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A sensitivity analysis on 3D velocity reconstruction from multiple registered echo Doppler views

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ABSTRACT

We present a new method for reconstructing a 3D + t velocity field from multiple 3D + t colour Doppler images. Our technique reconstructs 3D velocity vectors from registered multiple standard 3D colour Doppler views, each of which contains a 1D projection of the blood velocity. Reconstruction is based on a scalable patch-wise Least Mean Squares approach, and a continuous velocity field is achieved by using a B-spline grid.

We carry out a sensitivity analysis of clinically relevant parameters which affect the accuracy of the reconstruction, including the impact of noise, view angles and registration errors, using simulated data. A realistic simulation framework is achieved by a novel noise model to represent variations in colour Doppler images based on multiscale additive Gaussian noise. Simulations show that, if the Target Registration Error $<\mathbf{2.5}$ mm, view angles are $>\mathbf{20}^\circ$ and the standard deviation of noise in the input data is $<\mathbf{10}$ cm/s, the reconstructed velocity field presents visually plausible flow patterns and mean error in flow rate is approximately **10**% compared to 2D + t Flow MRI. These results are verified by reconstructing 3D velocity on three healthy volunteers. The technique is applied to reconstruct 3D flow on three paediatric patients showing promising results for clinical application.

1. Introduction

Many cardiac conditions are characterised by abnormalities of blood flow including regurgitation and narrowing of heart valves resulting in abnormal direction and velocity. Accurate 3D characterisation, quantification and visualisation of cardiac blood flow remains a challenge but has the potential to improve diagnosis of some cardiac diseases (Sengupta et al., 2012). In addition, 3D velocity information could be useful input to help constrain and validate patient specific cardiac models.

Latest advances in temporally resolved three directional flow-encoded 3D MRI (3D + t Flow MRI) over the past years have enabled non-invasive measurements of 3D velocities within the cardiovascular system. However, MRI is more expensive, requires long acquisition times compared to echocardiography (echo), and is incompatible with a number of cardiac implants such as pacemakers. In addition, transthoracic echo examinations are carried out 75 times more often than cardiac Magnetic Resonance Imaging (MRI) (Tsai-Goodman et al., 2004), which means that cardiac MRI is used on selected patients only, and always after an echo exam.

The recent introduction of 2D matrix array echo technology allows rapid acquisition of 3D B-Mode and 3D colour Doppler volumes. Nevertheless, Doppler velocity information is only a 1D projection of the true 3D velocity vector along the echo beam direction.

Crossed-beam techniques, which use multiple views to reconstruct the full velocity information, have the potential to overcome this limitation (Dunmire et al., 2000). One of the first crossed-beam approaches, proposed by Fox (1978), used simultaneous acquisition of several 2D Doppler images to compute an instantaneous 3D laminar flow on a 1D line. Xu et al. (1991) reconstructed 2D flows using more than two views, and improved reconstruction quality using two averaging methods. Recent work by Garcia et al. (2010) proposed the computation of 2D intraventricular flow using one colour Doppler image and boundary conditions from wall motion estimation. Uejima et al. (2010) proposed a method to compute 2D intraventricular velocity fields by splitting the flow field into a base field and a turbulence field using a single 2D colour Doppler image. In both the work by Garcia et al. (2010) and Uejima et al. (2010) the extension to 3D is not trivial since they both rely on the linear separability of the

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2D continuity equation in polar coordinates. Unfortunately, separation of variables cannot be applied to the 3D version of the continuity equation in spherical coordinates. Arigovindan et al. (2007) proposed to use 2D B-splines and regularisation to reconstruct smooth 2D blood velocities in the carotid bifurcation and 2D tissue motion in the myocardium.

To our knowledge previous approaches have only reconstructed 2D projections of the true underlying 3D flow (Sengupta et al., 2012). However, blood flow patterns may be complex 3D patterns and their 2D projection provides only a part of the flow information. In addition, quantification of flow with 1D and 2D velocity maps requires correct alignment of the image and the plane of interest during acquisition. An accurate 3D velocity map would allow retrospective flow quantification through arbitrary planes, i.e. planes at the location of interest with an arbitrary orientation.

We propose to reconstruct the 3D velocity field on a regular 3D B-spline grid. This, to our knowledge, is the first time a full 3D velocity field has been reconstructed from Doppler images. Our method is a reformulation of the 2D method proposed by Arigovindan et al. (2007). Extension of this method to 3D is more complex due to both algorithmic and data acquisition reasons. On the algorithmic side: reconstruction of velocity vectors in 3D instead of in 2D exponentially increases the computational complexity of the resulting linear system. We propose a patch-wise formulation which enables scalability of the method and allows us to reconstruct 3D velocity within arbitrary regions. On the data acquisition side: 3D vector reconstruction requires at least three Doppler images, each from a different view direction. However, colour Doppler acquisition is restricted by acoustic windows, so available view angles will be limited and will vary greatly between individuals. Colour Doppler images are noisy, and overall image quality depends greatly on anatomy of individuals. In addition the relative transformation between views must be accurately known, which we propose can be achieved using image registration. Each of these factors will influence the accuracy of 3D vector reconstruction. To determine the size of these effects we carry out a detailed sensitivity analysis using simulated data, and compare the results with 3D velocity reconstructed using echo data from three healthy volunteers and three patients.

In summary, the contribution of this paper is threefold: (1) it provides a scalable 3D flow reconstruction method which integrates Doppler information from multiple views, by reformulating the method by Arigovindan et al. (2007) into a 3D patch-wise approach; (2) it identifies and characterises the main parameters which contribute to inaccuracy of 3D velocity reconstruction in a clinical scenario and (3) it provides the range of these parameters for which 3D flow can be accurately reconstructed.

2. Methods

Calculation of 3D velocity vectors from multiple colour Doppler images using a patch-wise, regularized algorithm, is performed in two steps:

1. Registration of B-Mode images (Section 2.1).
2. 3D velocity reconstruction of the vector field which best fits the input Doppler data using error minimisation, where the error function incorporates physical constraints (Section 2.2).

Additionally we propose a simulation framework for assessing the sensitivity of the reconstruction method to different parameters. In particular a simple yet more realistic model for noise and variations in colour Doppler images is proposed (Section 2.3).

2.1. Image registration

In order to combine Doppler information from multiple N_v views the relative position between these views must be known. We calculate these relative positions using a registration algorithm which uses the phase-based similarity measure proposed by Grau et al. (2007), specifically designed for registration of multi-view 3D B-Mode echo images acquired from different acoustic windows. This similarity measure is based on the fact that the Fourier terms of an image are in-phase at edges (Mulet-Parada and Noble, 2000), and therefore high phase congruency across scales indicates presence of edges or features that can be used for registration. As proposed by Grau et al. (2007), registration was initialized by a point wise registration from three manually picked landmarks.

Colour Doppler acquisitions contain a B-Mode image and a colour-coded velocity image. These B-Mode images have a reduced FoV due to the large processing requirements for Doppler acquisition. This reduces the accuracy and capture range of the registration algorithm.

Our solution is to use a two-step registration approach where we also acquire a standard B-Mode image directly after each Doppler acquisition. The two steps of the registration are represented in Fig. 1. Our method firstly registers the reduced FoV B-Mode image to the corresponding standard (wide FoV) B-Mode image, which yields the matrix $M_{L_i}^{r_i}$, where r_i indicates the ith reduced FoV image and L_i indicates the ith wide FoV image as shown in Fig. 1a. This registration is easy to achieve as the images have been acquired from the same position. Then the wide FoV B-Mode images from N_v different views are registered to one of them, arbitrarily chosen as reference, which yields a set of matrices $M_{L_{ref}}^{L_i}$ $(i = 1 \ldots N_v)$ as shown in Fig. 1b. Therefore the resultant transformation between two Doppler views can be calculated from $M_{reg} = M_{L_{ref}}^{L_i} \times M_{L_i}^{r_i}$.

2.2. 3D flow reconstruction from multiple echo Doppler views

2.2.1. Description of the general solution

B-splines are smooth functions widely used in signal and image processing for their numerous advantages (Unser, 1999). Our method consists in solving a B-spline based linear system extended from Arigovindan et al. (2007). The full extension to 3D is described in Appendix A. In this section, the method is briefly presented. Let β^n be the B-spline of degree n, we note the scaled and displaced version as $\beta^n(t/s - l) = \beta^n_{s,l}(t)$.

Let $\mathbf{v}(\mathbf{p}) = [v_x(\mathbf{p})\ v_y(\mathbf{p})\ v_z(\mathbf{p})]^\top$ be the fluid velocity field evaluated at the point $\mathbf{p} = [p_x\ p_y\ p_z]^\top$. We can express $\mathbf{v}(\mathbf{p})$ in the space of uniform B-splines of degree n:

$$v_\gamma(\mathbf{p}) = \sum_{i=1}^{N_g^i} \sum_{j=1}^{N_g^j} \sum_{k=1}^{N_g^k} c^\gamma_{i,j,k} \beta^n_{s,i}(p_x) \beta^n_{s,j}(p_y) \beta^n_{s,k}(p_z) \tag{1}$$

where $\gamma \in \{x, y, z\}$, the B-spline grid has a size of $N_g^i \times N_g^j \times N_g^k$ and $\{c^x, c^y, c^z\}_{i,j,k}$ are the B-spline coefficients. The parameter s is the distance between grid nodes and determines the finest resolution of the resulting vector field (i.e. its scale). Each registered view provides an input Doppler data set $\{m_i, \mathbf{p}_i, \hat{\mathbf{d}}_i\}_{i=1 \ldots oK}$ where for each point i, m_i is the (projected) velocity measurement at position $\mathbf{p}_i$ where the echo beam direction is $\hat{\mathbf{d}}_i$ and K is the total number of input data points. Combining all views, the velocity field $\mathbf{v}$ is the solution that minimises the following energy term

$$J_{proj}(\mathbf{v}) = \sum_k \|\hat{\mathbf{d}}_\mathbf{k} \cdot \mathbf{v}(\mathbf{p}_k) - m_k\|^2 \tag{2}$$

Plugging (1) into (2) the energy can be rewritten in matrix form as

$$J_{proj}(\mathbf{C}) = \|\mathbf{DSC} - \mathbf{m}\|^2 \tag{3}$$