11th International Conference on Vibration Problems
Z. Dimitrovová *et.al.* (eds.)
Lisbon, Portugal, 9–12 September 2013

MONITORING BUBBLE FLOW IN ECHO PARTICLE IMAGE VELOCIMETRY

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Keywords: Echocardiogram, Cardiac Shunts, Bubble-Blood Interaction

Abstract. *Monitoring blood flow in cardiac chambers is a challenging problem to resolve critical issues in medicine. Bubbles or air emboli are mostly encountered between these chambers due to extreme conditions (hypobaric or hyperbaric environment). The quantification of bubble recognition is generally achieved manually in B-mode (Brightness mode) ultrasound by visual examination. A detailed procedure for bubble quantification would be performed via a novel approach called Echocardiographic Particle Image Velocimetry (Echo PIV). This non invasive technique would permit the generation of particle tracking. In this study, we aimed to measure particle properties with a conventional procedure of PIV applied to echocardiography which is also called Echo-PIV. Bubble movements in fluids are characterized with several approaches using approximations and models. Even bubble models offer spherical models to observe spatio-temporal evaluation; few studies have done on air emboli in blood and within heart. Blood which is a non Newtonian fluid had generally a unidirectional movement in capillaries. However, air emboli which arrive in cardiac chambers are under control of heart beats, blood turbulence and hidden shunts which create a medium or interface between fluxes. They introduce circular movements, affine, shearing and lateral effects. However their behaviors would differ in extreme conditions. In this paper, we examined the behavioral similarities between bubble jet through congenital shunt and theoretical model of bubbles in blood through an interface. After the initial phase, we noted a separation process of bubbles. We also developed a tracking system to evaluate bubble motion. This procedure was validated on two different simulations where bubble pathways were monitored. The initial phase of bubble crossing becomes crucial in echocardiography. It is remarkable to see that when separation phase starts, some bubbles would be out of view in Region of Interest where clinician examines total bubble number. For this purpose, we remarked the importance of bubble size and how separated bubbles would be tracked.*

1 INTRODUCTION

Over last decades, several multidisciplinary studies were performed about theoretical and observational effects of bubbles. Bubble shear stress, interaction and interface were also considered as challenging problems especially in fluid dynamics through simulation models and high resolution optical systems. This challenging problem is not yet fully simulated and studied in human body and especially within cardio-pulmonary system due to the imaging restrictions such as; noise, resolution, chaotic dynamics, vortex formation and non-Newtonian properties.

Single or multi bubble imaging is generally achieved in well monitored designs using high resolution cameras [1] or other imaging facilities within medical phantoms [2]. However, these models and observations would be found quite far away from the real interpretation of bubbles within the heart which is the core of blood circulation.

When several medical diseases or cases are taken into account, bubbles or so-called microembolism are found as the primary threat. These air filled structures which contribute to the circulation should pass from the heart. In general, bubble-blood interactions and dynamics were modeled and resolved for arteries such as carotids or cerebral veins. This choice was also due to the performance of actual medical imaging systems within these regions near the skin. However, this interaction would be better understood within the heart. Furthermore, bubble monitoring would also be crucial to reveal the unwanted effects of bubble separation or fusion.

Echocardiagraphic imaging is found as a golden standard in cardiology for its imaging capabilities and non-hazardous effects than other modalities. Furthermore, its imaging performance would be feasible to examine clinical effects of microembolism within the heart. However, bubble imaging requires special trainings and modalities to gather reliable angle of views. Bubbles have high contrasts regarding neighbour structures and are easily recognized by clinicians. On the other hand, their computational recognition requires special algorithms.

Particle Image Velocimetry is a well known optical technique in fluid dynamics to measure several properties of fluids or objects within the source fluid. Its application on medical area was found accurate in echocardiography. Its application on heart chambers was called Echo-PIV with the same principles to measure the velocity vectors, flux mesh and vorticity [3, 4, 5].

In this study, we focused on a new problem related to both bubbles and Echo-PIV. We adapted a similar methodology described by Kim et al. [4] to generate velocity fields. In echocardiographic monitoring, bubbles are used as contrast agents or they are inherently existent in some diseases. For both cases, their behavior and monitoring are important to generate possible results which are important in patient survey and diagnosis. We tested our approach using three different scenarios and obtained feasible velocity vectors. Firstly, we started to develop a realistic bubble model through echocardiographic images. Even though bubbles are modeled in spherical models, they have ellipsoid shapes within those frames. Therefore, this ellipsoid model was tested in the Echo-PIV system. Secondly, bubble contrast agents were monitored in echocardiography and measured through Echo-PIV. Finally, real intravascular bubbles were analyzed within our system.

Consequently, we developed a robust system which would be useful to reveal new aspects of the contrast agents (bubbles) and the real bubbles (microemboli) related to the vorticity within the heart. We aimed to show that the flux fields between bubble and blood could be a new routine for echocardiographic diagnosis which should be analyzed in several medical cases to satisfy its clinical reliability.

2 MATERIALS & METHODS

In this study, we performed the Echo-PIV analysis on both simulation and real data. The simulation step was achieved on two different cases; synthetic and realistic. Firstly, a synthetic data was created through a mathematical model using static window size as a heart chamber. Secondly, realistic bubbles were created using a contrast medium which was injected to a subject. Finally, real bubbles which were generated during a post-decompression phase of diving were observed by our proposed system. The study protocol was conducted in accordance with the Declaration of Helsinki and the subjects provided written informed consent before joining the study.

In order to generate our simulation and to test artificial bubbles, we started to extract bubbles from the original Brightness (B) mode echocardiography frames. Furthermore, we built up a two dimensional theoretical model to represent bubbles as in the heart. A synthetic bubble was generated through multivariate gaussian model (Figure 2). As in Figure 3, the frames were in two dimensions where a bivariate normal distribution was used as follows;

$$P(x_1, x_2) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-p^2}} e^{[-\frac{\kappa}{2(1-p^2)}]} \tag{1}$$

where

$$\kappa = \frac{(x_1-\mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2} + \frac{(x_2-\mu_2)^2}{\sigma_2^2} \tag{2}$$

and

$$\rho = cor(x_1, x_2) = \frac{V_{12}}{\sigma_1\sigma_2} \tag{3}$$

is the correlation of x_1 and x_2 and V_{12} is the covariance.

When extracted bubbles in Figure 1 were compared regarding its physical properties, our proposed model was found to offer similar representations. Their histogram profiles were also compared as in Figure 4 and bubbles were described mostly in ellipsoid forms except in the overlapping case.

In echocardiographic records, bubbles are travelling dynamically and same bubbles generally might be seen in two previous or posterior frames if there is not a massive opacification. This manual and visual tracking procedure is applied by clinicians to lower errors. In order to set the same echocardiographic environment and bubble behavior, synthetic microemboli would be either placed in previous or next frames by translating, rotating or removing.

Total number of bubbles during spatio-temporal analysis alters the diagnosis and medical assessment. When the number of bubbles in examined area is more or less than 20, generally the overlapping process might arise and the bubbles may not be differentiated visually like the first frames of Figure 5.

Simulated frames were set as 160×120 pixels, the average size of segmented LA in real records. Each video stream was 1 sec long and 25 frames/sec (*fps*). Bubbles on simulation datasets were placed randomly as in a realistic environment. Their contrasts were close to those of real emboli.

After completing the synthetic simulation, we started to test our method through contrast bubbles within real cardiac chambers. An agitated saline contrast medium which is composed of 9.5 ml saline and 0.5 ml air echo contrast medium (ad hoc sonicated mixture of 0.5 ml air

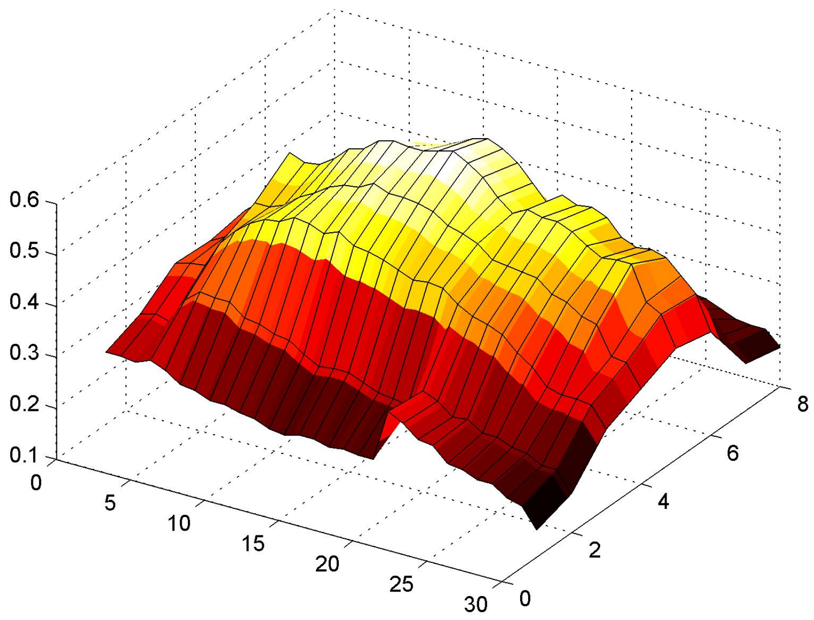

Figure 1: Bubble images acquired with B-mode ultrasound.

plus 9.5 ml plasma expander) was prepared. This solution was pushed back and forth 10 times in a double syringe system and injected through antebrachial vein. A massive opacification in the right atrium was visualized. The flux and overlapped bubbles were studied through Left and Right Atria.

Finally, real bubbles arising in post-decompression phase of diving were monitored. These bubbles were monitored in four chambers (both atria and ventricles).

2.1 Echo Particle Image Velocimetry

In this study, we performed a similar algorithm described by Kim et al. [4]. Like conventional PIV, this method is also based on a thecross-correlation analysis using Fast Fourier Transform (FFT). In echocardiographic frames, pixel size is smaller than the records using high resolution cameras. For this purpose, spatial resolution should be increased to generate accurate velocity vectors.

In order to generate velocity vectors, the cross correlation was calculated between two successive frames. Moreover, we measured a second cross correlation in a larger window. The multiplication of these two correlations generated an amplification of the velocity while the noise peaks remained constant. This amplification revealed the velocity vectors as they are visualized in Optical PIV. Furthermore, we reduced the window size to one quarter, therefore the resolution was doubled. We used the calculated vectors to set the optimal location of the window in the second image and the cross correlation was repeated. Finally, the optimal spatial resolution was obtained to create velocity vectors.

3 RESULTS

In this study, three different analysis were performed. We started our analysis with synthetic bubbles. Velocity fields of contrast bubbles were represented in Figure 5. We noted that the sep-

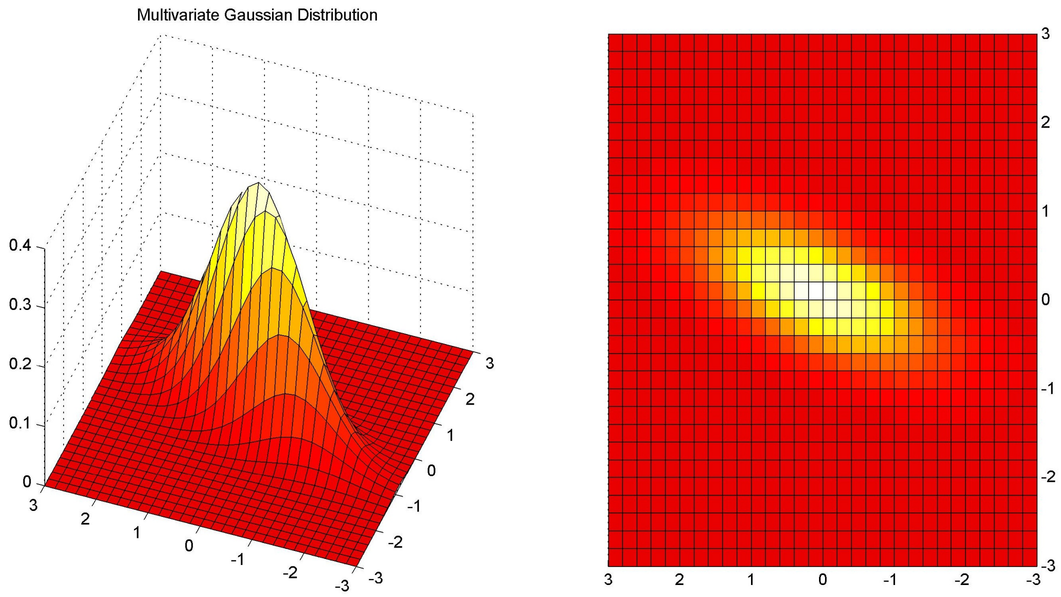

Figure 2: Development of a synthetic bubble using multivariate Gaussian distribution.

aration phase was clearly described. In this scenario, a congenital defect was existent. Bubbles coming from Right Atria could pass to Left Atria through a small shunt. The separated bubbles were better visualized in the fifth and sixth frames.

Moreover, the real bubbles were monitored during the post-decompression phase of diving. In this case, separated bubbles were present in all chambers. The velocity vectors rendered the behavior of bubbles within the heart and provided a tracking procedure to estimate the following situation in the consecutive frames.

4 CONCLUSION

PIV is also tool to visualize and interpret the vorticity and the shear stress in several disciplines. In medicine, its applications are generally implemented through the capillaries or the tissues near the skin. Echo-PIV is a new tool to characterize same features regarding the ultrasonic medical imaging. New studies consider this method as an alternative approach for cardiologic diagnosis through ultrasonic imaging.

In this study, we proposed a new application area of this method through bubbles which are found responsible to cause microembolic diseases. The visualization and the flux of bubble is a challenging task through the ultrasound within the heart. However, the vorticity of these bubbles is not yet fully understood due to the noise, artifacts or view angle of the probe. We tested the PIV method on theoretical bubble simulation, contrast bubbles and real post-decompression bubbles.

Even if, bubble shape and volume is introduced as a sphere, they are visualized as ellipsoids in video frames. Therefore, our proposed model used a similar way to place random bubbles in a frame. The bubble size is important to control the independent velocity field for each bubble. However, overlapping bubbles are found more important to describe the earlier phase (Figure 5) of the separation within the jet. In real cases (Figure 6), bubbles would travel separately but may coincide and overlap regarding the gradient of velocity and their orientation.

Consequently, our proposed method is found feasible to generate accurate velocity fields

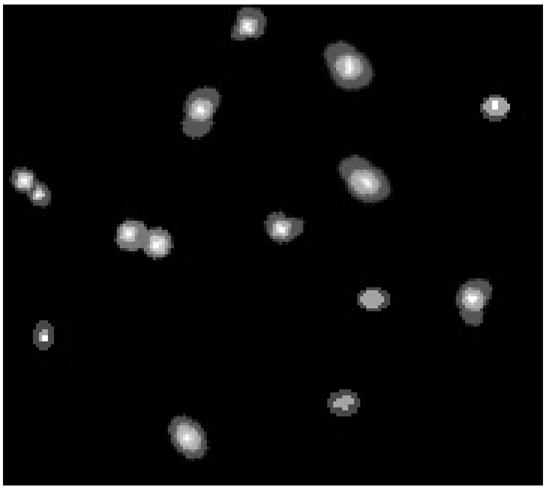

Figure 3: Representation of a frame with sythetic bubbles; separated and overlapped.

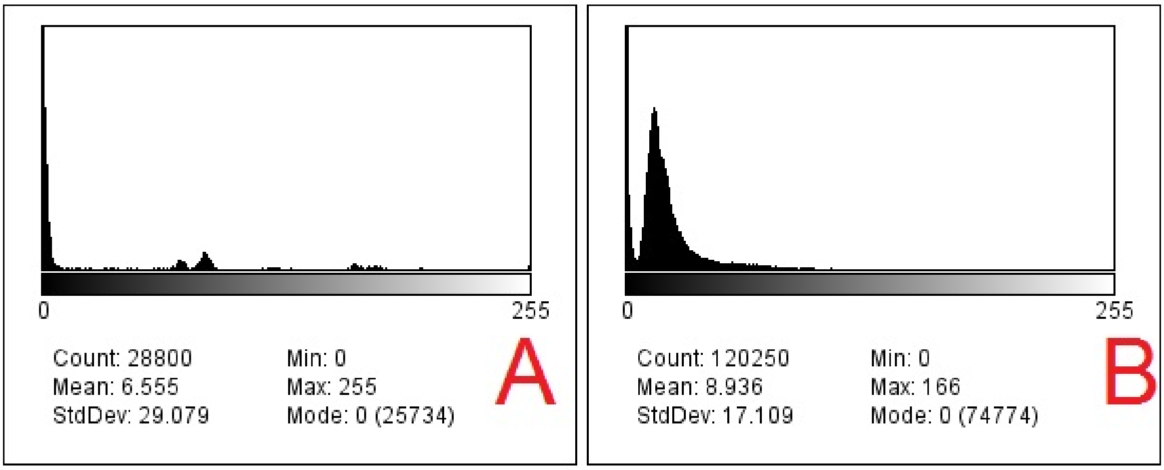

Figure 4: Histogram profiles of synthetic (A) and real (B) bubbles.

within the heart. We are planning to develop our approach as a diagnostic tool to study new cases related to the bubbles. The velocity vectors would better describe the behavior of bubbles within the heart and provided an automatic tracking procedure to the clinicians by eliminating the noise and false positive bubbles introduced by a manual survey.

5 ACKNOWLEDGMENTS

This study was supported by Bogazici University Foundation (BUVAK). We thank you DAN-Europe for the acquisition protocol and other facilities.

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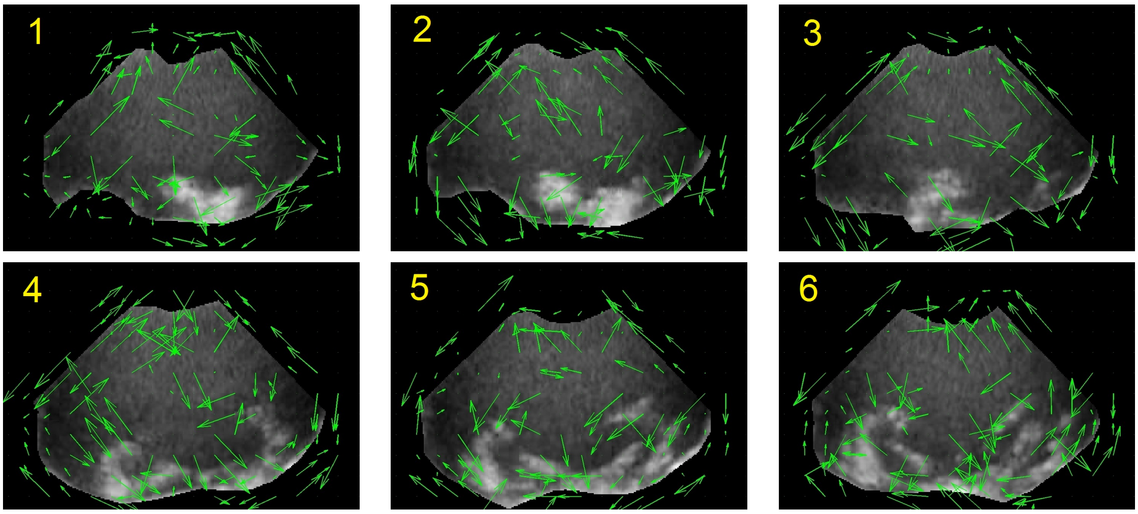

Figure 5: Measurement of velocity vectors of contrast bubbles by Echo-PIV in consecutive frames.

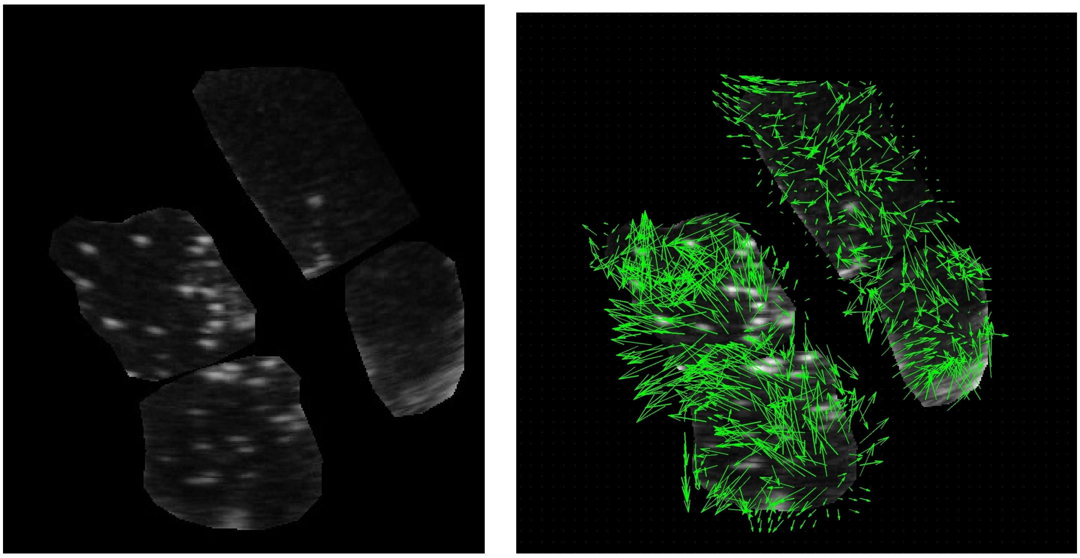

Figure 6: Measurement of velocity vectors of real bubbles by Echo-PIV.

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