CFD-based evaluation of the thrombogenic potential of altered hemodynamics at the LV apex-LVAD cannula interface

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Background and Aim of the Study

- The use of **left ventricular assist devices (LVADs,** Fig. 1) has emerged as the mainstay of therapy for patients with advanced heart failure (HF). The LVAD is intended to partially or totally replace the function of the diseased left ventricle (LV). Despite the **increased survival rate associated with LVAD therapy**, those devices are affected by **post-implant thrombotic complications**.

-In particular, thrombus formation in the pump has been observed to **generate at the LV apex-LVAD inflow cannula interface** [1], where **altered hemodynamics** promote abnormal **platelet activation** and a shift of endothelial cells (ECs) toward a **pro-thrombotic phenotype** [2-4].

- In this study, a CFD-based model able to investigate the **thrombogenic potential of altered hemodynamics and wall shear stress (WSS) mechanical loading** has been developed. A whole cardiac cycle for both **healthy**-LV and **pathological** HF-LV models has been simulated to compare hemodynamic conditions at the LV apical region.

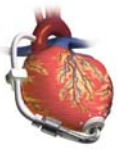

Fig. 1 LVAD

Materials & Methods

4 different LV models have been analyzed:

A. Patient-specific healthy LV with ejection volume of 70 cc (3D TT-ECHO images of a healthy volunteer (Fig. 2A))

B. Paradigmatic HF-LV (i.e., dilated) with a residual ejection fraction (EF) of 50% (Fig. 2B)

C. Paradigmatic HF-LV (i.e., dilated) with a residual EF of 10% (Fig. 2B)

D. HF-LV (i.e., dilated) LV with a residual EF of 10% + the LVAD inflow cannula inserted into the LV apex (Fig. 2C)

HF-LV geometries (end-diastolic configuration) have been realized in ANSYS Workbench, since 3D TT-ECHO images of LVAD recipient's ventricle have not been acquired yet.

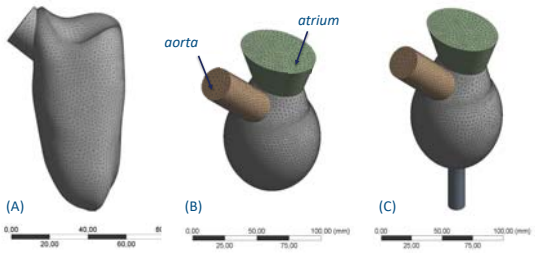

Fig. 2 Meshed geometries (tetrahedral elements) of healthy patient-specific LV (A), paradigmatic dilated LV (B), paradigmatic dilated LV with inflow cannula inserted in the apex (C)

In the healthy model, physiological cardiac pressures have been applied at the mitral and aortic orifices [5] (Fig.3).

Aorta and atrium volumes have been included in the paradigmatic HF-LV geometries (Fig. 2B and 2C) to apply *zero-pressure* boundary conditions (BC) during the cardiac cycle.

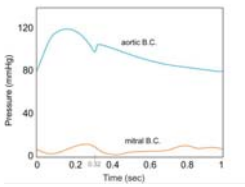

Fig. 3 Pressure BC

Grid motion

The dynamics of the cardiac cycle was simulated in ANSYS Fluent through the implementation of **mesh motion UDFs**, which assign a proper displacement (u_x u_y u_z) to each node of the ventricular wall.

The resulting movement is:

- **Contraction** and **twist** during systole
- **Expansion** and **untwist** during diastole

Contraction and **expansion**

- *Homothetic* movement
- Displacement assigned as a function of the z coordinate (i.e. long axis of the ventricle)
- Global displacement directed *normal to the ventricular wall*
- Displacement temporal variation mimics *ventricular ejection* (fig. 3A) and *filling* (fig. 3B)

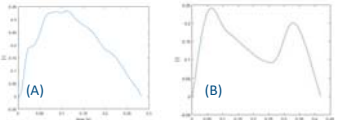

Fig. 3 (A) LV ejection trend in time during systole; (B) LV filling trend in time

Twist and **untwist**

- Global displacement *tangential to the ventricular wall*
- Opposite rotation of apex and ventricular base (fig. 4)

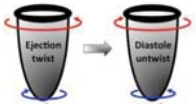

Fig. 4 Twist and untwist movement of the LV

- Temporal variation of the twist rate (fig. 5) [6]

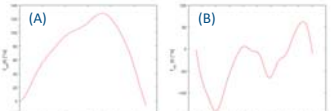

Fig. 5 LV twist trend in time during systole (A) and diastole (B)

Results and Discussion

Resulting grid motion

Fig. 6 shows the superimposition of the end-systolic and end-diastolic configurations in the A. B. D. cases. C. case is equal to case D. without the cannula. As shown in the zoomed areas the models have *different apical nodal displacements.*

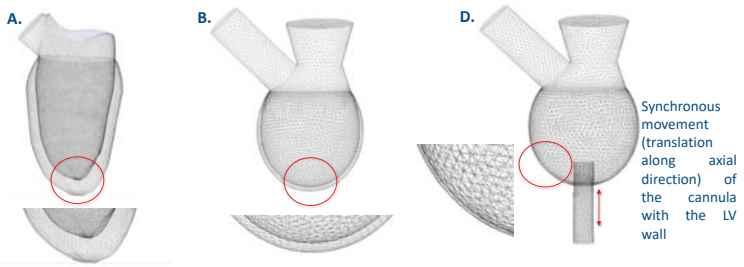

Fig. 6 End-diastolic and end-systolic meshes superimposition for the heathy LV (A), HF-LV with EF=50% (B), HF-LV with EF=10% with cannula (D). Zoom to underline the different amounts of displacement.

Streamlines for the 4 considered conditions at the systolic peak (fig.7). Different outflow velocities and trajectories were observed. In particular, in case D (HF-LV with cannula) no flow occured across the aortic valve, being the blood sucked into the cannula (fig. 7D).

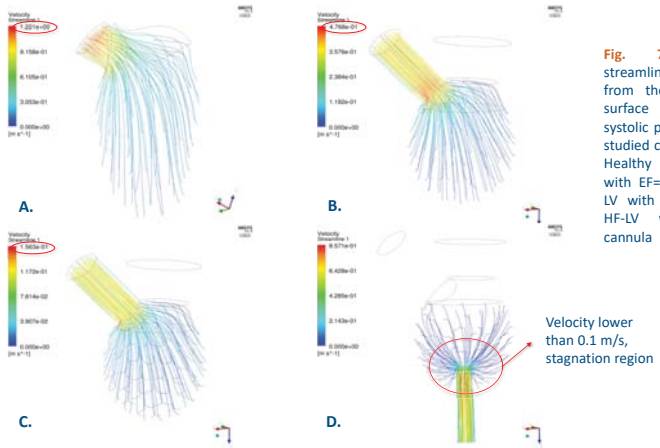

Fig. 7 Velocity streamlines starting from the ventricular surface during the systolic peak for the 4 studied conditions: (A) Healthy LV; (B) HF-LV with EF=50%; (C) HF-LV with EF=10%; (D) HF-LV with inflow cannula

WSS evaluation

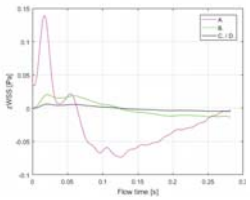

Fig. 8 z-WSS in systole for healthy A. B. C./D. conditions

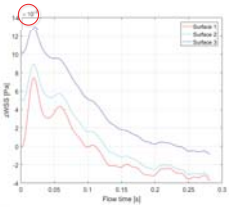

Fig. 9 z-WSS in systole, D. condition

The z component of the WSS is one order of magnitude higher for the healthy LV w.r.t. the pathological ones (fig.8). Reducing the contractile capacity, the z-WSS reduces as well (fig 8, curves B and C/D).

The z-WSS trend for the condition D. shows decreasing values approaching the apex (surface 1) (fig.9), indicating that the cannula generates prothrombotic low velocity profiles at the interface with the LV.

Conclusions

In this study we developed a CDF model able to investigate the thrombogenic potential of hemodynamics at the LV – inflow cannula interface. In particular, the role of shear-mediated activation was analyzed. The simulation of the whole cardiac cycle was performed considering both healthy and pathological conditions (different contractile capacities, presence of the LVAD inflow cannula), in order to extract WSS trends in the apical region.

On-going studies

The numerical tool will be used to extract WSS curves starting form a patient-specific geometry derived from 3D TT ECHO images of LVAD recipients. Those curves will be used **to guide the design of an endothelialized microfluidic platform,** able to expose ECs to flow and shear abnormalities specific of diseased LVs and LV-VAD inflow interface. The effects of these flow and shear profiles will be evaluated measuring the expression of cell adhesion, activation and inflammatory markers.

References: [1] J. Bhama et *al*. JACC. 2013. **[2]** W. Chiu et *al*. Jou of Biomech Eng. 2014. **[3]** PS. Frenette et *al*. The Jou of Experimental Med. 2000 **[4]** D. Chappel et *al*. Circulation research. 1998. **[5]** A. Imanparast et *al*. Jour of Biomech. 2016. **[6]** A. Omar et *al*. Circulation: Cardiovasc Imaging. 2015.

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