Acceleration of Velocity Encoded Phase Contrast MR. New Techniques and Applications

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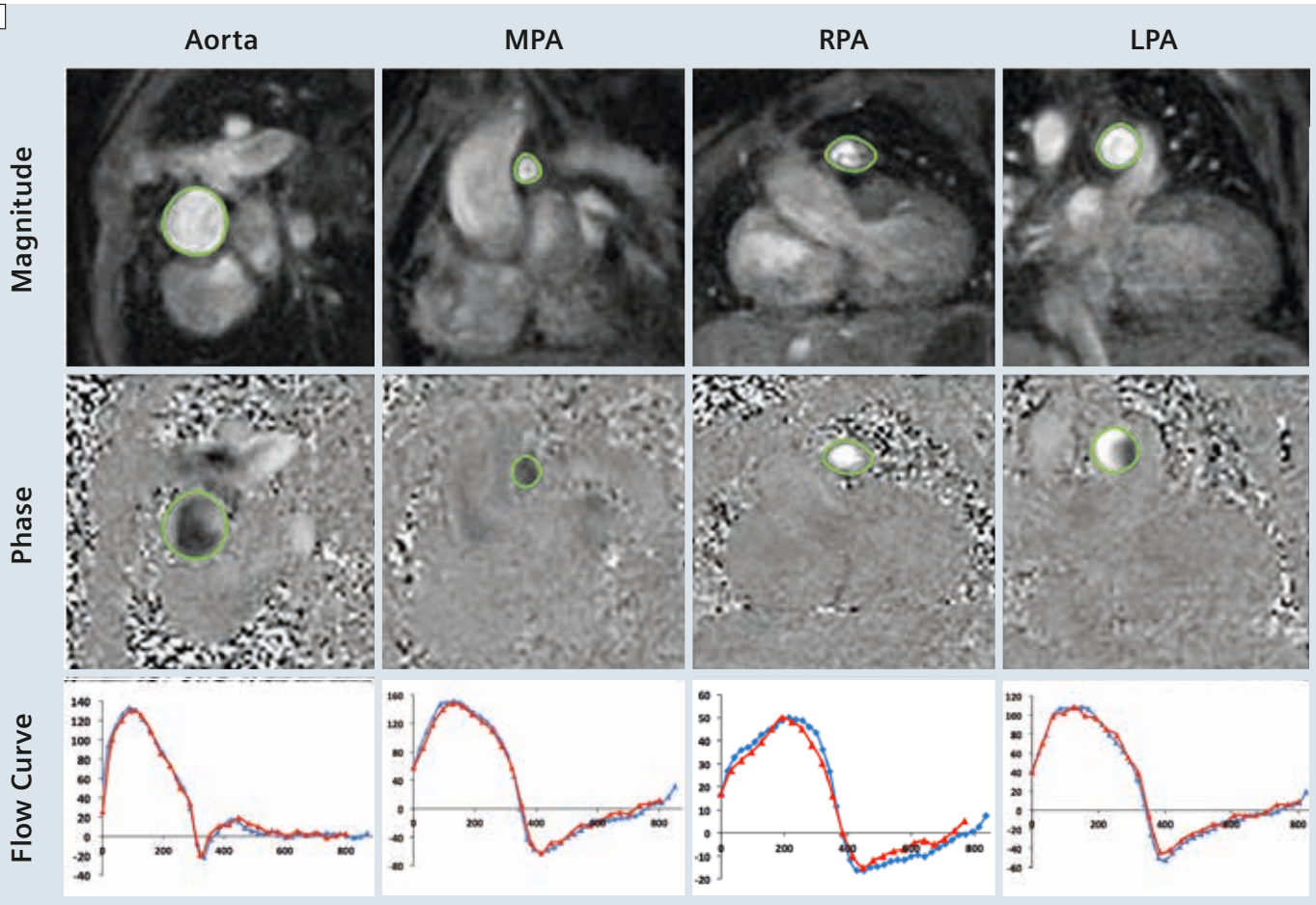


1 Rapid Cardiac-Gated PCMR achieved using undersampled spiral trajectories, in a child, age 2 years. Flow curves show good agreement with a conventional Cartesian acquisition throughout the entire cardiac cycle (blue: retrospectively-gated Cartesian PCMR acquisition, red: prospectively-gated undersampled spiral acquisition).

Introduction

The cardiovascular system is characterized by motion, whether that be of the blood, the myocardium or the valves. For this reason, cardiovascular disease is often associated with abnormalities in flow and movement. Thus, assessment of motion is a vital part of the cardiovascular work-up. One of the most important methods of assessing motion is to measure the velocity of a moving structure and this is an area in which cardiovascular magnetic resonance (CMR) has an important role to play. In fact, CMR has become the gold standard method of assessing volume blood flow in conditions such as congenital heart disease. However, velocity encoded CMR techniques are slow and this has limited their uptake in some clinical situations. In this review we will address novel acceleration techniques that are opening up new areas for CMR velocity quantification.

Basic CMR velocity encoding

The CMR technique that is most commonly used to measure velocity is phase contrast MR (PCMR). PCMR is achieved through the addition of a bipolar velocity-encoding gradient to a standard spoiled gradient echo sequence. This bipolar gradient induces an additional phase in moving objects, which is directly proportional to the velocity. Thus, the velocity of an object (i.e. blood) can be calculated using the phase image. Once the velocities are known, it is trivial to estimate volume flow in a region of interest. This technique has been widely validated both *in-vivo* and *in-vitro* and is considered the reference standard method of measuring volume flow. Thus, it has become heavily used in the assessment of cardiac output, cardiovascular shunts and valvar regurgitation. However, PCMR is intrinsically slow because each line in *k*-space must be acquired twice (with different velocity-encodings) in order to perform background phase subtraction. This prolongs the acquisition time and can become extremely problematic in patients in whom several flow maps must be acquired (i.e. congenital heart disease). Consequently, there has been a significant push to accelerate PCMR sequences.

Acceleration techniques

To accelerate CMR, it is necessary to fill *k*-space more quickly. As we have already reached the physical limits of MR gradient systems, this can only be accomplished through undersampling of *k*-space or more efficient filling. Undersampling in *k*-space leads to fold-over artifacts, which makes the data unusable if the artifact overlays the region-of-interest. Parallel imaging techniques (e.g. SENSE or GRAPPA) can be used to reconstruct artifact free images from undersampled data, through the use of independent coil sensitivities. These parallel imaging techniques can significantly speed up 2D PCMR (typically up to 2 times for Cartesian acquisitions. Data undersampling is currently used by most CMR units to speed up the acquisition of flow data. However, the amount of achievable acceleration is limited, leading to studies into alternative techniques for reconstructing artifact free images. The most obvious examples are temporal encoding techniques (e.g. *k-t* BLAST) that can be used alone or in conjunction with parallel imaging techniques (e.g. UNFOLD-SENSE). These techniques offer higher acceleration factors, although often at the cost of some temporal blurring. Currently, these techniques have not become clinically mainstream, however they should further improve workflow when they do.

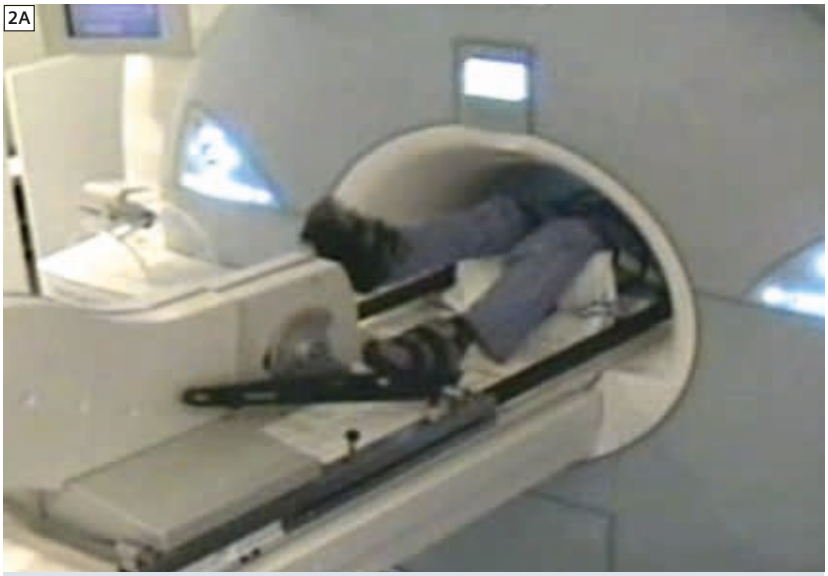
An additional method of accelerating PCMR is more efficient filling of *k*-space, using a non-Cartesian trajectory. Examples are EPI and spiral *k*-space filling, both of which can significantly speed up acquisition. Furthermore, they can be combined with the previously mentioned techniques to achieve high levels of acceleration. In the next section we will discuss specific uses of acceleration in PCMR.

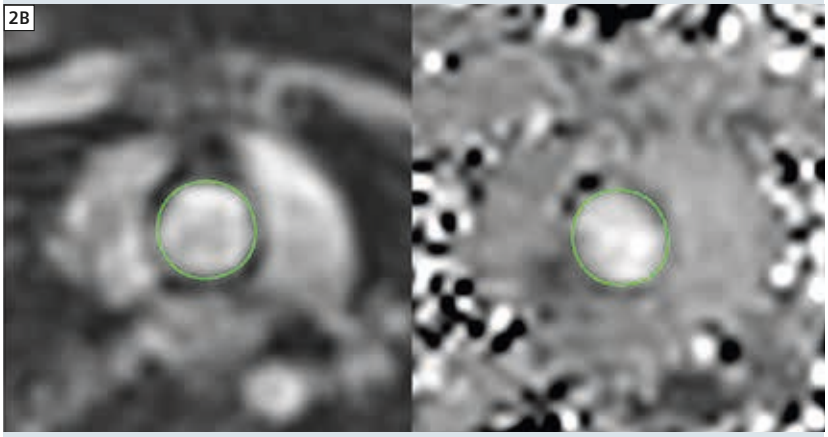
Rapid cardiac-gated PCMR

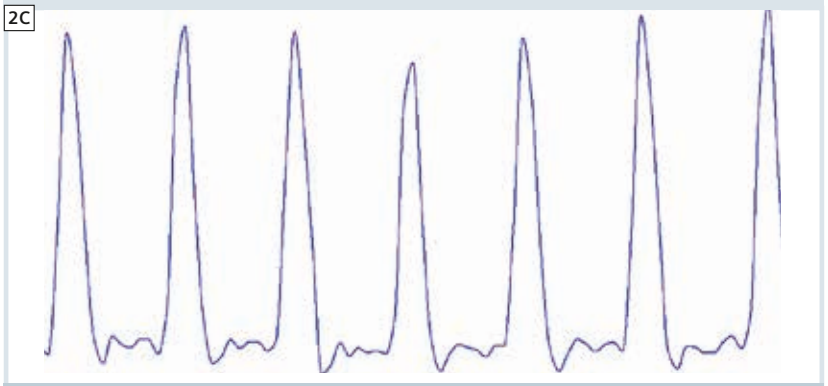
PCMR is heavily used in the assessment of conditions such as congenital heart disease, where between 4 to 8 separate flow measurements are often performed. However, particularly in children[1], the accuracy of PCMR is dependent on spatial and temporal resolution. Thus, in this population it is desirable to perform high spatio-temporal resolution flow imaging. Unfortunately because PCMR is intrinsically slow it is difficult to acquire this sort of data in a breath-hold. Hence, cardiac-gated PCMR often relies on multiple signal averages to compensate for respiratory motion, resulting in scan times of approximately 2 minutes. Therefore, complete flow assessment can take around 10 minutes. Thus, in this population there is a need for a high spatio-temporal resolution gated PCMR sequence that can be performed within a short breath-hold.

Previous studies have investigated speeding up Cartesian gated PCMR with the use of SENSE parallel imaging. Beerbaum, et al. [1, 2] showed that undersampling by factors of 2 or 3 did not hamper their ability to measure stroke volumes and pulmonary-to-systemic flow ratios. Lew, et al. [3] were able to show that breath-hold PCMR (acquisition time: 7-10 seconds) was possible if accelerated by SENSE (x3). Thus, parallel imaging can be combined with PCMR to significantly accelerate acquisition.

Even greater acceleration is possible if parallel imaging is combined with efficient *k*-space trajectories. Our group has shown that combining efficient spiral *k*-space filling with SENSE (x3) allows high temporal-spatial resolution PCMR data (Fig. 1) to be acquired in a short breath-hold (6 RR-intervals) [4]. Further-





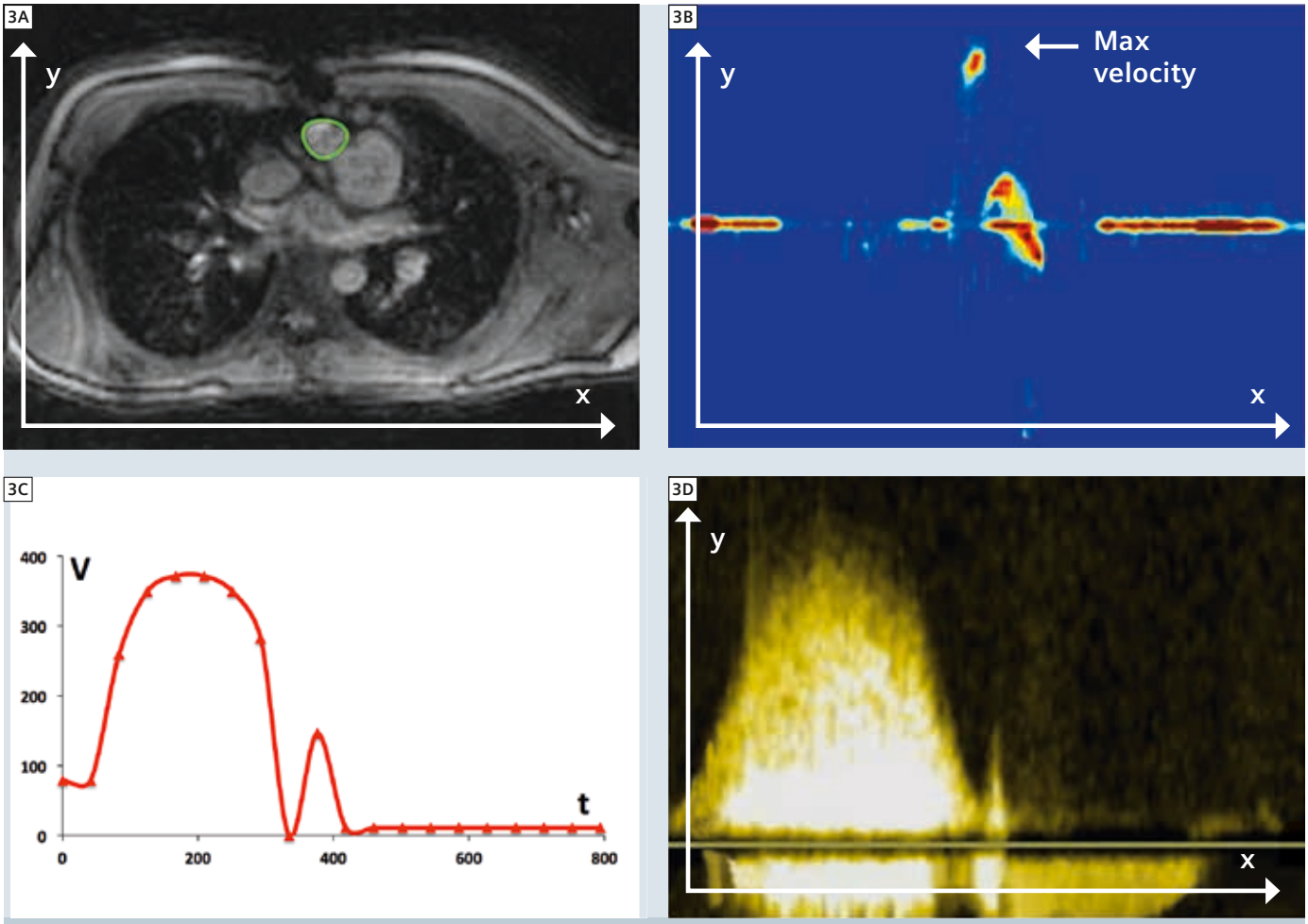


2 Real-time PCMR used for quantification of flow during exercise. **(2A)** MR-compatible ergometer used within the scanner (MR cardiac ergometer Up/Down, Lode, Groningen, Netherlands). **(2B)** Example of image quality achieved using undersampled spiral trajectories in the ascending aorta, left: magnitude, right: phase. **(2C)** Real-time flow curves achieved using this technique.

more, we have shown in a large group of children[1] and adults with congenital heart disease that there were no significant differences compared to a free-breathing Cartesian sequence.
Such sequences allow a reduction in the total duration of flow imaging in congenital heart disease from ~10 minutes, to less than 1 minute. This would lead to a marked reduction in total scan time and has implications for patient throughput and compliance for congenital cardiac MR scanning.
Another approach that has recently become popular is temporal encoding. Baltes, et al. [5] have shown that Cartesian PCMR accelerated with *k-t* BLAST or *k-t* SENSE can lead to significant reductions in scan time. In the future, these temporal encoding techniques could be combined with efficient *k*-space filling strategies to produce very high acceleration factors.

Real-time PCMR

Gated PCMR is the mainstay of clinical flow imaging. However, there are several situations where gated imaging is not suitable, for example, during exercise. Exercise is a powerful stimulator of the cardiovascular system and can be used to unmask subtle disease. However, real-time PCMR is necessary to measure flow during exercise. This can also be achieved through data undersampling and efficient *k*-space filling. For example, Hjortdal, et al. [6] have demonstrated the use of efficient EPI trajectories, with partial-Fourier acquisition, to achieve real-time imaging for the investigation of flow during exercise. This sequence was used to successfully assess exercise hemodynamics in complex congenital heart disease.
Our group has investigated the use of efficient spiral trajectories combined with SENSE (x4) to measure flow at rest and during continuous exercise [7]. The sequence had a high temporal resolution and was validated against a standard gated Cartesian PCMR sequence at



3 Fourier Velocity Encoding using an undersampled spiral acquisition, in one patient. **(3A)** Acquired data in x-y, MIP'd through v. **(3B)** Velocity spectrum along x, at time of peak flow. **(3C)** Velocity profile through time as measured from the spiral MR acquisition. **(3D)** Velocity profile in the same patient as measured using Doppler Ultrasound.

rest, with good agreement (Fig. 2). Using this sequence it was possible to comprehensively assess the response to exercise both in volunteers and patients [8].

Of course, one major problem with this approach is the long reconstruction times associated with non-Cartesian parallel imaging. For example, our group has investigated continuous flow assessment over ~10 minutes during exercise [9]. Using the scanners CPU-based reconstruction, images would only be available ~1 hour after the end of data acquisition. This is too long to be used in a clinical environment; therefore it was necessary to develop a faster reconstruction. One method to achieve this was to use graphical processing unit (GPU)-based reconstruction. This methodology has previously been shown to significantly speed up complex MR reconstructions [10]. In our implementation, a separate GPU-based reconstructor was linked into the scanners reconstruction pipeline, allowing online reconstruction that is hidden from the end-user. Using this technique, images were available ~10 seconds after the end of data acquisition. This type of highly accelerated acquisition and real-time reconstruction may open up many novel areas in cardiovascular MR that are currently impeded by long reconstruction times.

Fourier velocity encoding

Real-time PCMR requires significant acceleration because each frame must be acquired quickly. However, acceleration is also required if large data sets are to be acquired in a short period of time. One good example is Fourier velocity

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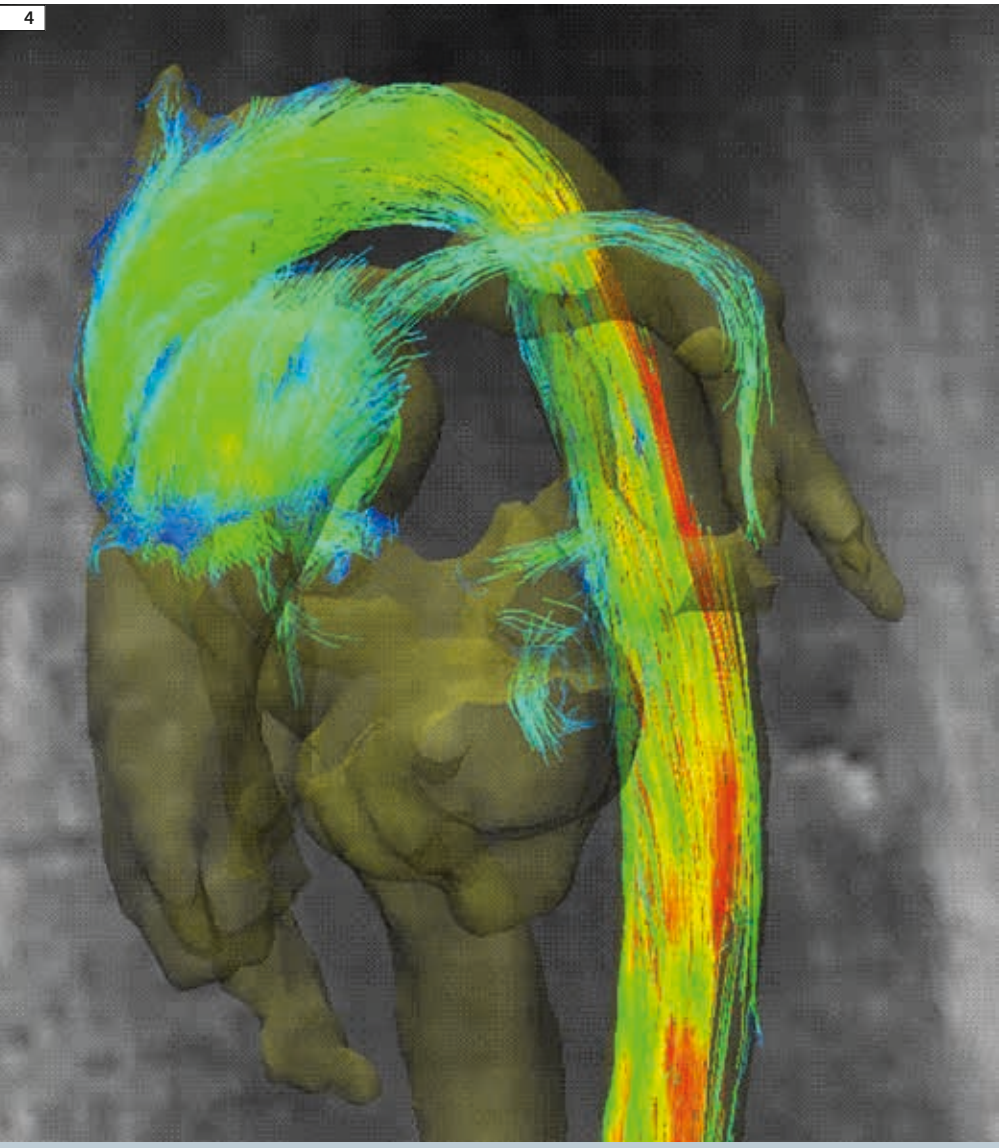

4 4D PCMR data acquired *in-vivo* using an undersampled spiral acquisition.

encoding (FVE), which is a 3D *k*-space acquisition with spatial encoding in two dimensions (*x* and *y*) and velocity encoding in the z direction (denoted as *kv*). Multiple *kv* positions are acquired using bipolar flow-encoding gradients with different first-order moments. Inverse Fourier transformation of *k*-space produces a 3D image with each point in *x-y* space associated with a spectrum of velocities in *v*. This spectrum of velocities allows accurate assessment of stenotic flow, which is often underestimated by traditional PCMR. The main problem with FVE is that it is time consuming to acquire and thus rarely used in the clinical setting.

Time-efficient spiral trajectories with partial-Fourier acquisition along the velocity-encoding dimension have been used to speed up FVE [11]. This form of acceleration does allow breath-hold FVE to be achieved (of 7 RR-intervals), although with a low spatial resolution (of 7 mm). Other groups have investigated the use of *k-t* SENSE for Cartesian FVE [12] with higher acceleration factors (x8 and x16) allowing better spatial resolution (of 1.3-2.8 mm, within a breath-hold of 15-20 seconds).

Our solution to achieve high resolution FVE was to combine spiral trajectories with SENSE in *kx-ky* (x4), in addition to partial-Fourier acquisition in *kv* (67%) and velocity unwrap in the *v* dimension (Fig. 3). The result of all these different acceleration techniques is that it is possible to achieve high spatial (~2.3 mm), temporal (~41 ms) and velocity resolution (14-25 cm/s) FVE data in a relatively short breath-hold (of 15 RR-intervals) [13].

This FVE technique was shown to provide more accurate peak velocity measures than PCMR *in-vitro* and *in-vivo*, compared to Doppler US. Thus, by using acceleration techniques it was possible to bring a technique that has been available for some time, into the clinical environment.

4D Flow

Another technique that has been available for some time, but is rarely used clinically, is time-resolved 3-dimensional PCMR imaging. This technique acquires flow in three encoding directions (known as 4D PCMR) and allows quantification of flow in any imaging plane, in addition to the visualization of complex flow patterns. However, 4D PCMR is rarely used in the clinical setting due to long acquisition times, often in the order of 10-20 minutes.

Several acceleration approaches have been investigated in 4D PCMR. For instance, SENSE and *k-t* BLAST can accelerate the acquisition of Cartesian 4D PCMR at 1.5T and 3T [14]. Using such techniques, it is possible to acquire high-resolution data in ~10 minutes, giving reasonable agreement in terms of stroke

volumes with gated 2D PCMR. Another possibility is the use of combined parallel imaging and compressed-sensing to accelerate the acquisition of 4D PCMR [15]. *K*-space data can be acquired with variable-density Poisson disc undersampling with a total acceleration of 4–5, giving an acquisition time of ~11 minutes.

We have taken a similar approach to FVE and used a stack-of-spirals acquisition in addition to data undersampling, and reconstructing with SENSE to greatly reduce the acquisition time for 4D PCMR. For example, a developed spiral SENSE sequence with 8 uniform density spiral interleaves in *kx-ky*, and 24 slices, can be acquired with a SENSE undersampling factor of 4 in *kx-ky*, and SENSE undersampling factor of 2 in *kz*, giving a total undersampling factor of 8. This allows a temporal resolution of ~49 ms and a spatial resolution of 2.6 × 2.6 × 2.5 mm, to be achieved within a scan time 2 minutes 40 seconds (Fig. 4). In this case, accelerated imaging can offer huge reductions in scan time.

Conclusion and future

Accelerated techniques offer the possibility of significantly speeding up PCMR acquisitions. This should allow better real-time imaging, as well as the acquisition of larger data sets in much shorter times (e.g. 4D PCMR). In the future new acceleration techniques such as compressed sensing may further improve our ability to acquire this sort of data. However, as the acceleration techniques become more complex, faster reconstruction will become necessary. Thus, the advent of GPU based MR reconstruction has a pivotal role to play in the development of new accelerated PCMR sequences.

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[1] MR scanning has not been established as safe for imaging fetuses and infants under two years of age. The responsible physician must evaluate the benefit of the MRI examination in comparison to other imaging procedures.

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