Analysis of local and global Hemolysis Index in 2D velocity field of regurgitant flow in mechanical heart valve

Guanglei WANG[1], Giuseppe D'AVENIO[1], Carla DANIELE[1], Mauro GRIGIONI[1]

[1] *Dept. of Technology and Health, Istituto Superiore di Sanità, Rome, Italy*

Correspondence: guanglei.wang@iss.it; Istituto Superiore di Sanità,Viale Regina Elena 299, Roma, Italy

Introduction

Mechanical heart valves, specifically bileaflet valves, are widely applied to take place of diseased native valves. However, the physiological blood flow may be disturbed by prosthetic devices with large pressure variations and high shear stresses. These artificial effects may cause critical damages to blood components, that may change the membrane properties of blood cells, or even worse bring complete destruction.

Previous works presented Hemolysis Index (HI) to access the damage to blood cells in artificial organs [1][2]. HI evaluates the concentration of plasma free hemoglobin, that leaks from red blood cells due to the holes in membrane [3] because of the mechanical stresses in the fluid caused by artificial conditions. In this paper we used HI for comparison with other authors.

The purpose of this study is to investigate local and global quantities related to blood cells damage (HI) induced by bileaflet mechanical valve. Properties of fluid dynamics, such as velocity and turbulent shear stress, are measured in 2D by PIV.

Materials and Methods

In order to calculate HI(%) with equation (1) in each point of the flow field, a previous evaluation of the exposure time of the blood cells, under the respective shear fields, is necessary. To achieve this point, we analyze exposure time and maximum shear stress for the blood cells moving along the longitudinal axis in the measured 2D flow field. A small section ΔL along the longitudinal axis with a constant velocity of moving blood cells is assumed, as shown in Fig 1. The longitudinal axis is divided into N sections.

$$N = \frac{L}{\Delta L} \qquad (1)$$

where L is total distance of blood cells transporting along longitudinal axis in measured field.

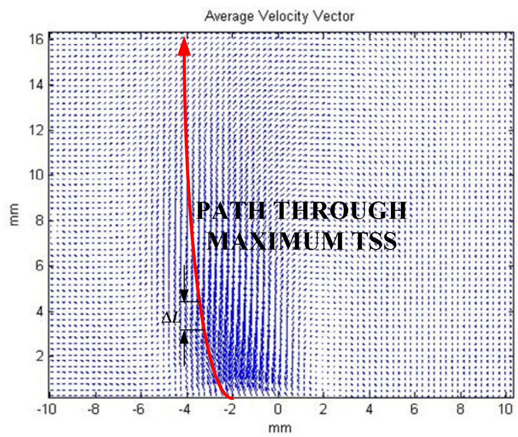


Fig 1. Path line for blood flow direction

The exposure time for each point can be estimated as follow:

$$t_{\exp} = \frac{\Delta L}{V \times \cos\theta} \qquad (2)$$

where $\tan\theta = v_x / v_y$.
Then hemolysis index (within section) can be calculated as

$$HI_{\sec}(\%) = C * t_{\exp}{}^{\alpha} \tau^{\beta} \qquad (3)$$

According to newly published work of Taskin et al [2], $C = 1.21 \times 10^{-5}$, $\alpha = 0.747$, $\beta = 2.004$.
After calculating all section of the flow field, the global hemolysis index [4] can be given as

$$HI_{tot}(\%) = \sum_{N} HI_{\sec}(\%) \qquad (4)$$

In this study, the values of HI_{tot} (%) were assessed consistently with scanned slices in regurgitant leakage jet of bileaflet mechanical valve. Flow visualization was achieved by PIV. Measured slices were from 1mm to 11mm away hinge plane corresponding to slice numbers N_s 1 to 11.

Results

Figures 2 (a) (b) show the measured average velocity and turbulence shear stress in 2D regurgitant leakage flow of mechanical valve. Figure 2 (c) shows local HI_{sec}(%) distribution calculated according to equation (3) in one scanned 2D slice.

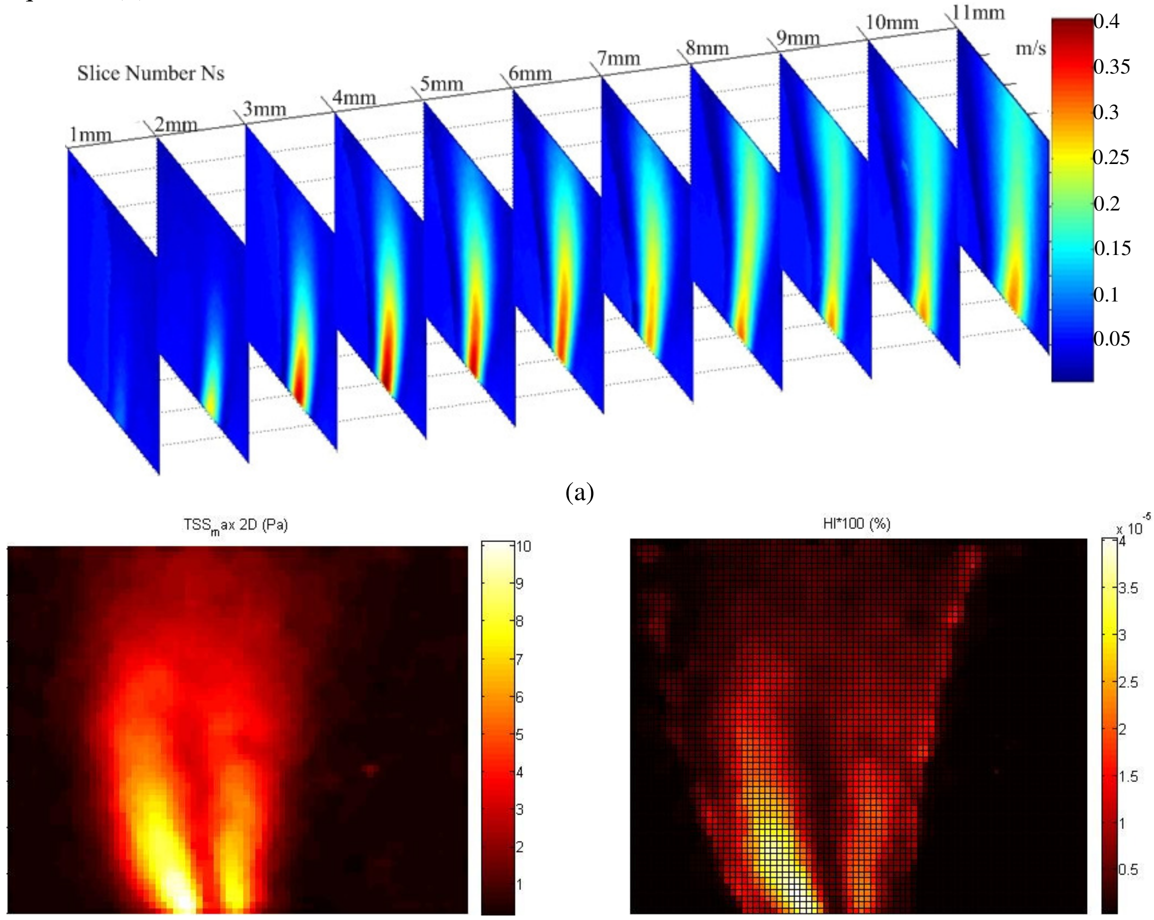
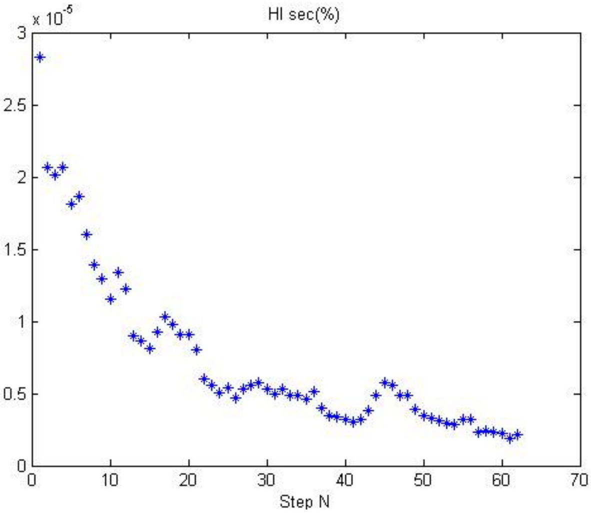
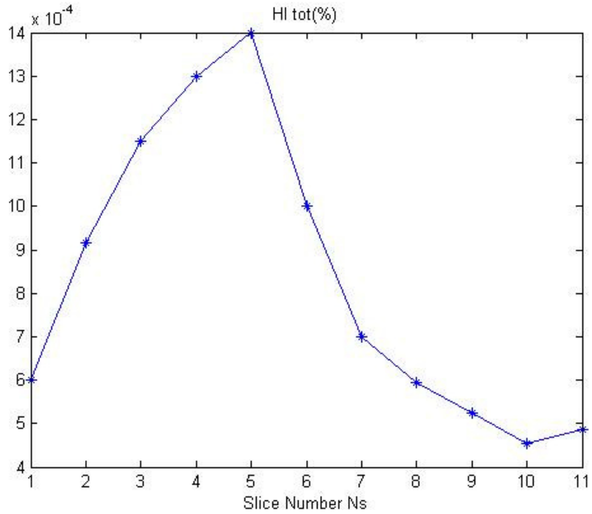


Fig 2: (a) 2D velocity along slice number Ns; (b) Turbulence Shear Stress distribution in 2D measured flow field; (c) Hemolysis Index(%) distribution in 2D field

HI_{sec} (%) along longitudinal axis was illustrated in figure 3(a). The local values of HI(%) decreased gradually as evaluated point moving along the longitudinal axis. The global values of HI(%) ,defined in equation (4), were shown in fig. 3(b), according to the order of slice numbers in fig.2(a). We observed that the peak value of global HI(%) was 1.4×10^{-3} in scanned slice 5, which was 5mm away from hinge plane.



(a)



(b)

Fig 3: (a) Hemolysis Index Section(%) along pathline through TSS_max (b)Hemolysis Index Total(%) in different measured plane

Conclusion

The study offered a comprehensive experimental evaluation of blood injury induced by prosthetic mechanical heart valve. Furthermore, the evaluation of a local and global hemolysis index, by using local shear stresses and velocities values generated by PIV, allows to quantify and to compare the propensity for hemolysis of different mechanical heart valves. The results will be used for comparisons with simulation data.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under *grant agreement* n° 238113 (project MeDDiCA).

References

1. K. Fraser, M. Taskin, T. Zhang, B. Griffths, and Z. Wu. Comparison of shear stress, residence time and lagrangian estimates of hemolysis in different ventricular assist devices. *In 26th Southern Biomedical Engineering Conference, SBEC 2010, April 30 - May 2, volume 32, pages 548-551,2010.*

2. Taskin M. E., Fraser K.H., Zhang T., Gellman B., Fleischli A., Dasse K.A., Griffith B. P., Wu Z.J., Computational Characterization of Flow and Hemolytic Performance of the UltraMag Blood Pump for Circulatory Support. *Artificial Organs, 34(12):1099–1113, 2010*

3. Lieber M., Steck T., A description of the holes in human erythrocyte membrane ghosts. *The Journal of Biological Chemistry, 257(19):11651-11659, 1982*

4. Grigioni M., Daniele C., Morbiducci U., D'Avenio G., Benedetto G. D., Barbaro V., The Power-law Mathematical Model for Blood Damage Prediction: Analytical Developments and Physical Inconsistencies. *Artificial Organs 28(5):467–475, 2004*