Flow Imaging and Validation of MR Fluid Motion Tracking

K.K.L. Wong[1,3], R.M. Kelso[2], S.G. Worthley[3], P. Sanders[3], J. Mazumdar[1] and D. Abbott[1]

[1] Centre for Biomedical Engineering and School of Electrical and Electronic Engineering, University of Adelaide, SA 5005, Australia
[2] School of Mechanical Engineering, University of Adelaide, SA 5005, Australia
[3] Cardiovascular Research Centre and School of Medicine, Royal Adelaide Hospital and University of Adelaide, SA 5005, Australia

Abstract — **This paper presents flow results of a magnetic resonance imaging velocimetry system which relies on fluid motion estimation, and uses vorticity map differencing for calibrating its reliability. To validate this new concept, phase contrast magnetic resonance imaging on the right atrium of a healthy subject has been suggested. The study has demonstrated the state of change in blood flow patterns within a cardiac chamber using our implemented system and a well established flow imaging modality. Based on the gold standard imaging technique, flow fields can be used to establish a set of reference data to compare against magnetic resonance fluid motion tracking results. We conclude that our validated technique can be reliable enough for establishing a cardiac based velocimetry system.**

Keywords — **Phase contrast magnetic resonance imaging, Fluid motion tracking, Right atrium**

I. Introduction

Using a velocimetry framework that is different from velocity encoded medical imaging modalities, we implemented MR fluid motion tracking [1] which is based on motion estimation of blood signal shifts that appears as changes in intensity distribution over the entire registered signal image. The speed of the latter technique in terms of processing these images is dependent on the computational platform and the machine that runs it. A strong limitation, however, is the accuracy of the motion predication which is highly affected by the configuration of the algorithm as well as the clarity of signal contrast temporally. And it is the key purpose of this study to validate the output flow fields of MR fluid motion tracking against those produced by phase contrast magnetic resonance images.

For our implementation, we have developed a dual flow imaging and comparison system that enables processing of phase contrast data as well as MR fluid motion tracking of non-velocity encoded MR images. Since velocity flow field is limited in terms of flow analysis, vorticity measurement has been devised to present the strength of rotational blood in the heart chamber. In addition, we have described a concise flow visualisation system which encompasses flow imaging, flow vector presentation, and vorticity mapping, to analysis of vorticity pertaining to the imaged fluid.

Our article is organized as follows: Section II gives an overview of the system implementation for flow results comparison based on two imaging techniques. Section III provides the information on preparing a subject for MRI scanning and data analysis. The results of the two imaging modalities are displayed for selected time frames of a cardiac cycle in section IV. We give a discussion on the reliability of MR fluid motion tracking based on the flow results and in the last section, a conclusion of our implementations and findings.

II. Vorticity visualisation system implementation

A. MR Fluid Motion Tracking

A series of MR images are taken temporally as the fluid is in motion. The velocity of dynamic fluid can be quantified in real time by computing the shift of intensities within the quantised regions of every prior and post images numerically. A velocity flow field can be constructed using a graphical plot as such and other fluid dynamics properties can be derived from the velocity flow measurement. From the results, the characteristics of the fluid flow can be analysed using these properties.

Application of flow based on the use of motion estimation algorithm [2] allows us to produce flow vectors over the region of defined analysis. This technique makes use of images from two subsequent phases to predict flow field. Typically, cine MRI scanning results in a sequence of N phases. Post-processing of data from (N-1) pairs of images gives a series of vector fields for evaluation and analysis.

B. Phase Contrast MRI Velocimetry

Phase contrast MRI works on the concept that hydrogen nuclei from blood that has been exposed to magnetic fields accumulate a phase shift in spin that is proportional to blood velocity in x, y, and z directions [3,4] as shown in Fig. 1.

To quantify a velocity in one spatial dimension, at least two phase images has to be taken for subtraction of flow-induced phase shift from background phases caused by susceptibility-induced non-homogeneities and coil sensitivity changes [5]. Blood velocity can be aliased to an artifi-

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cially low value if it exceeds the maximum velocity encoded (VENC) by flow sensitization gradients.

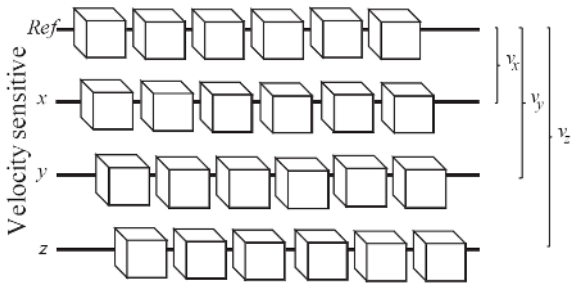

Fig. 1. Phase contrast MRI velocimetry. Velocities v_x, v_y and v_z can be calculated by subtraction of spin phase of measured volumes with that of the reference spaces *Ref*.

C. Visual tools for presentation of flow fields

The magnitude of vorticity ω (in units of s^{-1}) can be indicated by a colour contour map. Reconstruction of such a vorticity map as a colour image display can be achieved by representing vorticity using colours over a spatial grid. The presence of red pixels illustrates counter-clockwise swirling of blood while the blue ones correlate to clockwise swirl. Therefore, the colour and intensity of the image can give an indication of the magnitude of vorticity as well as the direction of rotation over a region.

D. Vorticity Field Differencing

Using Fig. 2, we demonstrate the systematic implementation of vorticity field differencing based on four stages.

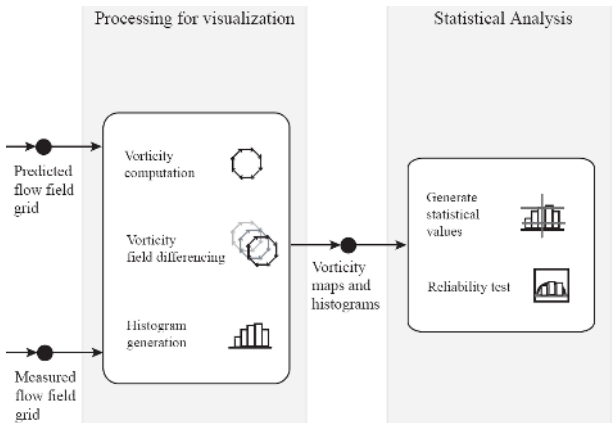

Fig. 2. Reliability test system for MR fluid motion tracking based on vorticity differencing. This system is specially constructed to calibrate the performance of MR fluid motion tracking against the well-established phase contrast MR image velocimetry system.

The first stage starts with scanning of a normal heart with steady-state free precession MR imaging and on a separate occasion, the same scanning using phase contrast MR imaging. During this pre-processing stage, blood motion information is encoded within images in a different manner. The cardiac MR images contain temporal positions of magnetic resonating blood, whereas the phase contrast images have local blood velocities encoded within them. In the visualisation processing stage, both field grids are further processed to give their respective vorticity field, which are then differenced.

III. Methodology

A. Subject for Case Study

In this study, we performed flow imaging on the right atrium of a 22 years old normal subject using phase contrast VENC flow imaging, and then using MR fluid motion tracking. The flow information from these two types of imaging can be used to explain the behaviour of vortices that develop in the right atrium of a heart.

B. Investigation Procedure

A scan is performed at the section of the heart where the atria are positioned. The scan section is taken at a location shown in Fig. 3 whereby the scan is perpendicular to an axis joining the top of the heart to the apex through the septum. Table I is created to configure the flow velocimetry system so that the tracking can be effected.

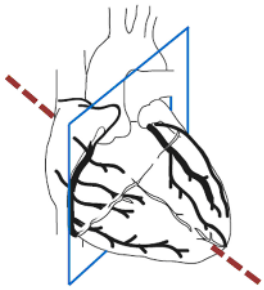

Fig. 3. MRI scan through heart of normal subject. The scanning of the heart is taken at short axis and through two chambers, namely the left and right atria. Therefore this sectional view pertains to the 2-chamber short axis scan.

C. MRI Scan Procedure

The velocity-encloded MR imaging was performed using a Siemens Avanto, 1.5 Tesla, model—syngo MRB15 scan-

ner with Numaris—4, Series No: 26406 software. Cine-MR imaging was performed using one slice in short axis views through the atria. All images were acquired with retrospective gating and 25 phases (from t=1 to 25) for a single slice.

D. Phase Contrast MRI Scan Procedure

For this purpose, velocity-encloded MR imaging was performed using a Siemens Sonata, 1.5 Tesla, model—syngo MR 2004A scanner with Numaris—4, Series No:

Table 1 MR imaging and vorticity measurement properties. The scan properties of standard True FISP and phase contrast MR imaging are presented here. The vorticity flow maps can be determined from them. These parameter values are used to calibrate these flow maps, as well as indicating the sampling vorticity mask size in metric units.

1 - TRUE FISP MRI SCAN 2 - PHASE CONTRAST MRI SCAN

Symbol	Quantity	1	2	Units
p	Pixel spacing	1.67	1.54	mm/pixel
t_s	Trigger time interval	35.72	29.43	ms
s	Slice thickness	6	6	mm

VORTICITY MEASUREMENT PARAMETERS

Symbol	Quantity	Value	Units
X	Image width	120	pixel
Y	Image height	150	pixel
W_v	Velocity interrogation window	3x3	pixel

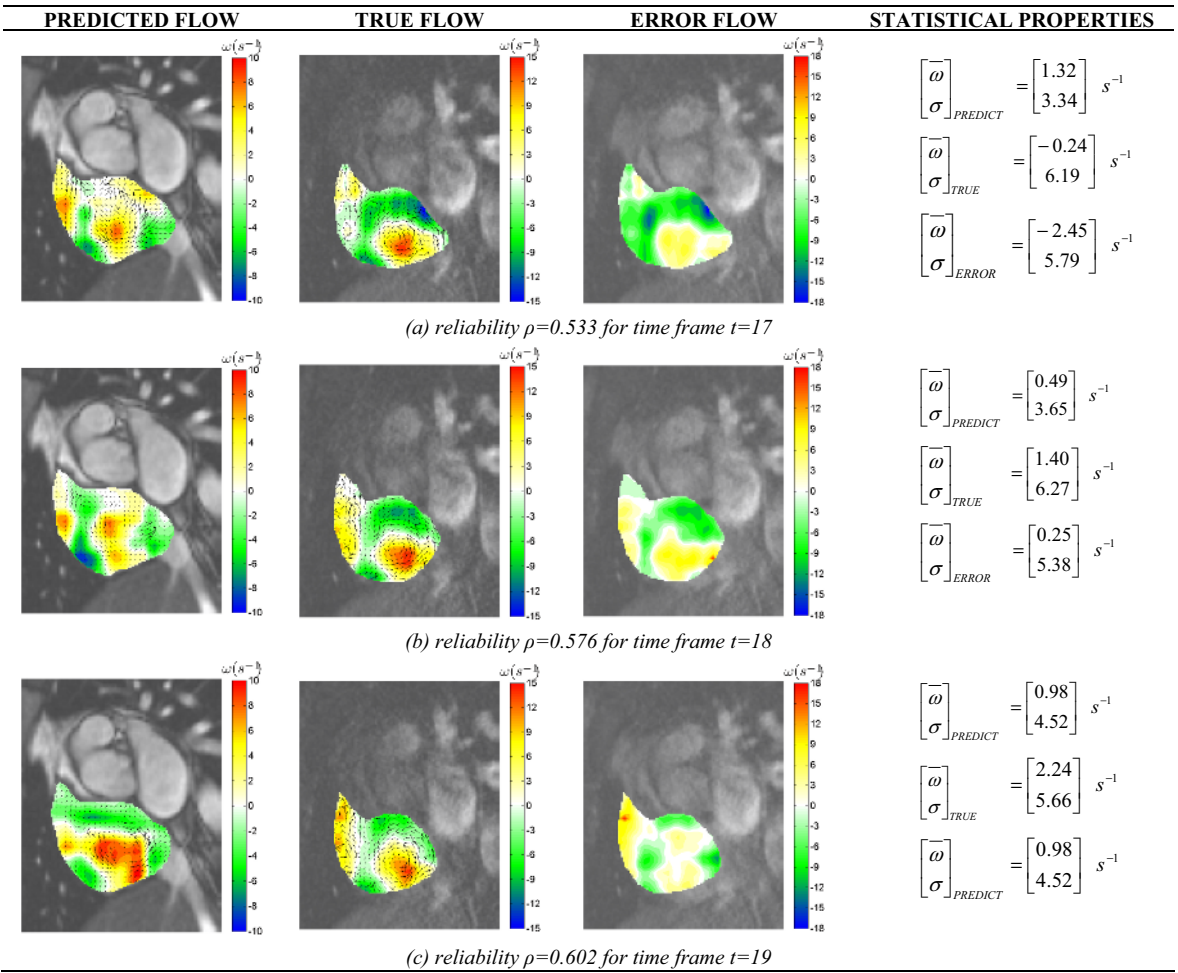

Fig. 4. *Vorticity differencing based on MR fluid motion field and phase contrast MR image field.* Predicted flow fields are verified against the measured ones based on phase contrast MRI velocimetry (taken as true data). Their vorticity map differences can be taken as the deviation of MR fluid motion field from the true flow field. We have performed flow field differencing using time frames t=[17,18,19] out of 25 frames in a cardiac cycle.

21609 software. Cine-MR imaging was performed using one slice in short axis views through the atria. All images were acquired with retrospective gating and 25 phases.

E. Parameters for Data Analysis

The histogram of a vorticity map with vorticity values in the range [0, *L*-1] is a discrete function $h(r_k) = n_k$, where r_k is the kth vorticity value and n_k is the number of pixels in the flow map having vorticity value r_k [6].

Statistical quantification of the blood vorticity map in the right atrium is performed by translating all the scalar values into histogram format. The size of right atrium is different for every phase. Normalization is performed by standardizing the total count of pixels within a segmented region of interest to create an equal integral area under the frequency plot of the flow map. The total counts correspond to the number of pixels representing the atrium per slice.

IV. Results

We varied this parameter from (3×3) to (33×33) pixels with increments of 2 pixels at each interval to chart the reliability of flow measurement using MR fluid motion tracking versus phase contrast MR imaging technique. From Table 1, the width of flow image is 120 pixels, and we have set the interrogation window to a 3 by 3 pixels frame. We observed vorticity flow maps pertaining to time frames t=[17,18,19] out of a maximum of 25 frames in a cardiac cycle for a series of sampling window sizes in Fig. 4.

V. Discussion

In this study using a normal atrium, we assume that the true-score variance σ_{TRUE}^2 is the equivalent of the vorticity variance based on a true map measured by phase contrast MRI. We note that the error variance with the expression σ_{ERROR}^2 is the variance of an error map which is produced by differencing the predicted and true vorticity maps. The reliability of flow field prediction using MR fluid motion tracking ρ is the ratio of true vorticity variance σ_{TRUE}^2 to total measured variance given by $(\sigma_{TRUE}^2 + \sigma_{ERROR}^2)$ [7]:

$$\rho = \sigma_{TRUE}^2 / (\sigma_{TRUE}^2 + \sigma_{ERROR}^2) \quad (1)$$

Implementing an appropriate sampling window size for vorticity measurement can bring the vorticity maps to be as close as possible to the physically measured one.

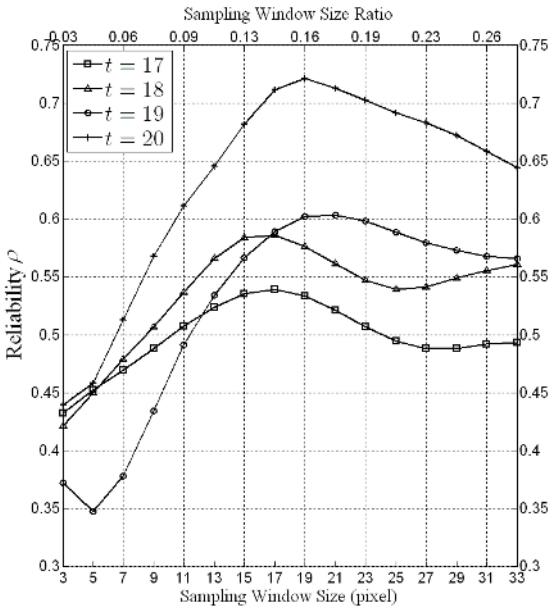

Fig. 5. Reliability study using predicted and true variance. Reliability for the predicted MR fluid motion field data ρ with respect to the phase contrast MRI data (taken as the true data) is computed. The variation of vorticity sampling window size can affect the reliability of computational measurement of the vorticity.

The graph of reliability measurement is shown in Fig. 5 for sampling window dimension of (3×3) to (33×33) pixels. The results are based on 4 cardiac time frames from t=17 to 20 to illustrate variation of measurement reliability.

VI. Conclusion

We have successfully studied one chamber at this stage. The framework developed in this work can be extended to assess flow in the other heart chambers or cardiovascular structures. This study has improved our understanding of blood motion within the heart chamber, which may have implications in the study of blood circulation efficiency.

Considering that the True FISP and phase contrast magnetic resonance imagings are performed on separate occasions with slight dissimilarities in planar imaging configuration, perfect alignments of the right atria region is difficult. Based on this discrepancy, we have to take into account additional error contributed by the imperfect comparison scheme. Therefore, the results suggest that MR fluid motion tracking is reliable enough for cardiac flow assessment.

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