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● *Original Contribution*

DEVELOPMENT AND VALIDATION OF A PHASE-FILTERED MOVING ENSEMBLE CORRELATION FOR ECHOCARDIOGRAPHIC PARTICLE IMAGE VELOCIMETRY

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Abstract—A new processing method for echocardiographic particle image velocimetry (EchoPIV) using moving ensemble (ME) correlation with dynamic phase correlation filtering was developed to improve velocity measurement accuracy for routine clinical evaluation of cardiac function. The proposed method was tested using computationally generated echocardiogram images. Error analysis indicated that ME EchoPIV yields a twofold improvement in bias and random error over the current standard correlation method ($\beta_{Pairwise} = -0.15$ vs. $\beta_{ME} = -0.06$; $\sigma_{Pairwise} = 1.00$ vs. $\sigma_{ME} = 0.49$). Subsequently a cohort of eight patients with impaired diastolic filling underwent similar evaluation. Comparison of patient EchoPIV velocity time series with corresponding color M-mode velocity time series revealed better agreement for ME EchoPIV compared with standard PIV processing ($R_{ME} = 0.90$ vs. $R_{Pairwise} = 0.70$). Further time series analysis was performed to measure filling propagation velocity and 1-D intraventricular pressure gradients. Comparison against CMM values indicated that both measurements are completely decorrelated for pairwise processing ($R^2_{Vp} = 0.15$, $R^2_{IVPD} = 0.07$), whereas ME processing correlates decently ($R^2_{Vp} = 0.69$, $R^2_{IVPD} = 0.69$). This new approach enables more robust processing of routine clinical scans and can increase the utility of EchoPIV for the assessment of left ventricular function. (E-mail: pvlachos@purdue.edu)

Key Words: **Echocardiography, Particle image velocimetry, Diastolic dysfunction.**

INTRODUCTION

Recent advancements in cardiac flow visualization have changed the way cardiac disease progression is studied (del Álamo et al. 2009; Hong et al. 2013; Muñoz et al. 2013). Ultrasound and magnetic resonance imaging (MRI) now provide high-resolution information on blood flow within the chambers of the heart. Despite advancement, inherent limitations for each modality still exist. Color M-mode (CMM) collects blood velocity measurements along a thin scan line, preventing visualization of flow structures, whereas 2-D Color Doppler has low temporal resolution (Muñoz et al. 2013). Further, color Doppler modalities are accurate only at high velocities and unreliable for low-velocity measurements. MRI velocity measurements also provide low temporal resolution, and high operational costs limit widespread use (Muñoz et al. 2013; Sengupta et al. 2012).

Echo particle image velocimetry (EchoPIV) is an emerging method that provides 2-D planar views with temporal resolution higher than that of color Doppler and MRI, which allows improved visualization of cardiac flow (Muñoz et al. 2013; Sengupta et al. 2012). EchoPIV employs contrast-enhanced B-mode ultrasound imaging, commonly used in cardiac chamber geometry measurements. Flow measurements are made through Fourier-based correlation algorithms commonly used in image processing (Willert and Gharib 1991). Applications of EchoPIV range from cylindrical flow through peripheral arteries and veins (Kim et al. 2004; Zhang et al. 2011) to complex flow through the heart (Sengupta et al. 2007). General development and limitations of EchoPIV are provided in review articles (Bazilevs et al. 2010; Bermejo et al. 2015; Borazjani et al. 2013; del Álamo et al. 2009; Hong et al. 2013; Muñoz et al. 2013; Pedrizzetti and Domenichini 2015; Poelma 2017; Sengupta et al. 2012).

Clinical EchoPIV research studies have focused primarily on left ventricular (LV) flows, analyzing the vortexes that form during diastolic filling, linking properties of the

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vortex to cardiac health (Gharib et al. 2006), although agreement on universal relationships varies (Ghosh et al. 2009; Stewart et al. 2012). Complex topology of flow within the left ventricle presents a challenging condition for many non-invasive imaging modalities because of the need for adequate frame rates and spatial resolution (Arvidsson et al. 2016; Hendabadi et al. 2013). This has motivated use of EchoPIV as one of the primary tools for the study of blood flow within the left ventricle and has allowed researchers to investigate cohorts that include healthy patients (Cimino et al. 2012), LV diastolic dysfunction (LVDD) (Prinz et al. 2013), heart failure (Abe et al. 2013) and congenital heart disease (Kutty et al. 2014; Lampropoulos et al. 2012). Each of these works has furthered the potential diagnostic capabilities of vortex properties.

Although promising, these studies employ optimized scan settings and well-controlled contrast agent infusion (Gao et al. 2011) for performing EchoPIV flow visualization, which is not always achievable in standard clinical settings. Furthermore, the majority of these studies forego capture of accurate peak velocities and, instead, obtain the "general" flow pattern, biasing quantitative measurements of vortex rotation and circulation. There is a need to develop robust EchoPIV methodologies, techniques that consistently provide accurate velocity measurements with limited or no erroneous measurements, in the presence of increasing and spatiotemporally varying noise and image artifacts as they appear in EchoPIV images. With velocity measurements that are accurate in magnitude and direction, clinical measures of diastolic function such as propagation velocity (V_p) and intraventricular pressure difference (IVPD), along with complex flow observations (*i.e.*, vortex shape and position), can be obtained and related from a single scan.

In the work described here, we implemented and tested a short-time moving ensemble (ME) correlation on contrast-enhanced B-mode echocardiograms, coupled with dynamic phase filtering of the cross-correlation, and tested the hypothesis that this approach results in more robust, high-fidelity EchoPIV velocity measurements. The proposed method was validated using artificial ultrasound images, and subsequently we determined its feasibility using a cohort of patients with clinically diagnosed LVDD. For each subject, the resulting EchoPIV velocity measurements were compared against respective CMM velocity measurements. Further time series analysis was conducted to determine ME EchoPIV capabilities for measuring filling wave V_p and IVPD.

METHODS

Particle image velocimetry

Standard pairwise cross-correlation. Particle image velocimetry uses cross-correlation between two sequential images to estimate particle image pattern displacements; herein we refer to this standard approach as pairwise correlation (Willert and Gharib 1991). The method was developed for images obtained from laser-illuminated particle-seeded flow fields that, under proper seeding, illumination, and exposure, produce bright-intensity particle images on dark, low-intensity backgrounds. Contrast-enhanced B-mode images taken for EchoPIV processing do not produce such images. The images are subject to speckle patterns with very high background noise levels. The resulting elevated noise floor in instantaneous correlation planes leads to erroneous velocity estimates (Keane and Adrian 1992).

Moving ensemble cross-correlation with phase filtering. Ensemble-average cross-correlation was originally developed for microscale PIV as a means to increase the correlation signal-to-noise ratio (SNR) for images containing high background noise and out-of-focus particles (Delnoij et al. 1999; Meinhart et al. 2000). This technique is typically reserved for steady-state flows with little temporal velocity variation. Pairwise correlation planes from a large frame series are enumerated to produce an average correlation plane (Delnoij et al. 1999; Meinhart et al. 2000; Violato and Scarano 2011),

$$\bar{R}(s) = \frac{1}{N}\sum_{i=1}^{N} R_i(s) \tag{1}$$

where the correlation coefficient values R_i at each position s are summed to obtain the average correlation plane estimate $\bar{R}$. The result from this correlation plane is a displacement estimate that would not significantly change with the addition of another pairwise correlation plane. Ensemble-average correlation may also reduce the influence of image artifacts (*i.e.,* sensor noise, additional fluid particulate). However, the traditional ensemble correlation is not appropriate for performing cardiac EchoPIV because of the unsteady nature of blood flow. Alternatively, ME correlation across a short time series of images can be employed,

$$\bar{R}(s) = \frac{1}{M}\sum_{i=j-M}^{j+M} R_i(s) \tag{2}$$

where j refers to the center frame for the ensemble, and N is the neighborhood half-width. This approach offers a mechanism for attaining accurate velocity measurements from noisy data (Violato and Scarano 2011). The ME method is based on the notion that all correlation planes have a common statistical correlation peak near a constant displacement.

Our proposed processing strategy is illustrated in Figure 1. This method incorporates the ME correlation in conjunction with a novel approach in correlation phase fil-