High-frame-rate velocity vector imaging echocardiography: an *in vitro* evaluation

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***Abstract* ð High-frame-rate ultrasound imaging using diverging waves has demonstrated its potential as a useful cardiac imaging method. It has been shown that the compounding of steered beams improves static images quality. In the presence of high-velocity tissue motion, however, the combination of successive steered diverging waves is incoherent and thus deteriorates the image contrast. Motion compensation (MoCo) integrated in the coherent compounding process has recently shown to be a very promising technique to provide high-contrast B-mode images of the cardiac muscle. Ultrafast cardiac motion estimation based on speckle tracking could greatly benefit from this original method. In this study, Velocity Vector Imaging (VVI) was applied on high-frame-rate envelope images performed with MoCo to estimate the myocardium 2-D motion. The method was investigated *in vitro*, using a rotating disk. With sequences of steered diverging waves (pulse repetition frequency = 4500 Hz) generated by the full aperture of a 2.5 MHz phased array, high-contrast high-resolution images were constructed at 500 FPS using MoCo. Standard cross-correlation and phase correlation in the Fourier domain were applied to generate VVI on the pre-scanned envelope images at 100 images/s. The estimated *in vitro* velocity vectors were consistent with the expected values, with an average normalized error of 6.0% +/- 0.4% in the radial direction, and 13.1% +/-1.2% in the cross-range direction. These results make us confident to pursue the study with *in vivo* investigations.**

Keywords ð Ultrafast Imaging, Motion Compensation, Diverging Waves, Velocity Vector Imaging

I. INTRODUCTION

Echocardiography is one of the most common modality for imaging the heart due to its high temporal resolution, its low cost and its ease of access. In addition, it is a safe diagnostic-imaging modality allowing dynamic cardiac imaging in real time [1]. The quantification of the cardiac deformations by ultrasound imaging is of clinical relevance to assess the heart function. Conventional ultrasound imaging with focused beams returns cardiac B-mode images at frame rates ~ 80 frames per second (fps). Echocardiography at high-frame-rate (~500 fps) can help to better characterize the fast motion variations of the cardiac muscle. High-frame rate ultrasound imaging is possible with diverging waves and compounding of steered beams to preserve spatial resolution [2]. The method is efficient for static scatterers but may result in incoherent summation and a loss of contrast when tissues are moving. It has been shown that high-frame-rate high-contrast images can be achieved when Motion Compensation (MoCo) is integrated in the coherent compounding process [3]. Since the speckle patterns are preserved, Velocity Vector Imaging (VVI) based on speckle tracking could profit from this method for ultrafast cardiac motion estimation.

An original MoCo method has been developed by Porée *et al.* and produced high-contrast cardiac B-mode images [3]. We propose to combine this motion compensation with speckle tracking to obtain high-frame-rate velocity vector imaging echocardiography and quantify the 2-D myocardium motion. In this study, our original approach was validated by a preliminary *in vitro* evaluation using a rotating disk with outer speed values ranging from 1 to 36 cm/s. The acquisitions were obtained with a Verasonics research scanner.

II. THEORETICAL BACKGROUND

A. Coherent Compounding and Motion Compensation

Diverging waves as large as 90° can be transmitted to produce high-frame-rate ultrasound cardiac images. To improve the contrast and spatial resolution, several images with different steering must be compounded coherently. When imaging the heart, the fast motion of the myocardium impairs the common compounding approach since significant phase delays can appear. The summation can thus be incoherent and destructive: the speckles are poorly preserved and the contrast decreases. We proposed in a precedent paper a motion compensation approach during the compounding process to preserve the coherence of individual complex envelopes before summation. This method is based on tissue Doppler [3]. In PoréeÕs MoCo method, the tilt angles of the transmitted wavefronts are organized in a triangular arrangement. This ensures the coherent summation of the main lobes, while the sidelobes are summed incoherently to eliminate their side-effects [3].

B. Velocity Vector Imaging

Speckle tracking is one of the most popular velocity measurement techniques in ultrasound imaging and is based on the conservation of the speckle patterns present in the B-mode images. The standard technique is based on the cross-correlation. An image ensemble, constituted of successive frames, is divided into several regions of interest; to improve computational complexity, the cross correlations can be performed in the Fourier domain (FFT-cross correlations).

Ensemble correlation (average of the cross-correlation matrices) makes the motion estimation more robust, under the assumption that the velocity is nearly constant during the time of the successive acquisitions. In this study, this first step was applied on the pre-scanned envelope images. The motion can then be estimated by two different methods, whose efficiency depends on the motion amplitude. The standard cross-correlation (SCC) seeks the location of the normalized cross-correlation peak. The second approach uses the phase correlation matrix (which is the Fourier transform of the cross-correlation, PCC). For motions greater than one-tenth of a pixel and less than one quarter of the kernel size [6], the peak of the normalized cross-correlation is detected and its location provides the displacement. The peak can then be fitted with a paraboloid to obtain a subpixel precision. For motions smaller than one-tenth of a pixel, the phase approach (PCC) is recommended. The phase correlation matrix can be fitted with a plane whose slopes are related to the 2-D motion. In practice, this phase technique is limited by aliasing and noise. A robust fitting of the small-frequency components is thus essential.

Speckle tracking is only possible if there is conservation of the speckles between successive frames. We aimed at demonstrating that MoCo guarantees this essential condition on image quality.

III. METHOD

The measurements were all performed with a Verasonics research scanner (V-1-128, Verasonics Inc., Redmond, WA) and a 2.5 MHz phased-array transducer (ATL P4-2, 64 elements). The images were beamformed in a polar space with 256 radial lines. The acquisition and post processing parameters are shown in Table 1.

Parameters	Values
Acquisition	
Probe central frequency	2.5 MHz
Pulse repetition frequency	4500 Hz
Number of probe elements	64
Angular width of the sector	90 °
Tilt angles	[-16 : +16]°
Number of transmits	36
IQ data sampling	5 MHz
Post Processing	
MoCo overlap	75%
B-mode images	500 images/s
VVI ensemble	20 images
VVI images	100 images/s
Disk	
Diameter	10 cm
Angular velocity	[0.2 : 6.6] rad/s
Angular velocity step	0.2 rad/s
Outer speed	[1 : 35] cm/s

Table 1. Acquisition and post processing parameters for in vitro experiments

In vitro experiments were performed with a 10-cm-diameter rotating disk connected to a motor to control its speed. The disk center was placed at a distance of 7cm from the probe: the geometrical characteristics of the experiment were concordant with those observed in echocardiography: the disk upper edge was 2 cm far from the probe, and the maximum depth was 12 cm. The acoustic properties of the disk were tissue-like, with the following composition: agar 3%, Sigmacell cellulose powder 3%, glycerol 8% and water. The outer speeds (velocity amplitude at the edge) ranged from 1 to 35 cm/s with a 1.1 cm/s step which corresponded to a maximum angular velocity of 7 rad/s and a 0.2 rad/s step. The disk velocities were chosen to reproduce the different velocities of the myocardium which can exceed 20 cm/s in some exercise situations. The Nyquist tissue velocity was 35 cm/s, which is much higher than the physiological myocardial speeds.

We used series of 36 tilted 90°-wide diverging beams to get high-quality compound image sequences with the MoCo approach (see [3] for details). The tilt angles followed the triangle arrangement described in the theoretical background II.A. High-contrast high-resolution images were constructed at 500 FPS. To reach this frame rate, we implemented a 36-sample sliding window with 75% overlap (PRF / 36 × 4 = 4500 / 36 × 4 = 500 FPS). Velocity óvector images were then obtained with the speckle tracking based on the ensemble FFT-cross-correlation (SCC) and the ensemble phase correlation (PCC) described in the theoretical background II.B. The velocities were estimated on ensembles containing 20 polar envelope images. The echocardiographic velocity maps were compared with the theoretical maps determined from the known angular velocities.

IV. RESULTS

As in [3], there was no contrast loss when MoCo was applied during the compounding process. Without MoCo, the speckles were not preserved when the Doppler velocities were relatively large (Figure 1.).

Figure 2 illustrates an estimated motion field on the rotating disk, consistent with the theoretical pattern. The motion and error maps for two different rotation speeds of the disk, both in radial and cross-range directions, are represented in Figure 4: the estimated disk velocities are close to the ground-truth values. The larger errors were observed at the upper edge and might be caused mostly by the strong specular reflections in the interface water/disk.

The average normalized errors (measured *vs.* theoretical velocities) are reported in Figure 3 for the radial and cross-range estimations. With the standard cross-correlation (SCC), the average normalized errors were 6.9% +/- 2.6% in the radial direction, and 14.0% +/-1.7% in the cross-range direction. The errors decreased with increasing speeds: the SCC is indeed known to be more efficient with motions greater than half a pixel. Regarding the phase correlation approach (PCC), the average normalized errors were 6.0% +/- 0.4% in the radial direction, and 13.1% +/-1.2% in the cross-range direction. Because of aliasing, the errors increased with increasing speeds. With low motions (velocities less than 20 cm/s), PCC decreased the radial and lateral errors contrary to the SCC, as shown in the Table 2. Inversely, (velocities greater than 20 cm/s) the SCC results were more accurate than PPC results because of aliasing with large motions (Table 2).

Disk Maximum Rotating Speed Range		SCC	PCC
[1:35] cm/s	Radial	14.0 +/-1.7	6.0 +/- 0.4
	Cross-Range	6.9 +/- 2.6	13.1 +/-1.2
[1:20] cm/s	Radial	8.6 +/- 2.3	**5.9 +/- 0.5**
	Cross-Range	15.3 +/- 1.2	**12.4 +/- 0.6**
[20:35] cm/s	Radial	**4.8 +/- 0.4**	6.1 +/- 0.2
	Cross-Range	**12.5 +/- 0.5**	14.0 +/ -1.1

Table 2. Normalized errors (%) in radial and cross-range directions for the SCC and PCC methods, considering different velocity ranges.

These results allowed us to conclude that our VVI approach based on an original MoCo and a common speckle tracking motion estimator (SCC or PCC) can accurately measure fast motions using diverging wave imaging.

V. Discussion

This paper introduces an innovative method for high-frame-rate velocity vector imaging. Motion compensation preserved the speckle patterns, thus allowing post processing applications such as Velocity Vector Imaging based on speckle tracking. This high-quality imaging process was applied on ultrafast echography *in vitro*. The *in vitro* study realized with a spinning disk validated two classical motion estimation methods. The two different speckle tracking algorithms were complementary. The SCC was more accurate for the largest velocities, while the PCC gave better results for low-motion tissues. Consequently an adaptive algorithm combining SCC and PCC could be developed to adapt the described methods to echocardiography in an ultrafast imaging context.

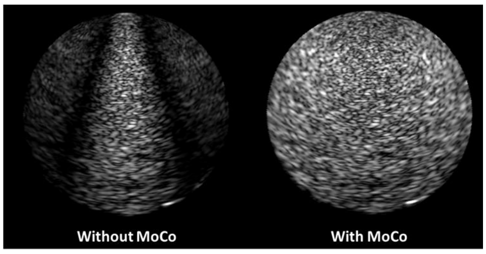

Figure 1. B-Mode images of a rotating disk obtained without MoCo (left) and with MoCo (right); Outer speed = 9.8 cm/s

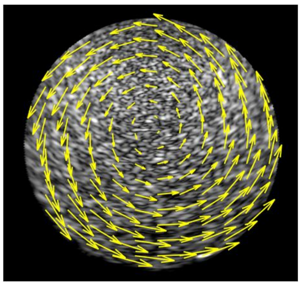

Figure 2. Example of estimated motion ýelds on the rotating disk, speed = 9.8 cm/s

VI. Conclusion

In this paper, we presented an approach combining motion compensation and speckle tracking to perform highï frame-rate Velocity Vector Imaging of the myocardium. The method was validated *in vitro* by using a spinning disk with geometric and velocity parameters compatible with those observed in the *in vivo* echocardiographic conditions. This validation shows that motion compensation provides compound images whose quality is suitable to common motion estimators. We will next extend this method *in vivo* to generate high-frame-rate velocity vector images of the cardiac muscle. To get accurate motion estimation during the whole cardiac cycle, a robust adaptive algorithm combining SCC and PCC will be implemented.

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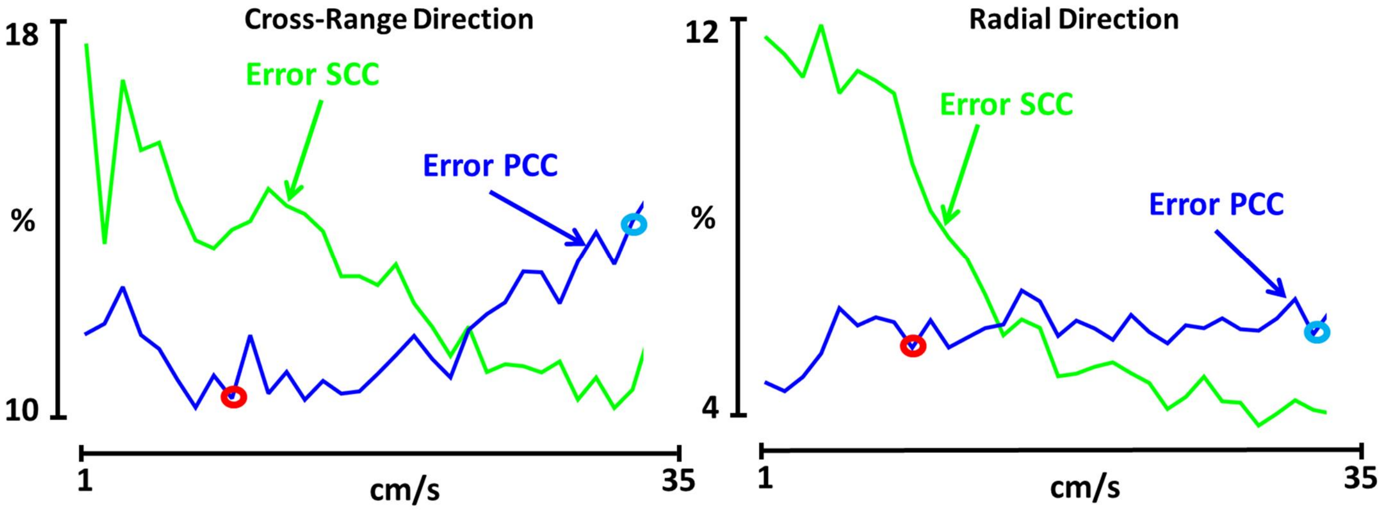

Figure 3. Average normalized errors of the cross-range (left) and radial (right) displacements measured by SCC (green) and PCC (blue). The abscissa represents the outer speed of the disk. The dots refer to the examples illustrated in Figure 4.

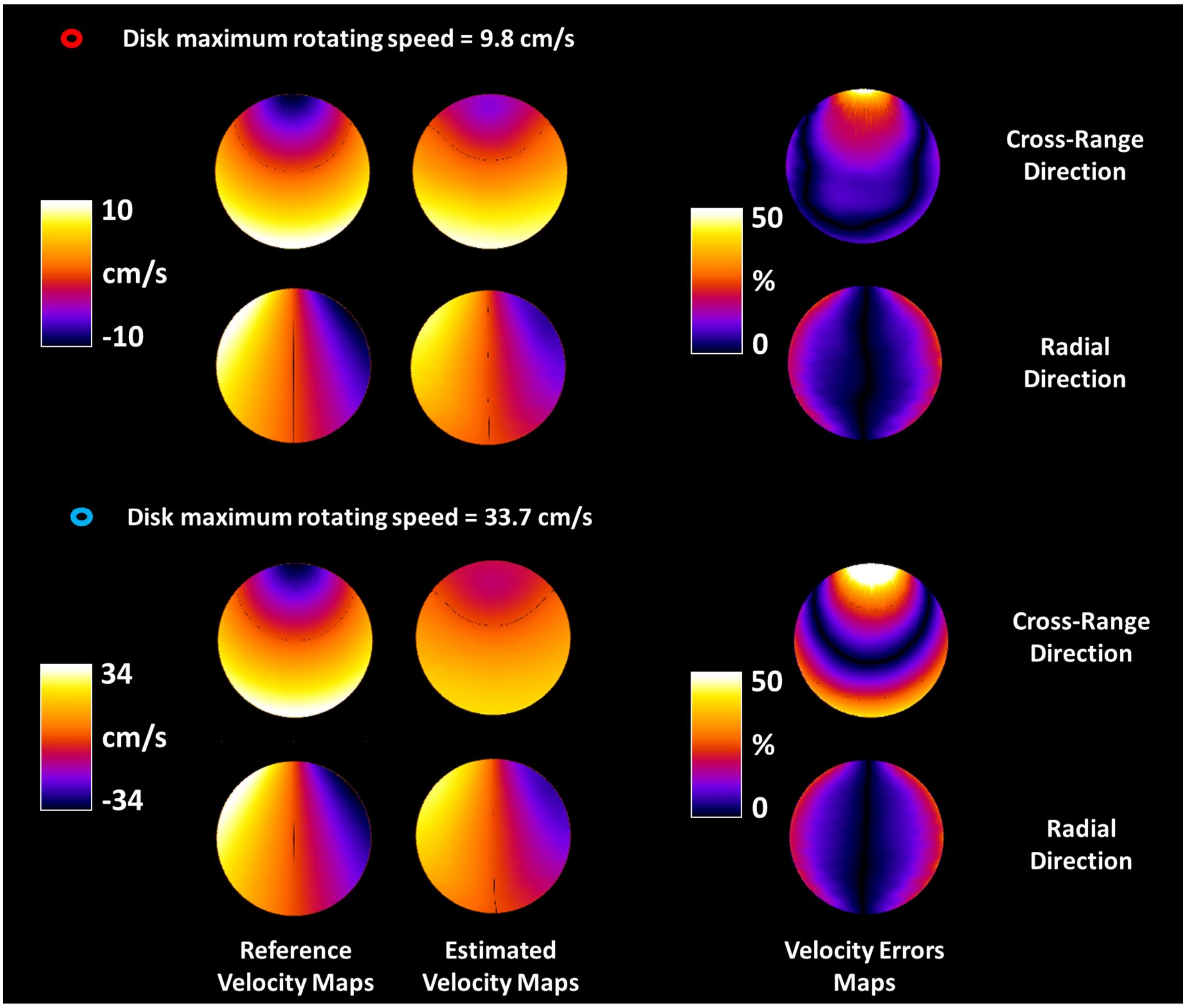

Figure 4. Velocity and errors maps: PCC-derived velocities *vs.* ground-truth.