Parallel Imaging for Cardiovascular Applications

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INTRODUCTION:

The use of parallel imaging for cardiovascular application has become virtually ubiquitous. Substantial progress since the Zurich Parallel Imaging Workshop held in 2004 has led to improved image quality, reduced exam times, and reduced breath-hold duration. Real-time imaging may be used for free-breathing studies and in patients with arrhythmias or heart rate variation. Cardiac MR imaging is challenging due to the simultaneous need for moderately high resolution, ability to image during cardiac and respiratory motion, and relatively low SNR of imaging in the heart at the center of the torso. Parallel imaging offers a means of decreasing acquisition time which offers the user more flexibility to meet these challenges.

New developments over the past 5 years include:

1) algorithms
   a) more robust auto-calibration
   b) improved exploitation of dynamic data using k-t methods
   c) improved regularization
   d) non-Cartesian methods
   e) performance characterization
   f) channel compression
2) hardware
   a) increased number of receiver channels
   b) availability of cardiac arrays
   c) real-time image reconstruction
3) applications
   a) large number of imaging sequences and protocols
   b) large number of clinical validation studies

The number of cardiovascular imaging applications and methods is quite extensive, however in the limited scope of the syllabus only a few examples have been selected. Several examples illustrate the improvement that is provided in terms of breath-hold reduction which lead to improved workflow and patient comfort, whereas other examples highlight applications such as real-time and peak velocity measurements that are actually enabled by means of parallel imaging. Real-time acquisition permits imaging patients that might otherwise be excluded (e.g., arrhymthias, heart failure, pediatric) or in other cases enables measurements under physiologic conditions. The references cited provide an overview of recent work and highlight some of the promising new directions.

FUNCTION:

Cardiac function is typically measured using cine imaging of the heart with 1-2 mm spatial resolution on a stack of (2D) slices covering the full heart. Steady state free precession (SSFP) or TrueFISP is most commonly used to provide high contrast between blood and myocardium. LV volumes and ejection fraction may be quantified and regional wall motion abnormalities are characterized by local wall thickening. In order to acquire sufficient spatial and temporal resolution, the acquisition is frequently segmented over many heart beats acquired during a breath-hold. A challenge is to provide non-breath-held real-time imaging with sufficient spatial-temporal resolution, or to greatly reduce the breath-hold duration. Real-time imaging may also be used in patients with irregular heart beats or extreme difficulty holding their breath.

Example breath-held cine SSFP imaging at 192x108 with approx 25 ms temporal resolution is shown in Fig 1 comparing various accelerations to reduce the breath-hold duration. Example real-time SSFP imaging at approx 20 fps 192x80, with SENSE rate 4 is shown in Fig. 2. Both cine examples use auto-calibrating TSENSE reconstruction. Acceleration rates of 6-8 have been demonstrated using k-t methods with improved regularization.

Imaging of the full heart using 3D imaging, and 2D SENSE with 2-dimensional surface coils arrays has great potential to decrease exam time and provide datasets which minimize multi-slice registration errors due to respiratory

motion. A number of researchers have demonstrated navigated/self-navigated 3D cines or single breath-hold 3D cines with reduced resolution. Although 3D imaging with 2D SENSE has the potential to achieve higher acceleration factors, volume excitation significantly reduces the myocardial-blood contrast, thus limiting the performance. More work is required to realize this full potential in practice.

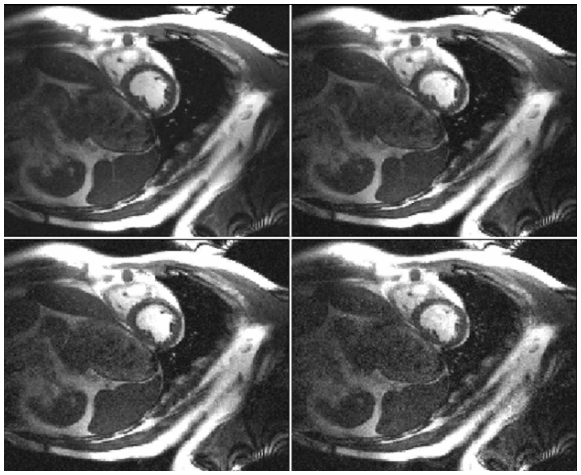

Figure 1. Breath-held cine with BH durations were 16, 8, 6, and 4 heartbeats for acceleration at rates 1 (unaccelerated), 2, 3, and 4, respectively.

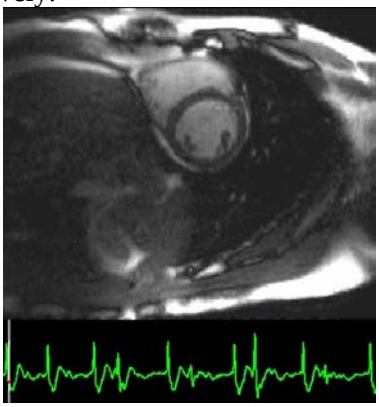

Figure 2. Real-time imaging of patient with arrhythmia images acquired using rate 4 free-breathing without ECG triggering.

An example (Fig. 3) of a single-breath-hold gated, segmented cine function acquired using a SSFP sequence with TSENSE rate 4x3=12 uses a 32-element 2D-array, 192x108x18 matrix and discarding 4 slices achieves 1.8x2.4x7 mm^3 spatial resolution. This is acquired using an 18 heart-beat breath-hold, achieving 28 ms temporal resolution.

Undersampled non-Cartesian acquisition with parallel imaging reconstruction offers the potential for high acceleration for both 2D and 3D imaging. An example of real-time 2D radial imaging used for exercise stress function is shown in Fig. 4. (128x128 matrix with approx 35 ms temporal resolution).

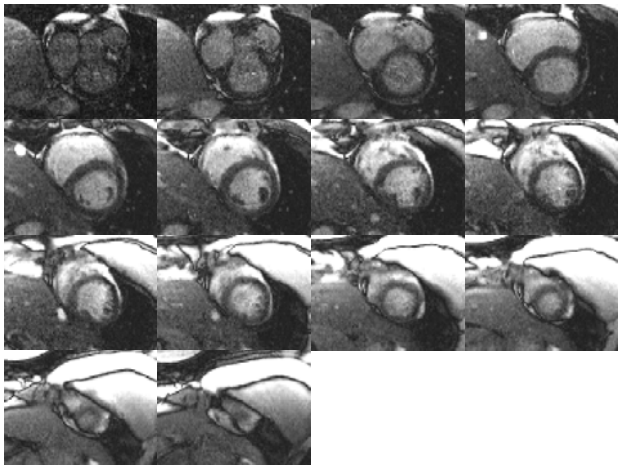

Figure 3. Single breath-hold 3D cine using 2D SENSE [4].

Figure 4. Real-time radial kt-SENSE (rate 8) during exercise stress (from Lurz, et al, UCL Institute of Child Health, London, UK) [3].

PERFUSION:

First pass contrast enhanced imaging with single RR temporal resolution for perfusion quantification, and full heart coverage is difficult to attain. Imaging durations must also be kept short to minimize motion related artifacts. Typically, saturation recovery (SR) is used to provide T1-weighted contrast. Parallel imaging may be used to minimize acquisition time, which enables acquisition of more slices and/or 3D imaging, lengthier SR prep time for improved CNR, and/or increased spatial resolution for better visualization of regions with perfusion deficits.

Example images of multi-slice 2D perfusion using SR-GRE-EPI are shown in Fig. 5. This example uses rate 2 acceleration with TSENSE auto-calibration to cover 3 slices per RR, echotrain length=4, 128x80 matrix, at heart rates up to 120bpm. The imaging window is approx 60 ms which minimizes occurrence of

motion related dark rim artifacts (DRA). Higher spatial resolution may be achieved with increased acceleration which may further mitigates dark rim artifacts (Fig 6). An example of 3D first pass perfusion with whole heart coverage is shown in Fig. 7 acquired using SR-GRE with 2D undersampling at rate 2x3=6. Images were acquired in approx. 300 ms during mid-diastole with a matrix of 100x66x10.

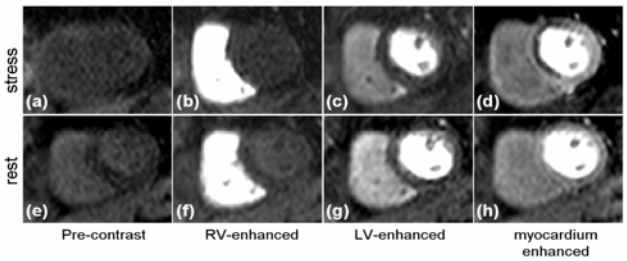

Figure 5. First-pass contrast enhanced perfusion using SR-GRE-EPI sequence (acceleration factor 2). Stress perfusion (top row) shows defect in LAD territory. (Kellman & Arai, JCMR. 2007;9(3):525-37). [6]

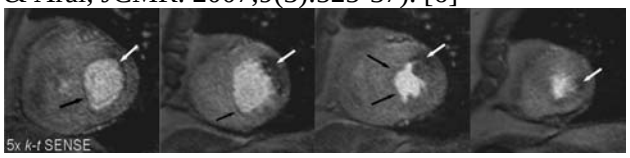

Figure 6. First-pass contrast enhanced perfusion with high spatial resolution to mitigate dark rim artifacts, achieved using 5x ktSENSE (Plein, et al. MRM 2007; 58:777). [8]

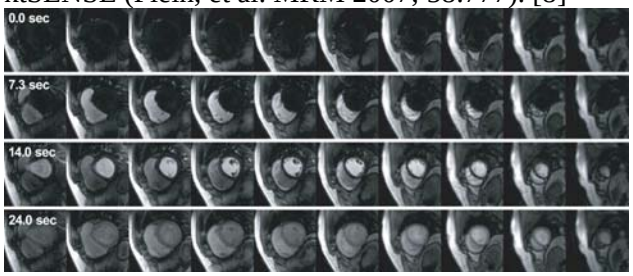

Figure 7. 3D first-pass perfusion using 2D undersampling at rate 2x3=6 to obtain full heart coverage each RR interval (Shin, et al, JCMR. 2008 Dec 11;10(1):57).[10]

VIABILITY:

Delayed contrast enhanced imaging is used to detect and characterize myocardial infarction (MI). Parallel imaging may be applied to late enhancement imaging for decreased breath-hold duration in conventional segmented scans or to enable single-shot imaging with sufficient spatial resolution for patients with arrhythmias or poor breath-holding ability.

Example delayed enhancement images using a phase sensitive inversion recovery (PSIR) sequence are shown in Fig. 8 for segmented turboFLASH and single-shot TrueFISP sequences, respectively, both 2x accelerated using SENSE with 256x128 matrix. The segmented PSIR turboFLASH required 6 heartbeats while the single-shot IR TrueFISP required 2 heartbeats (1 heart beat for IR image and 1 for background phase reference).

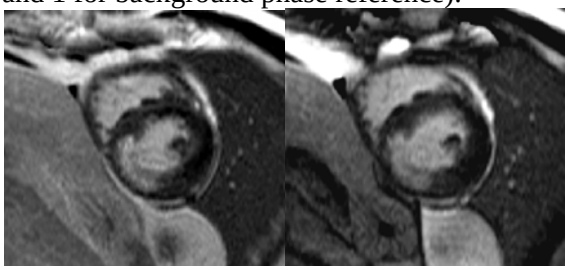

Figure 8. PSIR late enhancement images acquired using rate 2 SENSE acceleration for (a) breath-held, segment turbo-FLASH acquisition in 6 heartbeats (right) and (b) single-shot SSFP imaging (right).

FLOW:

Phase contrast (PC) or Fourier velocity encoding (FVE) may be used to image flow in the heart or vessels. Parallel imaging for flow measurement with phase contrast techniques may be used to reduce the breath-hold duration while maintaining the spatial and temporal resolution. FVE requiring additional measurements is actually enabled by means of highly parallel imaging. Using FVE with 8-fold accelerated kt-SENSE, it has been demonstrated to be possible to measure the high peak velocities in stenotic vessels. Parallel imaging also enables measurement of flow in real-time using spiral acquisitions (Fig 9) and has also been used to measure flow during exercise stress.

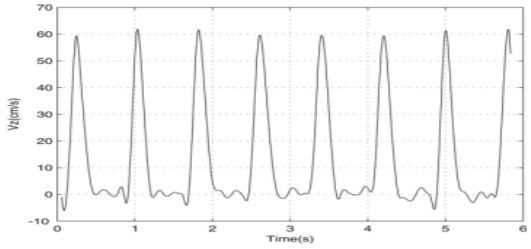

Figure 9. Real-time flow measurement of aortic blood velocity using spiral acquisition with 4-fold acceleration (Nezafat, et al, MRM. 2005 Dec; 54: 1557–1561). [21]

ANGIOGRAPHY:

MR angiography with sparse dynamic enhancement derives a large benefit for 3D acquisition with 2D undersampled parallel imaging and high acceleration factors. Example of dynamic MRA of the head is shown in Fig. 10 for a case of 192x114x96 matrix acquiring volumes every 3 sec. Parallel imaging is applied only to the dynamic signal component which improves the image quality. Parallel imaging is also used routinely for non-contrast MRA to reduce the acquisition time on lengthy navigated scans for cardiac gated segmented 3D acquisitions. An example non-contrast MRA is shown in Fig. 11 for acquisition using 256x256x120 matrix, with rate 3 acceleration using GRAPPA.

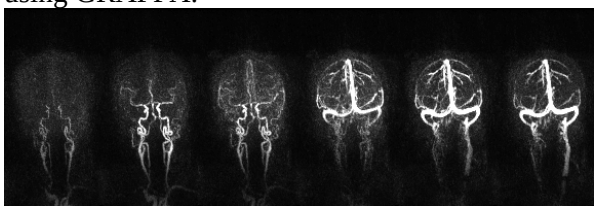

Figure 10. Dynamic angiography using contrast enhanced 3D FLASH with 2D undersampling at rate 3x3=9 using TGRAPPA (courtesy of Randall Kroeker & Gerhard Loeb, Siemens Medical).

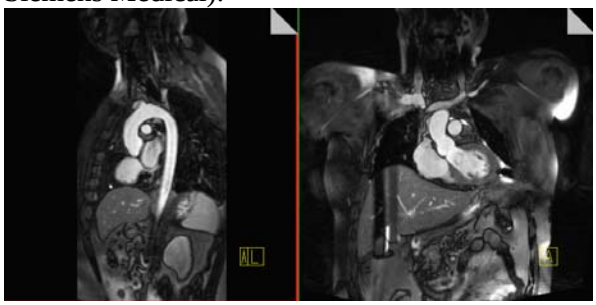

Figure 11. Non-contrast MRA using 3D accelerated (rate 3) SSFP respiratory navigated, cardiac gated acquisition.

DISCUSSION:

There has been significant progress in achieving robust implementations of parallel imaging that are in widespread use for cardiovascular application. While 2D imaging applications are relatively mature, there is still unrealized potential in the area of 3D dynamic cine imaging at higher acceleration rates taking advantage of 2D undersampling, and in the use of highly undersampled non-Cartesian imaging. Furthermore, hybrid reconstruction schemes that combine parallel imaging with compressed sensing are emerging for cardiovascular applications. Higher field imaging with parallel transmission to correct field inhomogeneities offers promise for cardiovascular applications as well. A future direction for both improved workflow and robust handling of difficult patient studies would be the free-breathing, non- or self-gated exam.

Characterizing the performance of parallel imaging algorithms is important for comparing methods, evaluating coils, as well as optimizing imaging protocols. Methods are available for measuring the SNR and g-factor of both image and k-space domain parallel imaging techniques. However, as k-t methods exploit the spatio-temporal signal characteristics to improve image quality, new metrics are needed to quantify signal fidelity and temporal filtering effects. Similarly, caution must be used in measuring the SNR for non-Cartesian imaging with non-uniform noise density.

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