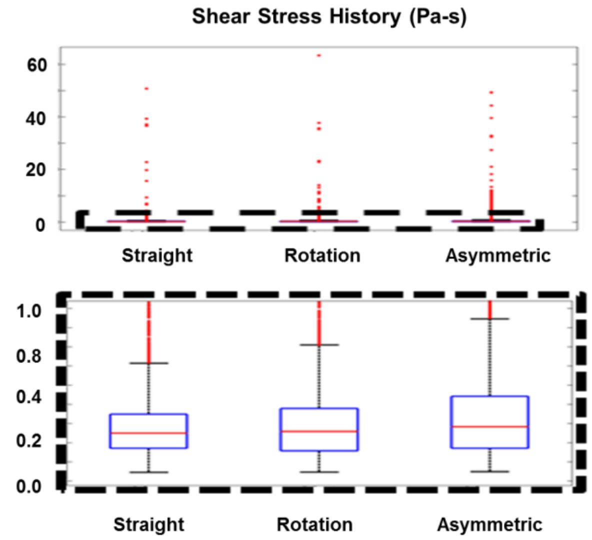

Figure 5: Box plots of shear stress history.

The percentage of the particles remaining within the LV after 7s of simulation was comparable for simulations with straight and rotation inflow, while it decreased significantly for asymmetric inflow. Moreover, particles experienced higher accumulative shear stresses with the asymmetric inflow (Table 1).

Table 1: Median and outlier information for RT and SH.

		Straight	Rotation	Asymmetric
RT (s)	**Median**	3.82	1.92	2.18
	Outliers (Max, %)	6.99, 19	6.99, 18	6.99, 13
SSH (Pa-s)	**Median**	0.25	0.26	0.29
	Outliers (Max, %)	50.78, 2	63.48, 3	49.46, 6

DOI: 10.3217/978-3-85125-826-4-08

Discussion

The previously validated numerical simulation [8] was used in this study to investigate the effect of atrial boundary conditions on the ventricular flow pattern during LVAD support.

Consideration of the rotational boundary condition at the mitral annulus creates lower washout and consequently larger stagnation volume, mainly at the apex around the LVAD inflow cannula, compared to the conventional straight boundary conditions. While stagnation volume was associated with thrombus formation by previous studies [10], it was shown that inaccurate simulation of the blood stasis region could result in misprediction of these aforementioned regions of stagnation.

Further, inclusion of the asymmetric boundary conditions resulted in an overall significant increase in SSH values and a larger proportion of particles that experienced exposure to high RT, indicating elevated risk of platelet activation and thrombus formation [9].

Neglecting the atrial flow conditions could lead to inaccurate simulation of ventricular blood flow. Therefore reliable prediction of blood component's behavior and the evaluation of the risk of thrombosis demand careful consideration of the atrial inflow conditions.

Acknowledgements

This study was partially funded by the Jubiläumsfonds of the Austrian National Bank Project Nr. 17314 and the Austrian Research Promotion Agency (FFG): M3dRES Project Nr. 858060.All the simulations were performed on Vienna Scientific Cluster.

References

[1] J. K. Kirklin *et al.*, “Eighth annual INTERMACS report: Special focus on framing the impact of adverse events,” *The Journal of Heart and Lung Transplantation*, vol. 36, no. 10, pp. 1080–1086, Oct. 2017, doi: 10.1016/j.healun.2017.07.005.

[2] D. Acharya *et al.*, “INTERMACS Analysis of Stroke During Support With Continuous-Flow Left Ventricular Assist Devices,” *JACC: Heart Failure*, vol. 5, no. 10, pp. 703–711, Oct. 2017, doi: 10.1016/j.jchf.2017.06.014.

[3] A. D. DeVore and G. C. Stewart, “The Risk of Stroke on Left Ventricular Assist Device Support,” *JACC: Heart Failure*, vol. 5, no. 10, pp. 712–714, Oct. 2017, doi: 10.1016/j.jchf.2017.08.002.

[4] Long Q., Merrifield R., and Yang G. Z., X. Y. Xu, P. J. Kilner and, and D. N. Firmin, “The Influence of Inflow Boundary Conditions on Intra Left Ventricle Flow Predictions,” *Journal of Biomechanical Engineering*, vol. 125, no. 6, pp. 922–927, Jan. 2004, doi: 10.1115/1.1635404.

[5] S. Liao, M. Neidlin, Z. Li, B. Simpson, and S. D. Gregory, “Ventricular flow dynamics with varying LVAD inflow cannula lengths: In-silico evaluation in a multiscale model,” *Journal of Biomechanics*, vol. 72, pp. 106–115, Apr. 2018, doi: 10.1016/j.jbiomech.2018.02.038.

[6] V. K. Chivukula *et al.*, “Left Ventricular Assist Device Inflow Cannula Angle and Thrombosis Risk,” *Circulation: Heart Failure*, vol. 11, no. 4, p. e004325, Apr. 2018, doi: 10.1161/CIRCHEARTFAILURE.117.004325.

[7] M. Ghodrati *et al.*, “The influence of left ventricular assist device inflow cannula position on thrombosis risk,” *Artif Organs*, vol. 44, no. 9, pp. 939–946, Sep. 2020, doi: 10.1111/aor.13705.

[8] M. Ghodrati *et al.*, “Validation of numerically simulated ventricular flow patterns during left ventricular assist device support,” *Int J Artif Organs*, vol. 44, no. 1, pp. 30–38, Jan. 2021, doi: 10.1177/0391398820904056.

[9] C. Mahr *et al.*, “Intermittent Aortic Valve Opening and Risk of Thrombosis in Ventricular Assist Device Patients:,” *ASAIO Journal*, vol. 63, no. 4, pp. 425–432, 2017, doi: 10.1097/MAT.0000000000000512.

[10] C. N. Bagot and R. Arya, “Virchow and his triad: a question of attribution,” *British Journal of Haematology*, vol. 143, no. 2, pp. 180–190, Oct. 2008, doi: 10.1111/j.1365-2141.2008.07323.x.