Evaluation of Flow
Research Promises: What can we expect in the Future?

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Introduction

Flow sensitive MR imaging is an established technique that has been traditionally used to provide quantitative measures related to cardiac flow. In clinical practice, phase contrast (PC) MR is frequently used for 2D cine imaging with through-plane velocity encoding to obtain values such as instantaneous flow rate by integrating over the vessel area and flow waveforms throughout the cardiac cycle, cardiac output, or regurgitation volumes across valves by integrating over time as well (1). In some applications, two-directional velocity encoding is used, e.g. for measuring the maximum velocities in blood flow across a stenosis or valve. Commercial software packages allow for intuitive post-processing and analysis including background phase error corrections, semi-automated vessel boundary detections and reporting tools.

Over recent years, advances in hardware and accelerated imaging approaches have facilitated (1) realtime PC MR imaging and (2) the use of expanded acquisitions that capture data with three-directional velocity encoding over a 3D volume throughout the cardiac cycle in clinically feasible scan time, frequently referred to as ‘4D MR Flow’. Here we will discuss the research promises of these two imaging techniques.

Realtime PC MR

PC MR acquisitions are intrinsically long because the velocity encoding bipolar gradients significantly prolong the echo time and, therefore, the repetition time, and because of the need for a reference scan in addition to the velocity sensitive scans for each encoding direction. Consequently, clinical 2D PC cine acquisitions stretch over multiple heartbeats with a segmented acquisition and temporal and spatial resolution are chosen such that the scan can be completed in single heartbeat. However, this approach is problematic in patients with irregular heartbeats and limited breathholding capabilities such as uncooperative patients including young children and those with severe cardiovascular disease.

Realtime flow imaging can be very beneficial to overcome these limitations, even at the expense of reduced spatial and or temporal resolution. It can also provide an ultrasound-like experience for interactive examinations with color flow encoding(2). Realtime PC MR approaches have been pursued with alternative trajectories such as spiral imaging (3-4) and sliding window reconstructions (2) for more efficient k-space sampling. In addition, realtime PC MR can be used to assess flow changes in response to a time varying stimulus such as exercise (3,5), stress (6), hyperemic response or others. Ultrafast PC MRI can also be used to acquire Fourier velocity encoded (FVE) flow measurements to overcome errors and artefacts in regions of highly pulsatile and turbulent flow (7).
**4D MR Flow**

To overcome limitations derived from repeated 2D slice imaging, volumetric phase contrast imaging was introduced to provide continuous coverage of vascular regions of interest (8-9). To fully characterize the flow patterns, velocity encoding in all three spatial directions can be obtained by sequentially applying bipolar gradients in each direction of the encoded velocity vector. However, the necessary four acquisitions for 3-directional velocity encoding and volumetric acquisitions excessively prolong the acquisition time. Only recent innovations have reduced the scan time to durations acceptable to patients. Image acceleration techniques, hardware improvements particularly in coil and gradient technology, and mere computational power have dramatically reduced scan and postprocessing times and spurred renewed research with various alternative acquisition schemes. 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.

These ‘4D MR Flow’ techniques have been used 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 (10). 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. Examples of qualitative parameters include streamlines and vorticity and helicity (11-12) while quantitative parameters include the calculation of pressure gradients across vessel narrowings to establish hemodynamic significance (13), pulse wave velocity for the assessment of vessel wall stiffness (14), wall shear stress for assessing stimulus for vessel wall remodeling (15), kinetic energy measures for assessing loads and efficiency (16), turbulence intensity (17) and others. In contrast to frequently used computational fluid dynamic (CFD) simulations (18), these 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 (19).

Significant research efforts have been directed at further reducing the long scan times. That includes improved gating and view sharing schemes (20-21), the use of parallel imaging (22), non-Cartesian 3D sampling such as radial (23) and spiral (24) as well as the exploration of spatial-temporal correlations in the data with k-t-BLAST and k-t-SENSE (25) and k-t-GRAPPA(26) as well in combination with compressed sensing (27).

**UTE PC**

It is well known that PC MRI can suffer from intravoxel dephasing in regions of disturbed flow and from displacement artefacts in regions of accelerated flow. One promising approach to significantly reduce these artefacts is the use of ultrashort echo time (UTE)
PC MRI, which relies on a radial sampling scheme where each acquired k-space line traverse from the origin to the perimeter of the covered circle (2D) (28) or sphere (3D) (29).

Summary
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 additional functional parameters through realtime or 4D MR flow imaging as described above. These noninvasive measures can possibly enhance diagnosis, therapy planning, and therapy monitoring in a wide range of cardiovascular imaging including all major vascular territories and the ventricles and atria. 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. Technical limitations currently include the lack of product sequences for realtime and 4D MR Flow acquisition packages as well as intuitive post-processing packages, which are crucial for successful clinical adaptation of these techniques.

References


