
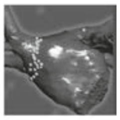
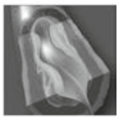

Visualization of blood flow with echocardiography: the future for heart failure diagnosis

"…in the human heart … [blood] flow is redirected within the cardiac chambers through vortex formation, which avoids excessive dissipation of energy and facilitates the efficient passage of blood … visualizing multidirectional [intracavity blood] flow using echocardiographic techniques may open up new possibilities in assessing cardiac blood transport efficiency in health and disease."

KEYWORDS: blood flow ▪ heart failure ▪ hemodynamic efficiency ▪ vortex

The prognosis of heart failure (HF) after hospital discharge remains dismal, with high readmission rates and mortality [1,2]. Transthoracic echocardiography is commonly used to follow up with HF patients for serial assessment of cardiac chamber size, function and for noninvasive estimation of chamber filling pressures. In particular, estimation of left atrial pressure may allow earlier identification of incipient cardiac decompensation and guide adjustment of vasodilator and diuretic dosing [3]. Doppler-derived indices of diastolic dysfunction, particularly the ratio of early transmitral velocity to tissue Doppler mitral annular early diastolic velocity (E/e′), is considered a noninvasive estimate of left ventricular filling pressure [4]. However, nearly half of patients displaying symptoms of HF have preserved left ventricular ejection fraction (HFpEF) and E/e′ may not be reliable in patients with HFpEF [5]. Moreover E/e′ may not be an appropriate measurement for evaluating HF patients with pacemakers and cardiac resynchronization therapy [6]. The search for alternative echocardiography indices continues. Some investigators have suggested that flow of the blood may be immediately affected by changes in left ventricular (LV) morphology and intracavity filling pressures. Therefore, flow can be a more robust marker for characterizing chamber filling dynamics [7].

Vortex formation: a marker hemodynamic efficiency

More than 500 years ago, Leonardo da Vinci introduced the concept of circular flow formation in the sinus of Valsalva [8]. Such a fluid structure that possesses circular or swirling motion is defined as a vortex. Vortices are considered as reservoirs of kinetic energy. Theoretically, in an ideal fluid this energy can never be dissipated and the vortex would persist forever. However, in reality, the resistance of the fluid (viscosity) reduces the energy. *In vitro* experiments have demonstrated that fluid transport can be laminar, vortical or turbulent. Within these patterns, vortex ring formation is the most efficient for periodic changes in the direction of the flow [9,10].

Pattern of blood flow in a normal heart

The pattern of flow in the human heart changes dramatically during one cardiac cycle. However, flow is redirected within the cardiac chambers through vortex formation, which avoids excessive dissipation of energy and facilitates the efficient passage of blood [11]. Inside the ventricle, just after ejection, the direction of flow reverses towards the apex, which initiates early diastolic filling. During early diastolic filling, an asymmetric vortex ring is formed, with a larger anterior vortex ring and a small posterior ring. This vortex continues to enlarge anteriorly during diastasis, and overall rotation of flow is further accentuated during atrial contraction. The specific geometry and anatomical location of the vortex formed during diastolic filling are critical determinants of directed blood flow during ejection [9]. After the mitral valve closes and before the aortic valve opens, the vortex changes direction of flow towards LV outflow tract. This maintains the transfer of kinetic energy from diastolic filling into ejection. Lastly, at the LV end-ejection phase, the vortex diminishes in size as the flow is ejected across the aortic valve [12,13].

Vortex formation in decompensated heart failure

The formation of abnormal vortices relates to the underlying fluid dynamics in LV dysfunction [14,15].

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When this geometric arrangement is broken, for example in dilated left ventricles, undesirable vortices develop and there is an increase in the dissipated energy [9]. In end-stage systolic HF, ventricular dilatation decreases the strength of the diastolic vortex [16].

Noninvasive assessment of vortex formation

The term fluid velocity commonly describes the fluid motion. However, flow is multidirectional and vortical, with a tendency to curl or spin in the cardiac chambers [11]. In this respect, dynamical structure of a flow cannot be described by velocity alone. Therefore, investigators have attempted different approaches in characterizing vortex formation, ranging from mathematical indices to real-time visualization of vortices using parametric imaging in 2D or 3D.

In the experimental model, vortex rings develop from fluid ejected from a nozzle. The starting jet is typically produced by a piston-cylinder mechanism, which is commonly expressed through the stroke ratio as the ejected jet length divided by the effective jet diameter. This length-to-diameter ratio is often referred to as vortex formation time (VFT). VFT is a dimensionless measure of the time needed for optimal vortex ring formation [17,18].

"In end-stage systolic heart failure, ventricular dilatation decreases the strength of the diastolic vortex."

In the human heart, VFT can be calculated by transmitral flow and ejection fraction (EF) using the formula: VFT = $4 \times (1-\beta)/\pi \times \alpha^3 \times$ LVEF (β is the fraction of stroke volume contributed from the atrial component of LV filling obtained from the velocity-time integral of A-wave, the effective diameter of mitral geometric orifice area (GOA) and EDV. The parameter α^3 is a nondimensional volumetric parameter for the LV, obtained by dividing the EDV by cubic power of GOA) [19]. Other indices, such as vortex circulation and vortex dissipation [20], are known to represent the strength of the vortex. However, these indices have not yet been validated in clinical practice.

VFT in myocardial dysfunction

VFT has been previously shown to be an index of cardiac function [19]. In patients with acute myocardial infarction, LV diastolic VFT was shown to be strongly associated with the infarct size and LV untwisting rate, indicating that the mechanical sequence of diastolic restoration played a key role in early diastolic vortex ring formation [21]. VFT has also been used as a predictor of adverse events in HF patients. Poh *et al*. analyzed an adapted VFT (VFTa), where the β was measured from mitral annulus [22]. VFTa was markedly reduced in HF with reduced EF, and mildly abnormal in HFpEF compared with non-HF patients. VFTa of <1.32 was associated with significantly reduced event-free survival. In multivariate analyses, only E' and LA volume are significant independent determinants of VFTa, demonstrating that VFT is related to mitral annular recoil. However, since VFT is derived by EF, it is strongly influenced by EF. In addition, the feasibility of obtaining component parameters of VFT, such as the mitral diameter, has yet to be resolved.

Flow visualization

Flow visualization can be achieved by cardiac MRI [10] and echocardiography [23]. With respect to cardiac MRI, blood flow can be measured in any direction by the phase-contrast technique, without using contrast agents [24–26]. However, this technique is time-consuming and costly. By contrast, flow visualization using echocardiography is relative low cost and is suitable for routine clinical use. There are two methods for assessing flow pattern, color Doppler and echo-particle image velocimetry (PIV). Although color Doppler measurement has advantages in spatial resolution and has no need of contrast, it has some limitations. One limitation is that color Doppler is easily affected by noise. Another limitation is that it cannot measure flow velocities perpendicular to the Doppler angle. Alternatively, echo-PIV using contrast echocardiography tracks particle patterns in the field frame-by-frame and, the displacement data are converted to velocity using the time duration between the frames. PIV does not track individual particles. Rather, it tracks the patterns produced by groups of contrast particles.

"...vortex rings may help diastolic–systolic coupling for maintaining left ventricular cardiac output in remodeled hearts."

We recently performed a study to explore echo-PIV-derived measures of blood flow in 31 patients with HF [27]. LV vortex strength, defined as the amount of curl in the flow (vorticity), was significantly lower in patients with reduced LV ejection fraction (<50%) and related to the extent of LV spherical remodeling. LV late diastolic vortex strength was related to LV systolic longitudinal strain, suggesting that vortex rings may help diastolic–systolic coupling for maintaining LV cardiac output in remodeled hearts.

In summary, visualizing multidirectional flow using echocardiographic techniques may open up new possibilities in assessing cardiac blood transport efficiency in health and disease. Vortex flow influences stroke output and efficiency of the LV through optimum redirection of intraventricular flow. Increasing access to noninvasive hemodynamic assessment of LV fluid mechanics may therefore be a key to understanding the physiological drivers of stroke work in a remodeled LV. This may lead us to better understand how hemodynamics correlates to symptom status in HF patients.

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