Cardiac MRI: Clinical Challenges

4D Flow Imaging

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Highlights

- Comprehensive hemodynamic assessment is possible with 4D Flow MRI.
- Biomarkers such as pressure gradients, vessel compliance, and wall shear stress can assist in early diagnosis, treatment planning, and understanding normal physiology.
- 4D Flow MRI is used in research and in some instances in clinical practice.

Target Audience

Those with interest in methodology and clinical applications of 'cutting edge' flow MRI including physicians and scientists, current users of cardiovascular MR, with basic knowledge in cardiac MRI.

Objectives

- To review recent advances in phase contrast MRI methodology that allow for 4D Flow MRI acquisitions in clinically feasible scan times.
- To review physiological markers that can be obtained with 4D Flow MRI, including vorticity, pressure maps, pulse wave velocity, .and wall shear stress.
- To review potential limitations and potential sources of errors for velocity mapping and parameters derived from those measurements.
- To provide an overview of potential impact of such novel applications in research and clinical diagnosis.

Purpose

Recent advances allow for the acquisition of MRI data sets with three-directional velocity encoding over a 3D volume throughout the cardiac cycle in clinically feasible scan times of 20 minutes and less. This approach, frequently referred to as '4D Flow MRI' or '4D MR Flow' provides a new platform for comprehensive hemodynamic assessment of vascular territories with wide ranging potential applications in research and clinical practice. This presentation will review the data acquisition, post processing, clinical applications, and sources of errors for the analysis of such velocity-based measurements.

Methods

2D phase contrast MRI is widely used clinically for the noninvasive assessment of flow volumes and peak velocities in a single plane with one-directional velocity encoding [1]. Substantial improvements in MR hardware, sequence design, and image reconstruction have facilitated accelerated cardiovascular imaging. With those improvements, it is now possible to capture volumetric velocity fields with three-directional velocity encoding over a 3D volume throughout the cardiac cycle in clinically feasible scan times [2]. Data sets obtained from such examinations can provide information on the anatomy, vascular lumen, and hemodynamic information from a single acquisition, all inherently co-registered and obtained in 5-20 minute acquisitions, depending on cardiac and respiratory gating needs, spatial and temporal resolution, and volume coverage [3].

The reconstructed datasets are large in size since they contain scalar data volumes on velocities in x, y, and z as well as the averaged magnitude for all phases of the cardiac cycle, thereby providing unique opportunities and challenges. The data complexity poses a significant burden on the data processing and visualization chain. However, the simultaneous capture of

vascular anatomy and hemodynamics provide the basis for the direct derivation of hemodynamic parameters that play a role in numerous vascular diseases.

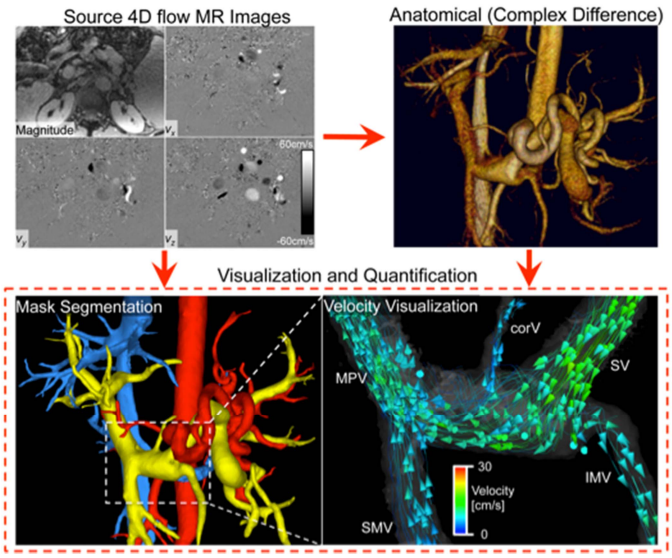

Figure 1: *Abdominal 4D flow MRI of a 59yo male patient with portal hypertension. The workflow starts with source magnitude and velocity images (upper left, axial plane), which are combined into an anatomical PC angiogram (PCA) using complex difference processing (upper right, surface shaded display). The PCA is segmented into color-coded vascular territories (bottom left, surface shaded display), followed by streamline or particle trace visualization (bottom right). Note the* ***reversed blood flow*** *in the coronary vein and inferior mesenteric vein, which would be very hard and/or time consuming to identify with ultrasound or repeated 2D PC measurements.*

Results

4D Flow MRI has been used for non-contrast enhanced MRA [4] as well as for the characterization of blood flow in various vascular territories including the head, neck, aorta, renal, hepatic, and peripheral vasculature as well as with the atria and ventricle [5]. Not only can this approach possibly reduce total scan time over multiple double oblique 2D PC MR measurements in complex vascular anatomies, but it also allows for the derivation of hemodynamic parameters beyond velocity and flow measurements. Some examples of qualitative parameters include streamlines and vorticity and helicity [6, 7] while quantitative parameters include the calculation of pressure gradients across vessel narrowings to establish hemodynamic significance [8], pulse wave velocity for the assessment of vessel wall stiffness [9], wall shear stress for assessing stimulus for vessel wall remodeling [10], kinetic energy measures for assessing loads and efficiency [11], turbulence intensity [12, 13] and others.

Discussion and Conclusions

The methods discussed here have the potential to significantly change the way flow imaging is clinically conducted as well as expand the indications for velocity sensitive imaging by providing unique insights into the velocity fields and additional functional parameters. These noninvasive measures can possibly enhance diagnosis, therapy planning, and therapy monitoring in a wide range of cardiovascular imaging including all major vascular territories including the heart.

In contrast to frequently used computational fluid dynamic (CFD) simulations [14], the parameters can be calculated directly from the measured dynamic velocity fields. As such, these biomarkers may well prove useful in the early stages of diagnosis of cardiovascular disease, and the decision making process for therapy and long term monitoring of the disease and follow up. There is a wide range of potential applications including aneurysms, stenoses, arterio-venous-malformations (AVMs), organ transplants, cardiac disease, congenital heart disease, stroke, and others [15].

However, to date these concepts have been mainly investigated in smaller clinical studies and clinical efficacy has to be demonstrated in larger, multi-center trials. Current technical limitations include the lack of product sequences for data acquisition as well as intuitive post-processing packages, which are crucial for successful clinical adaptation of these techniques.

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