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Post-operative ventricular flow dynamics following atrioventricular valve surgical and device therapies: A review

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ABSTRACT

Intra-ventricular flow dynamics has recently emerged as an important evaluation and diagnosis tool in different cardiovascular conditions. The formation of vortex pattern during the cardiac cycle has been suggested to play important epigenetic and energy-modulation roles in cardiac remodelling, adaptations and mal-adaptations. In this new perspective, flow alterations due to different cardiovascular procedures can affect the long-term outcome of those procedures. Especially, repairs and replacements performed on atrioventricular valves are likely to exert direct impact on intra-ventricular flow pattern. In this review, current consensus around the roles of vortex dynamics in cardiac function is discussed. An overview of physiological vortex patterns found in healthy left and right ventricles as well as post-operative ventricular flow phenomenon owing to different atrioventricular valvular procedures are reviewed, followed by the summary of different vortex identification schemes used to characterise intraventricular flow. This paper also emphasises on future research directions towards a comprehensive understanding of intra-cardiac flow and its clinical relevance. The knowledge could encourage more effective pre-operative planning and better outcomes for current clinical practices.

1. Introduction

Recently, there has been a renewed interest in intra-ventricular flow, especially regarding vortex pattern. Vortex is one of the important coherent structures that is thought to be responsible for the active dynamics of turbulent flow. In the heart, a vortex typically arises due to the separation of boundary layers [1]. Due to the variation of velocity in the shear layer formed between the inflow and the solid (tissue) boundary, fluid elements in this layer develop tendency to swirl and may curl back when separating from the solid surface, spinning away from the central inflow jet and forming a vortex [1–4]. Different vortical structures have also been observed in the cardiac atriums [5–7], possibly due to merging and interaction of the inflows from superior and inferior vena cava (SVC and IVC). In practice, vortex is usually identified as a connected region of vorticity or circulation.

The dynamic and beat-to-beat variability of three-dimensional vortex structure, somewhat similar to the chaos system [8], heightens its sensitivity to the smallest changes in environment. Attempts to characterise vortex patterns in patients exhibiting cardiomyopathy [9–11], diastolic dysfunction, and heart failure [12–15] have demonstrated the variation of vortex patterns associated with certain pathologies. Thus, vortex analysis could be a valuable diagnostic tool in clinical practice. Moreover, despite the incomplete understanding of vortex roles in cardiac environment, increasing evidence have suggested its importance in maintaining efficient cardiac function. Concurrently, altered flow and vortex patterns could modulate the heart towards long-term remodelling and adaptation. In this perspective, the knowledge of altered intra-cardiac flow after different cardiovascular procedures are particularly relevant, since vortex analysis could be an early indicator for cardiovascular outcome and provide an early risk diagnosis for patients prone to mal-adaptations [16]. On the other hand, this suggests that cardiovascular endpoint might benefit

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Abbreviations: A3C view, Apical three-chamber view; Echo-PIV, Echocardiographic particle image velocimetry; ETER, Edge-to-edge repair; KE, Kinetic energy; LV, Left ventricle; MV, Mitral valve; PC-MRI, phase contrast magnetic resonance imaging; PIV, Particle image velocimetry; RV, Right ventricle.

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from maintaining an appropriate hemodynamic environment rather than simply treating immediate symptoms. Alteration of flow in a detrimental way could lead to ventricular mal-adaptation and affect the long-term outcome.

Many studies have characterised flow patterns following certain cardiovascular procedures such as heart valve replacement or surgical repair. Most studies have assessed the effect of semilunar valvular procedures on intra-ventricular flow; however, those done on atrioventricular valves are still limited. Procedures performed on atrioventricular valves are likely to impact ventricular dynamics due to their critical anatomical locations. Moreover, in-depth qualitative and quantitative studies are lacking. The diverse methods and parameters make it difficult to derive a conclusive picture. Thus, a comprehensive review of these studies is needed to provide a platform for comparison and interpretation, and to suggest necessary future research.

In this review, the current consensus and debate on the roles of cardiac vortex are discussed, followed by an overview of vortex patterns found in healthy left ventricle (LV) and right ventricle (RV). Subsequently, research studies to quantify post-operative intra-ventricular flow following atrioventricular valvular procedures are reviewed. These include the findings on the post-procedural flow of mitral valve (MV) replacements and repairs, and the commentary note on the lack of knowledge regarding the RV flow and its relevant procedural alterations. Finally, the knowledge of the current intraventricular vortex identification schemes is summarised. This review addresses our current understanding on the subject of intraventricular vortex and points out the unanswered questions that need to be tackled. Knowledge of post-operative flow dynamics could provide important insights into the long-term outcomes influenced by their hemodynamic environments, and suggest potential improvements in current clinical design and practice.

2. Consensus on vortex roles in cardiac function

It is believed that the physiological intraventricular vortex flow could play several important roles in the cardiac environment, including facilitating MV closure to ensure minimum regurgitation [17] and influencing the blood mixing and blood residence time inside the LV to minimise apical thrombus formation [18–21].

In terms of energy, diastolic vortex formation was suggested to act as an energy-shunting mechanism, trapping a certain amount of energy into its rotary motion by constraining and stabilising the jet, instead of contributing to Bernoulli pressure rise which could impede the inflow kinetics [22,23]. Another mechanism was hypothesised in which an optimal vortex ring formation could maximise the total momentum delivered to the flow by transporting mass and momentum into the LV apex without vortex pinch off [13,24,25]; however, inconsistent results were reported on when and whether this pinch off happens during diastole [13,26]. Nevertheless, recent two-dimensional (2D) phase contrast magnetic resonance imaging (PC-MRI) assessment of LV flow and intraventricular pressure gradient in normal subjects revealed that the presence of vortex could assist in preventing the spread of the jet and the development of an adverse pressure gradient, thus enhancing LV function as a suction pump in the filling phase [23]. Contribution of LV vortex to diastolic transport was also quantitatively investigated using flow decomposition method with 2D echocardiographic *in vivo* imaging, showing that a significant fraction of filling flow is transported inside LV by vortex ring during diastole for healthy hearts in sinus rhythm at no energy or pressure cost [27]. Subsequently, an *in vivo* 4D (3D + time) PC-MRI study on athletes and control subjects found that majority of LV kinetic energy (KE) was within LV diastolic vortex [28]. Also, as evidenced by *in vivo* studies, the transport mechanism and energetics of LV vortex was significantly altered in pathological conditions [27,28]. Thus, these different literatures seemed to support the role of vortex in facilitating diastolic filling and stroke volume maintenance. Recently, another interesting hypothesis was proposed based on a consistent ratio of vortex and cardiac volumes in control subjects observed *in vivo* using 4D PC-MRI [20]. The authors conjectured that the size of normal MV is not fully utilised for maximum vortex ring generation, indicating a possible mechanism where the heart can “reserve capacity” for higher demanding situations through increasing the vortex volume in such cases, while keeping normal wall tension low at resting conditions. Subsequent studies to assess vortex flow and filling mechanics in other conditions, such as exercise or certain pathologies, are needed to validate this theory.

While an increasing number of evidences are supporting the important role of vortex in diastolic filling, its relevance in systolic pumping efficiency is still a matter of debate. The arrangement of physiological vortex was thought to redirect the blood flow towards the outlet in subsequent systolic phase to facilitate accelerating blood [28–31]. Thus, vortex was regarded as energy storage means, carrying momentum within its rotation which would then be used partly for systolic ejection. However, it is also known in fluid dynamics that vortex never unwinds smoothly [8,22,32]. Thus, whether the “trapped” KE in vortex is conserved to be used subsequently in systole or to ultimately be cascaded into heat remains unclear. Another argument looked at the insignificant amount of intraventricular KE compared to the LV total mechanical work. On one hand, several computational works demonstrated the negligible effect of different diastolic flow variations on systolic pumping efficiency [33,34]. On the other hand, some *in vivo* [31] and computational [35] studies have shown evidence that the minimal energy dissipation levels inside the ventricle are associated with the physiological flow arrangement as opposed to the geometrically modified MV-LV apparatus (which could be introduced by cardiac diseases such as cardiomyopathy or valvular replacements). This raises the question of whether configuration of a single, large coherent LV vortex would still be more energy saving compared to other random and more chaotic vortical arrangements, regardless of the dissipative nature of vortex in general. Moreover, though the energy loss inside the ventricle only makes up a small percentage of the total energy required to overcome blood flow resistances of the entire circulatory system, whether the heart feedback mechanism would respond to the reduced energy efficiency to adapt in the long-run remains unknown. More concrete evidence is needed to elucidate this debatable role of vortex regarding systolic energy expenditures.

At the cellular level, the remodelling role of vortex might be mediated through the influence of shear stresses and normal stresses on the tissue environment lining the ventricular wall [16,36–39]. Variation of normal flow could generate abnormal values with shifted distribution of wall shear stress sensed by the cardiac tissue, inducing different signalling pathways towards remodelling [36]. Unlike an established body of knowledge on vascular mechanotransduction mechanism and flow-guided cardiac embryogenic formation, similar research in the adult cardiac environment is currently lacking. In-depth cellular research could consider ventricular fluid dynamics as important environmental factors that would modulate remodelling and adaptations through variation of gene expression or phenotype intensity.

An important point to note is that most studies in the literature have been conducted primarily on the LV. It is, thus, uncertain whether vortex constitutes the same roles and the same extent of contributions in the RV. Indeed, previous *in vivo* studies have suggested different filling mechanisms [28] and energy patterns [40] in the two ventricles. This further questions the vortex phenomena and their specific energy and epigenetic roles in the two distinct environments.