Effects of motion on high frame rate contrast enhanced echocardiography and its correction

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***Abstract*—Contrast echocardiography (CE) ultrasound with microbubble contrast agents have significantly advanced our capability in assessing cardiac function, including myocardium perfusion imaging and quantification. However in conventional CE techniques with line by line scanning, the frame rate is limited to tens of frames per second and image quality is low. Recent research works in high frame-rate (HFR) ultrasound have shown significant improvement of the frame rate in non-contrast cardiac imaging. But with a higher frame rate, the coherent compounding of HFR CE images shows some artifacts due to the motion of the microbubbles. In this work we demonstrate the impact of this motion on compounded HFR CE in simulation and then apply a motion correction algorithm on in-vivo data acquired from the left ventricle (LV) chamber of a sheep. It shows that even if with the fast flow found inside the LV, the contrast is improved at least 100%.**

***Keywords*—** *In-vivo High frame rate / ultrafast contrast echocardiography, Motion effects and correction, Coherent compounding, Contrast enhanced ultrasound, Pulse Inversion*

I. Introduction

Ultrasound contrast agents (UCA), or microbubbles, for contrast enhanced ultrasound (CEUS) ultrasound imaging is revolutionising the role of medical ultrasound in clinical practice [1]. These bubbles are highly sensitive to ultrasound, and once introduced into the blood stream, they can generate significant signal enhancement. Various signal processing techniques have been developed to achieve highly sensitive, specific, and quantitative imaging of the bubbles for flow and perfusion imaging [2], [3].

Another significant advance in biomedical ultrasound is the development of high frame-rate (HFR) ultrasound imaging techniques for various clinical applications [4]. Different approaches have been proposed to improve the frame rate for cardiac imaging. These include multi-line acquisition, multi-line transmission and diverging wave transmission [5-11]. The benefit of imaging with diverging waves has been shown for both 3D cardiac Doppler [8] and cardiac elastography [9]. The first combination of HFR cardiac imaging using pulse inversion (PI) and diverging waves for contrast echocardiography (CE) ultrasound, named HFR CE, for in-vivo myocardium perfusion experiments was shown recently [11]. The contrast between the heart chamber full of ultrasound contrast agents and the myocardium was improved by a factor of 2 compared to standard focused transmission, even with a peak negative pressure for HFR CE that was 4 times lower than conventional focused CE transmission. Moreover, comparing to ~30Hz in standard CE, HFR CE can reach a frame rate of up to 5000Hz, allowing accurate tracking of fast flow structure and dynamics in the cardiac chambers.

Both contrast pulse sequences and spatial compounding involve coherent summation of echoes from a target at different time points. While previous studies have investigated the effect of target motion on final images after either contrast pulse sequence [12] or non-contrast spatial compounding [10, 13], their effects are very different and it is yet not clear of the impact of motion on compounded HFR CE images. Furthermore, there is no study to demonstrate the benefit of motion correction in compounded HFR CE.

The aim of this work is firstly to demonstrate the impact of the motion on compounded HFR CE in simulation and secondly to evaluate the motion correction algorithm in-vivo.

II. Materials and Methods

HFR CE Field II simulations were performed and in-vivo data were acquired with a HFR CE system based on a 128-Verasonics platform (Verasonics Inc., Redmond, WA) mounted with a 96 element P4-1 phased-array transducer. HFR CE transmission was based on the diverging transmission [10]. In order to obtain a diverging wave, a virtual point source was created behind the probe creating a diverging beam which enlarge the region illuminated. Similar to the plane wave imaging, a single diverging wave has a low contrast and resolution, therefore coherent diverging compounded image is obtained by varying the position (steering) of the virtual point source and by coherently averaging the echoes of the diverging transmissions. For each steering angle, two successive pulses

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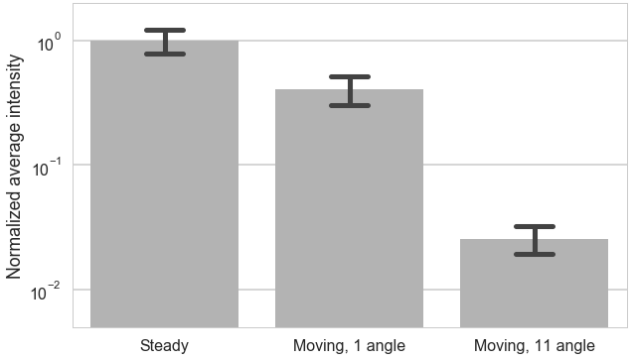

Fig. 1. Simulation results showing the maximum intensity of the beamformed image when a single bubble is present and is either steady or moving vertically with a speed of 0.5m/s. Values are normalized to the average intensity of stationary bubble and 300 different microbubbles are used to make each bar.

of opposite phase were transmitted and combined in post-processing to form the PI image.

A. Simulation

In simulation a single moving microbubble (MB) was placed 4 cm below the centre of the transducer. The propagation of the ultrasound wave was simulated via custom software interfaced with Field II [14, 15], while the MB response was derived by numerically solving the Marmottant model [16].

HFR CE simulation images were obtained by transmitting 1 or 11 diverging PI wave pair (3-cycles, 1.5MHz, MI 0.05) with angles between ±15 degrees, a scanning depth of 10 cm and coherently compounding to achieve a compounded frame rate of 2750 or 250 Hz respectively. The images were also filtered with a 5-th order Butterworth further isolate the contrast-generated second harmonic signal from the fundamental.

The microbubble mechanical parameters were matched to the SonoVue [17] and the size of each microbubble randomly chosen in accordance to the experimental size distribution of SonoVue [18]. For each simulated microbubble, the maximum intensity of the beamformed image is measured.

B. In-vivo experimental setup

The in-vivo CE experiment was conducted under licence from the UK Home Office at the University of Edinburgh. The HFR CE was evaluated in-vivo on an adult female Scottish Greyface sheep under terminal general anaesthesia maintained using isofluorane [19] The probe was held using a metallic arm in order to capture the same image of the left ventricle (LV) chamber. The sheep were positioned slightly on the left side that ensured optimal heart imaging and avoided reflections from the ribs. During the acquisition, ventilation was transiently paused by extubation to avoid chest movement.

HFR CE in-vivo images were obtained by transmitting using the same settings as in simulation. Moreover, the same Butterworth filter as in simulation was used to extract the second-harmonic signal of the PI images

C. Motion compensation

The motion compensation of this work uses the motion estimation based on an image registration model adopted from MRI. The model is based on the work of Rueckert et al. and Lee et al. [20, 21] and it can perform a rigid, affine, non-rigid, and a two stage motion estimation. A Matlab code is currently available to download [22] and more explanation about the motion estimation algorithms are given in our paper [23].

In this work, motion compensation is obtained by spatial alignment of beamformed radio frequency data with the central angle transmission, of each corresponding frame, as reference. Finally, the corrected data of all beamformed RF angles are coherently compounded.

D. Post-processing and analysis

In order to reduce noise and improve signal-to-noise ratio, an incoherently averaging in function of time of the HFR CE frames was applied in post-processing. Averaging 7 HFR CE frames, with a triangular window centered on the interested frame, corresponds to a similar frame rate as the standard CE transmission (~30Hz). The image are named HFR CE SUM 7 and the technic is applied with or without motion correction.

The motion compensation improvement was evaluated by measuring the contrast-to-noise ratio (CNR) between the LV chamber and the noise. The CNR was calculated for all frames and it defined as:

$$CNR = \frac{\left|\mu_{LVChamber} - \mu_{Noise}\right|}{\sqrt{\sigma^2_{LVChamber} + \sigma^2_{Noise}}} \qquad (1)$$

(2)

where in $\mu_{LVChamber}$ and μ_{Noise} are the mean intensity in the LV chamber and in the noise area, respectively. $\sigma_{LVChamber}$ and σ_{Noise} are their corresponding standard deviations.

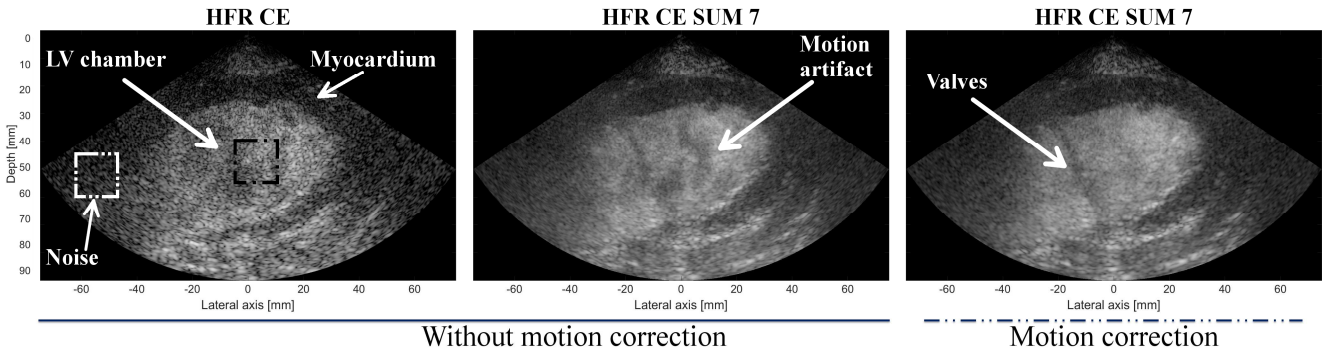

Fig. 2. In-vivo HFR CE acquisition without and with motion correction. HFR CE (Left) without processing while (Middle) and (Right) show HFR CE with a temporal average of 7 frames SUM 7. The ROI for CNR is shown in (Left): Left ventricle (LV) chamber area (Black) and noise area (White). All images are log-compress and displayed with a 50 dB dynamic range.

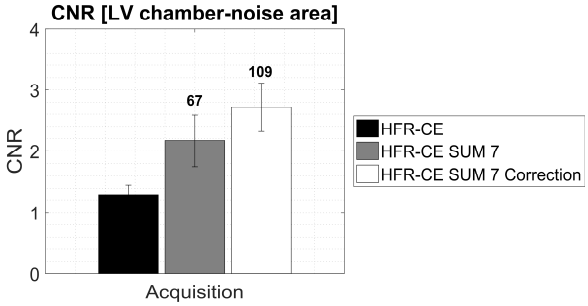

Fig. 3. Mean and standard deviation of HFR CE CNR between the Left ventricle (LV) chamber and the noise area. CNR is calculated with and without motion correction and with and without temporal filtering. The percentage of improvement against the initial HFR CE is given on the top of each bar.

III. Results

In Figure 1 the peak intensity in the beamformed image between steady and moving microbubbles obtained via simulation are presented. It is possible to appreciate how microbubble motion results in a reduction of signal intensity even for a single compounded angle, due to the relative shift of positive and negative PI images, but such reduction is much more accentuated when 11 compounding angles are used, because of the misalignment of the images for each angle.

Figure 2 shows the same in-vivo HFR CE frame without and with motion correction, respectively. The left image in Figure 2 highlights the region-of-interests (ROIs) for CNR calculation. The middle and right image of Figure 2 are obtained with the temporal averaging SUM 7. Without motion correction, several patterns inside the LV are visible. Thanks to the motion correction, the patterns disappears while information such as the valves are preserved.

Figure 3 gives the mean and the standard deviation of HFR CE for the LV chamber with the noise area. The values on the top of each bar give the percentage of improvement against the initial HFR CE. By averaging frames the normal HFR CE SUM 7 smooths the speckle pattern, reducing the noise and improving the contrast more than 50%. HFR CE SUM7 with motion correction improves the contrast at least 100%.

IV. Discussion and Conclusion

In this work, we show the impact of motion on coherent compounding in high frame rate (HFR) pulse inversion (PI) diverging wave and standard contrast echocardiography (CE) acquisition. Previous research studies have highlighted the effect of target motion on final images after either contrast pulse sequence [12] or non-contrast spatial compounding [10, 13] but no studies demonstrate the impact of the motion on compounded HFR CE and the importance of motion correction for proper representation of contrast concentration in in-vivo acquisition.

The simulation results show that the use of compounding causes a serious degradation of the signal intensity in the presence of motion, highlighting the need for motion correction methods in cardiac imaging with diverging waves.

The proposed motion correction for HFR CE acquisition is based on image registration [20] between angles of the same frames. More specifically, the optimal motion estimation, and so correction, has been obtained on PI filtered images (Figure 2).

As the in-vivo results show, if a temporal filter such as an incoherent averaging of successive frames (persistence / video filter in clinical system) is applied, the contrast-to-noise ratio CNR between the left ventricle (LV) chamber and the myocardium is improved more than 50%. However the combination of the image registration and the temporal filter improves the CNR by at least a factor of 2. Furthermore, the motion correction is robust to the flow velocity inside the chamber. A new particle image velocimetry tracking has been applied and shows a maximum flow velocity up to 0.45 m/s in this data set [24].

These preliminary results are promising and highlight the possibility of motion correction on HFR CE acquisition even with the presence of a fast flow. Further simulation, in-vitro experiments with controlled flow and in-vivo acquisition will be conducted to optimise the motion corrections parameters.

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