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## Letter to the Editor

## Left ventricular flow in the presence of aortic regurgitation



Dear Professor Guilak:

The utilization of left ventricular flow to characterize and stratify aortic regurgitation (AR) has increased in recent years. Clinical imaging based techniques such as phase contrast MRI (PCMRI), vector flow mapping, echo particle image velocimetry (echo PIV), have been utilized in order to study ventricular flow (Dyverfeldt et al., 2006; Kheradvar et al., 2010).

We read with great interest the recent article entitled “Jet Collisions and Vortex Reversal in the Human Left Ventricle” (Di Labbio and Kadem, 2018). The authors reported that the AR jet collides with the mitral inflow vortex resulting in increased viscous energy dissipation (VED), similar to previous observations (Okafor et al., 2017; Stugaard et al., 2015). Unlike in the aforementioned bodies of work, in the Di Labbio and Kadem study the authors utilized high-speed PIV to analyze the flow field within the left ventricle. In addition, the authors were able to implement a “physiological” atrial kick. We congratulate the authors on a well-conducted experimental investigation on the intra-ventricular fluid dynamics. However, with the utilization of high-speed PIV and the implementation of a physiological atrial kick, we are curious as to whether new physiologically relevant information can be gathered. We therefore have the following questions for the authors:

1. The authors report velocimetry evidence of the “vortex reversal” in the left ventricle during severe AR. How do we define a vortex reversal? Is it a similar definition as in that observed by Pedrizzetti (Pedrizzetti et al., 2010)? Or is the reversal of fluid motion observed in the LV a consequence of the vorticity and circulation of the regurgitating jet? Clarification on the nomenclature and cause of the vortex reversal will improve our understanding of the pathophysiological fluid mechanics.
2. As the authors acknowledge in their article, the angle of the aortic jet with the mitral inflow (could be defined by aorto-mitral angle) is perhaps influential in dictating the intra-ventricular flow. Recent flow visualization experiments have demonstrated such effects, albeit in a non-physiological environment (Houser et al., 2018). We were curious as to what the aorto-mitral angle was in this study and why? Could the observed vortex reversal be a function of the aorto-mitral angle, which was selected?
3. From our previous experience, a sample of  $N = 10$  for analyzing velocity field data was determined to be insufficient to obtain converged velocity field statistical data. Could the authors comment more on this? How different are the VED results between phase-averaged and instantaneous velocity fields as this may inform differences in results between PCMRI (cycle averaged) and echo PIV (instantaneous) results.
4. We agree that the “atrial kick” is influential in the cardiac mechanics and flow physics, from the observations in this

study, could the authors comment on any influence of the atrial kick inflow during the diastolic phase of VED? From Stugaard’s animal model observations, it appears there are two distinct peaks in the energy loss or energy dissipation, which could be due to the atrial kick inflow.

Such improved understanding of the pathophysiological fluid mechanics during AR is important to improve diagnostic capabilities. Using an advanced and more realistic left ventricle simulator – similar to the one developed by the authors of this study – is an important aspect of simulating all the cardiac mechanics that is relevant to the disease state.

## References

- Di Labbio, G., Kadem, L., 2018. Jet collisions and vortex reversal in the human left ventricle. *J. Biomech.* 78, 155–160. <https://doi.org/10.1016/j.jbiomech.2018.07.023>.
- Dyverfeldt, P., Sigfridsson, A., Kvitting, J.-P.E., Ebbens, T., 2006. Quantification of intravoxel velocity standard deviation and turbulence intensity by generalizing phase-contrast MRI. *Magn. Reson. Med.* 56, 850–858. <https://doi.org/10.1002/mrm.21022>.
- Houser, S., Okafor, I., Raghav, V., Yoganathan, A., 2018. Flow visualization of the non-parallel jet-vortex interaction. *J. Vis.* <https://doi.org/10.1007/s12650-018-0478-2>.
- Kheradvar, A., Houle, H., Pedrizzetti, G., Tonti, G., Belcik, T., Ashraf, M., Lindner, J.R., Gharib, M., Sahn, D., 2010. Echocardiographic particle image velocimetry: a novel technique for quantification of left ventricular blood vorticity pattern. *J. Am. Soc. Echocardiogr.* 23, 86–94. <https://doi.org/10.1016/j.echo.2009.09.007>.
- Okafor, I., Raghav, V., Condado, J.F., Midha, P.A., Kumar, G., Yoganathan, A.P., 2017. Aortic regurgitation generates a kinematic obstruction which hinders left ventricular filling. *Ann. Biomed. Eng.* 45, 1305–1314. <https://doi.org/10.1007/s10439-017-1790-z>.
- Pedrizzetti, G., Domenichini, F., Tonti, G., 2010. On the left ventricular vortex reversal after mitral valve replacement. *Ann. Biomed. Eng.* 38, 769–773. <https://doi.org/10.1007/s10439-010-9928-2>.
- Stugaard, M., Koriyama, H., Katsuki, K., Masuda, K., Asanuma, T., Takeda, Y., Sakata, Y., Itatani, K., Nakatani, S., 2015. Energy loss in the left ventricle obtained by vector flow mapping as a new quantitative measure of severity of aortic regurgitation: a combined experimental and clinical study. *Eur. Hear. J. - Cardiovasc. Imaging* 16, 723–730. <https://doi.org/10.1093/ehjci/jev035>.

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