A TECHNIQUE FOR THE RECONSTRUCTION OF THREE-DIMENSIONAL FLOW FIELDS FROM PHASE ENCODED MR VELOCITY IMAGES

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Introduction

The general problem of reconstructing three-dimensional data is an issue that arises in a variety of medical imaging applications [1-4]. In this paper we introduce an algorithm based on adaptive control grid interpolation (ACGI) that provides high quality reconstruction of three-dimensional flow fields from sets of phase encoded magnetic resonance (MR) velocity images. The motivation for this research arises from current practices employed in the treatment of single ventricle congenital heart defects (CHDs) in children.

Motivation

Single ventricle CHD's result from deviations in the developmental process that normally transforms a simple straight tube into a complex four-chamber heart with separate pulmonary and systemic circulations [5]. The problem is frequently observed, affecting two out of every one thousand babies [5]. The total cavopulmonary connection (TCPC) is a palliative surgical repair performed on children with single ventricle CHDs that improves the ability of the heart to function effectively. Children with such anatomies have a mixing of oxygenated and deoxygenated blood, which when left untreated leads to a variety of problems. The TCPC procedure results in a complete bypass of the right heart with the single ventricle driving blood through the entire circulatory system.

Much of the power produced by the single ventricle pump is consumed in the systemic circulation. For this reason minimizing power loss in the surgically created vasculature is critical for optimal outcomes. In order to accomplish this, underlying factors must be understood so that they may in turn be controlled. A need is thus created for an effective tool to evaluate post-operative power loss. Using this tool, the salient component of which is the reconstruction methodology presented in this paper, surgeons will be able to correlate specific components of successful surgeries with minimized power loss.

The proposed methodology employs combined use of MR imaging and fluid dynamics analysis to study flow conditions in the TCPC. MR images containing velocity information are acquired and used to reconstruct three-dimensional flow fields. Ultimately these reconstructions will be used to estimate power loss in the modified district using the viscous dissipation function. Because this form of analysis requires only velocity information, it can be carried out using reconstructed flow fields alone as input.

Methodology

The starting point for our reconstruction process is a series of transversely acquired contiguous phase encoded MR velocity images. Fields of displacement vectors are calculated describing the displacement of pixels from one image slice to the next. The determination of such displacement fields in fundamentally similar problems has traditionally been accomplished with block-based or optical flow-based motion estimation. In this work a novel technique for motion estimation called ACGI is employed. ACGI incorporates aspects of both block matching and optical flow. In the ACGI representation, the displacement field is obtained by partitioning the image into contiguous rectangular regions. The corners of these regions form control points that are used as the anchors from which the displacement vectors in between are derived via bilinear interpolation. So the algorithm resembles block matching in that the bilinear motion model is assumed to hold for a given region, but the motion field is determined within this framework by minimizing the error associated with the optical flow equation.

The algorithm partitions the image into sub-blocks of appropriate size to capture characteristics of anatomical transition and succesively subdivides regions where error remains large. This enables the algorithm to handle both translational and complex non-translational displacements by way of the optical flow equation. These characteristics of the algorithm are important, as they allow us to obtain an accurate and dense representation of the displacement field at a reasonable computational cost. In addition, we calculate the displacement field with an arbitrary degree of sub-pixel accuracy.

The motion field is determined based on the modulus images from the velocity data acquisition. From this dense displacement field and the associated pair of originally acquired velocity images we reconstruct intermediate velocity images. By following one of the displacement vectors a portion of the way from one slice to the next, a linear approximation of where a given pixel would be found in an intermediate slice can be made. Repeating this process for all pixels in a given slice allows us to obtain a reconstructed frame. Pairs of these reconstructed images are then combined in a spatially weighted sum to form a single interpolated slice. This process is then repeated and several interpolated images are stacked between the known images in anatomical proportion to produce a three-dimensional enhanced data set. Simply put, we effectively increase the spatial resolution in the out of image plane direction to an arbitrary degree in order to counteract the effects of the intrinsic undersampling associated with MR data acquisition. The result is a fully reconstructed three-dimensional block of data, describing the complete flow within the structure imaged by the initial scan.

Results

To simulate the conditions of the TCPC described in the introduction and motivation sections, glass models of the geometry were created. These models were then hooked up to a flow loop and physiologic input and output conditions based on data acquired from real patients were imposed. This model setup was then examined with MR and other methods to acquire velocity data. The MR data was then used as input for the previously described reconstruction methodology.

In order to evaluate the results of our reconstruction algorithm, image planes orthogonal to the original acquisition planes were extracted from reconstructed data. Each plane was then compared to a plane at the same spatial location within data sets acquired via other methods. Specifically comparisons were made to velocity data acquired with particle image velocimetry (PIV) and to velocity data extracted from computational fluid dynamics (CFD) simulations based on the same geometry. The comparisons were made on a plane by plane basis between images located at identical coordinates within the flow fields associated wtih the respective acquisition or simulation techniques. A reconstructed plane is shown along with the corresponding plane from a CFD simulation in Fig. 1. It is noteworthy that the reconstructed plane of velocity data displayed in Fig. 1 was generated entirely from out of plane images. Truly speaking, only a small number (approximately ten) of linearly oriented velocity vectors within the displayed plane were acquired with the original MR scan.

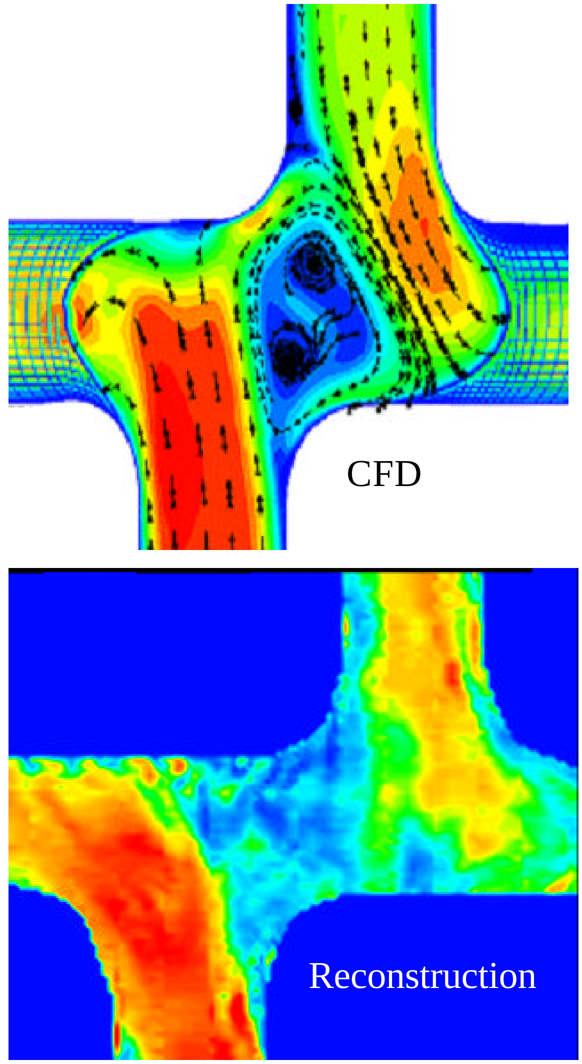

Fig. 1. Velocity magnitude images from CFD and reconstructed data.

Discussion and Conclusions

In vitro results from the reconstruction algorithm show excellent agreement with data acquired via other means. This is valuable because it presents a clinically implementable scenario for the accurate determination of three-dimensional flow fields in vivo, which has not to date been possible with other means. Furthermore, in the context of the TCPC, this methodology presents an opportunity to evaluate power loss within the surgically modified district based on in vivo data. The viscous dissipation function can be used to accomplish this as it requires only velocity gradient information to estimate power loss. Accordingly this technique is ultimately envisioned to play a role as a component of a post-operative surgical evaluation tool designed to provide quantitative feedback to surgeons elucidating the success or lack thereof associated with completed operations. Both qualitative and quantitative evaluations of the reconstruction technique will be discussed, as well as comparisons to alternative techniques.

Acknowledgements

This work was supported by a grant from the National Institutes of Health (R01HL67622). Children's Hospital of Philadelphia, Egleston Children's Hospital, Emory University, and the University of North Carolina have also contributed significantly to this research.

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