Cardiac 4D Flow MRI: Technical Innovations and Applications to Myocardial Infarction and Preterm Birth

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Abstract

Magnetic resonance imaging (MRI) is a medical imaging modality with the ability to acquire images sensitized to several different contrast mechanisms. One of the many mechanisms that can generate contrast in MR images is blood flow. “4D flow MRI”, a method for quantifying time-resolved velocity fields in 3-dimensional regions, is employed in the context of comprehensive flow assessment within the heart and major blood vessels but requires long acquisition and post-processing times. The aims of the work presented in this dissertation are to accelerate the acquisition and processing of cardiac 4D flow MRI images, and to apply 4D flow MRI to quantify intracardiac hemodynamics in two disease population: survivors of myocardial infarction and young adults born very-to-extremely premature. This work is divided into six research chapters.

The technical innovations introduced and evaluated in my work (Chapters 2-4) relate to the validation of accelerated 4D flow acquisitions and the development of fast, automated pipelines for 4D flow image analysis. In Chapter 2, I describe the construction of a model of the left ventricle of the heart and use it to compare acceleration acquisition techniques for 4D flow MRI. Using an optical imaging-based reference standard, I show lower error in velocity estimations at short scan times for one technique over the other, supporting the use of this technique in scan-time-limited scenarios and demonstrating a generalizable workflow for head-to-head comparison of image acquisition or reconstruction techniques which can be adopted in other applications in order to minimize acquisition time. In Chapters 3 and 4, I use deep learning to automate image processing tasks for quantitative flow assessment in 4D flow MRI of the chest. In particular, I automate the segmentation of the myocardial ventricles (Chapter 3), necessary for the measurement of ventricular kinetic energy or the analysis of ventricular flow components, and the placement of measurement planes (Chapter 4), necessary for the measurement of flow and peak velocity in

the great vessels of the heart. Both methods are thoroughly evaluated, finding similar performance to manual segmentation/plane placement. This enables 4D flow MR images of the chest to be processed in an automated fashion, vastly reducing the processing time required for users of 4D flow MRI and enabling large and longitudinal studies without biases between observers.

The applications of cardiac 4D flow MRI explored in my work are myocardial infarction (Chapter 5) and cardiac development after preterm birth (Chapters 6-7). In Chapter 5, I apply cardiac 4D flow MRI to study hemodynamics in the left ventricle after acute myocardial infarction. 4D flow data is compared region-by-region between myocardial infarction patients and controls, finding reduced flow in several left ventricular regions in patients relative to controls, perhaps providing indications of risk of post-infarction sequelae. In Chapters 6 and 7, I apply cardiac 4D flow MRI to study intracardiac hemodynamics in another at-risk population: young adults born very-to-extremely premature. I first compare intraventricular flow in young adults born premature to those born at term (Chapter 6), finding decreased right ventricular early-to-late diastolic kinetic energy ratios and increased viscous energy dissipation in preterm subjects relative to term subjects, suggesting altered right ventricular filling which may be relevant to the elevated early heart failure risk in this population. I then use acute pharmacological interventions to assess the effects of hemodynamic manipulations on cardiac hemodynamics measured by 4D flow MRI in young adults born premature (Chapter 7). Acute pharmacological reduction of pulmonary blood pressure increases cardiac function, suggesting that pulmonary hypertension may play a role in this group's heart failure risk. Recommendations for future work include assembling large multicenter databases aimed at using 4D flow to predict cardiovascular outcomes in the general population, a longitudinal 4D flow study of the developing preterm heart throughout childhood, and a prospective 4D flow study to predict post-myocardial infarction thrombus formation.