Ultrasound in Med. & Biol., Vol. 40, No. 1, pp. 210–221, 2014

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2013.09.013

● *Original Contribution*

DOPPLER VORTOGRAPHY: A COLOR DOPPLER APPROACH TO QUANTIFICATION OF INTRAVENTRICULAR BLOOD FLOW VORTICES

Forough Mehregan,[*†] François Tournoux,[‡] Stéphan Muth,[*†] Philippe Pibarot,[§] Régis Rieu,[‖] Guy Cloutier,[†¶#] and Damien Garcia[*†#]

[*] RUBIC, Research Unit of Biomechanics & Imaging in Cardiology, University of Montreal Hospital, Montreal, QC, Canada; [†] CRCHUM, Research Center, University of Montreal Hospital, Montreal, QC, Canada; [‡] Department of Echocardiography, CHUM, University of Montreal Hospital, Montreal, QC, Canada; [§] Department of Medicine, Laval University and Québec Heart & Lung Institute, Laval University, Montreal, QC, Canada; [‖] Aix-Marseille University, CNRS, UMR 7287, ISM, GIBOC, Marseille, France; [¶] LBUM, Laboratory of Biorheology and Medical Ultrasonics, University of Montreal Hospital, Montreal, QC, Canada; and [#] Department of Radiology, Radio-Oncology and Nuclear Medicine and Institute of Biomedical Engineering, University of Montreal, Montreal, QC, Canada

(*Received* 18 *June* 2013; *revised* 5 *September* 2013; *in final form* 9 *September* 2013)

Abstract—We propose a new approach to quantification of intracardiac vorticity based on conventional color Doppler images —Doppler vortography. Doppler vortography relies on the centrosymmetric properties of the vortices. Such properties induce particular symmetries in the Doppler flow data that can be exploited to describe the vortices quantitatively. For this purpose, a kernel filter was developed to derive a parameter, the blood vortex signature (BVS), that allows detection of the main intracardiac vortices and estimation of their core vorticities. The reliability of Doppler vortography was assessed in mock Doppler fields issued from simulations and *in vitro* data. Doppler vortography was also tested in patients and compared with vector flow mapping by echocardiography. Strong correlations were obtained between Doppler vortography-derived and ground-truth vorticities (*in silico*: $r^2 = 0.98$, *in vitro*: $r^2 = 0.86$, *in vivo*: $r^2 = 0.89$). Our results indicate that Doppler vortography is a potentially promising echocardiographic tool for quantification of vortex flow in the left ventricle. (E-mail: damien.garcia@crchum.qc.ca or garcia.damien@gmail.com)

Key Words: **Doppler echocardiography, Intraventricular blood flow, Vortex imaging, Vorticity, Doppler vortography, Vector flow mapping.**

INTRODUCTION

Within the left ventricle of a normal heart, diastolic filling is characterized by the formation of a swirling motion during early filling (Gharib et al. 2006; Kilner et al. 2000; Toger et al. 2012): A large diastolic vortex forms adjacent to the anterior mitral valve leaflet and rotates in the natural flow direction. In the normal heart, a large part of the left ventricular (LV) blood volume is actually involved in the vortex formation. Because flowing blood keeps moving at the end of diastole, flow transition to ejection is ensured, which makes systole tightly coupled with diastolic filling (Carlhall and Bolger 2010; Chan and Veinot 2011). Accordingly, recent *in vitro* and *in vivo* observations suggest that the normal vortex pattern might minimize the fluid energy dissipation and optimize LV myocardial efficiency (Charonko et al. 2013; Domenichini et al. 2007; Kilner et al. 2000; Pedrizzetti and Domenichini 2005). Vortices that form during LV filling thus have specific geometries and locations, which could be determinant factors of heart function (Hong et al. 2008; Nucifora et al. 2010). In patients with abnormal heart filling, there is an impairment of the wall/fluid dynamics that may disturb the flow patterns and, thus, affect the diastolic vortical structures (Nucifora et al. 2010). Reliable tools for imaging the intraventricular flow arrangements could be of major clinical interest for a better assessment of LV diastolic function. Comprehensive intracardiac velocity mapping can be measured by phase-contrast magnetic resonance imaging (MRI).

Address correspondence to: Damien Garcia, CRCHUM, Pavillon JA de Sève Local Y-1619, 2099 Alexandre de Sève, Montreal, QC H2L 2W5, Canada. E-mail: damien.garcia@crchum.qc.ca or garcia.damien@gmail.com

Acquisition of 3-D cine phase contrast velocity data can indeed provide time-resolved characterization of blood flow in the left ventricle (Eriksson et al. 2010; Markl et al. 2011; Mohiaddin 1995; Toger et al. 2012; Wigstrom et al. 1999). MRI, however, is difficult to implement in routine practice because of limited accessibility and cost. Besides MRI, several echocardiographic techniques have been proposed in the last two decades to make vortex imaging more easily available for clinical daily practice. So far, four principal echocardiographic techniques have been described:

1. The earliest echographic studies regarding diastolic flow patterns are those based on observations from 2-D color Doppler and color M-mode echocardiography (Delemarre et al. 1990; Rodevand et al. 1999; Van Dantzig et al. 1995). Normal and abnormal flows were defined qualitatively according to the diastolic arrangements of the Doppler spectrum waveforms or of the red/blue-encoded Doppler velocities in the left ventricle. No quantitative measures of the vortices, however, were proposed.
2. Vortex formation time (VFT) has recently been proposed as an echocardiographic parameter to quantify the formation of LV vortices. VFT is a non-dimensional index that characterizes the optimal conditions leading to vortex formation (Dabiri and Gharib 2005). It has also been claimed to be an index of cardiac function (Gharib et al. 2006). Recent clinical studies in acute cardiomyopathy have reported that VFT is reduced with impaired relaxation (Jiamsripong et al. 2009; Kheradvar et al. 2012; Nucifora et al. 2010; Poh et al. 2012). The VFT index, however, is simply a surrogate parameter that is calculated from standard echographic measures (stroke volume, mitral valve diameter, E and A waves). As a consequence, similarly to these standard parameters, it is expected that the VFT index may lack consistency in some situations. Whether this index is of clinical interest still remains questionable (Stewart et al. 2012).
3. Echo-particle image velocimetry (echo-PIV) is an efficient echographic tool for intraventricular velocity mapping (Cimino et al. 2012; Hong et al. 2008; Prinz et al. 2012). This technique, applied to contrast-enhanced echocardiographic images, is able to track ultrasound speckle displacements to estimate blood motion within the image plane (Gao et al. 2012; Kim et al. 2004). Recent studies have focused on LV vortex quantification by echo-PIV (Cimino et al. 2012; Faludi et al. 2010; Hong et al. 2008; Sengupta et al. 2012). This technique requires a continuous intravenous injection of contrast agent to reach an image quality suitable for motion tracking (Gao et al. 2012), seriously limiting the application of echo-PIV in daily clinical practice.
4. Cardiac Doppler vector flow mapping (VFM) is a technique based on 2-D color Doppler images and, thus, can be easily used for clinical applications. In the VFM approach, 2-D assumptions are used to develop an intracardiac vector distribution by deducing the velocity components perpendicular to the ultrasound beam within the entire Doppler field. Several techniques for intraventricular VFM have been recently been proposed (Arigovindan et al. 2007; Garcia et al. 2010; Uejima et al. 2010). Preliminary studies indicated promising results regarding the feasibility of LV vortex quantification in patients by VFM (Chen et al. 2012; Hendabadi et al. 2013; Lu et al. 2012; Zhang et al. 2012). Additional studies are still required to determine the accuracy and clinical reproducibility of Doppler VFM.

The new technique we propose—Doppler vortography—has been developed specifically to detect and quantify the intraventricular vortices that form during LV filling. Doppler vortography targets mainly particular local flow patterns present in the Doppler field using a fast detection algorithm. To detect and quantify the vortices, we propose an index called the "blood vortex signature" (BVS), obtained using a specific covariance-based kernel filter. This approach is thoroughly described in the next section. It is shown that Doppler vortography can estimate core vorticities accurately and that the results are concordant with those obtained by the vector flow mapping method.

METHODS

We here derive a new echocardiographic methodology, Doppler vortography, for detecting and quantifying the large-scale vortices that form in the left ventricle during diastolic filling. Figure 1 is a schematic example of vortex detection and quantification by Doppler vortography. As seen in this figure, for the particular case of a single large vortex, color Doppler exhibits an obvious antisymmetric imprint: negative mirror symmetry occurs with respect to the scan line crossing the vortex center. This anti-symmetry can also be used to detect intraventricular vortices. The Doppler vortography modality for intraventricular vortex imaging and the resulting BVS are described further below. *In silico* and *in vitro* studies were performed to validate the proposed technique and analyze the effects of transducer position and BVS filter kernel size. Doppler vortography was finally compared with VFM in patients using the VFM technique described by Garcia et al. (2010).