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Highly Accelerated Cardiovascular Magnetic Resonance Imaging: Concepts and Clinical Applications

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I. Introduction

Cardiovascular MR imaging (CVMR) has become a valuable diagnostic imaging modality for the non-invasive detection of cardiovascular diseases [1, 2]. CVMR requires speed and efficiency due to physiological motion and flow constraints which dictate the viable window of data acquisition. To meet these challenges one must balance the competing constraints of spatial and temporal resolution, image quality and imaging speed.

Imaging speed is fundamentally limited in conventional cardiovascular MRI but with the introduction of parallel MRI alternative means for increasing acquisition speed have become clinically available [3, 4]. For conventional radio-frequency (RF) coil array designs and typical imaging volumes, signal-to-noise ratio (SNR) losses associated with parallel imaging have constituted a significant practical obstacle, as has the limited number of receiver channels available on most MR scanners, so that current clinically used accelerations generally do not exceed a moderate factor of four. This constraint has prompted the development of many-element RF coil arrays in conjunction with many-receiver systems [5, 6], which represent a key enabling factor for highly accelerated CVMR:

- Increasing numbers of densely packed RF coil array elements offer baseline SNR improvements over arrays with fewer elements.
- Increasing numbers of RF coil array elements extend maximum possible accelerations to the level of an order-of-magnitude and beyond while the flexibility and robustness at typical low accelerations is improved.
- A sufficient number of receivers allows the use of multi-dimensional RF coil array arrangements capable of multi-dimensional accelerations in 3D imaging, which serve to preserve SNR as compared to traditional one-dimensional accelerations [7, 8].
- Large 3D volumes also help to recover SNR via noise averaging over large data matrices.

The speed and efficiency gain associated with highly accelerated parallel MRI may be translated into extra diagnostic value in a number of ways, including (i) shortening long examinations, (ii) enhancing temporal and spatial resolution, (iii) improving patient comfort, (iv) enabling volumetric MRI with whole heart coverage, (v) overcoming physiological and physical constraints and (vi) eliminating the need for time consuming localization scans.

In this review, examples of each of these strategies will be surveyed. First key concepts and practical considerations of parallel CVMR are outlined. Next, highly accelerated CVMR applications are reviewed, ranging from cardiac anatomical and functional assessment to myocardial perfusion and viability to MR angiography of the coronary arteries and the large vessels. Finally, current trends, including the broad move towards high field imaging, and future directions in highly parallel CVMR are considered.

II. Concepts and Practical Considerations For Parallel MRI

Coil sensitivity encoding: Parallel MRI acquisition strategies, use RF detector coil sensitivities to encode simultaneous spatial information. Undersampled data are acquired using a coil array, with a reduced number of encoding gradient steps as compared with the traditional approach, and the missing information is reconstructed using knowledge of the coil sensitivities. Three intuitive pictures are helpful to understand the undersampled acquisition and image reconstruction approaches of parallel imaging:

- *k-space picture,* exemplified by the original SMASH technique, which involves the regeneration of missing k-space lines [3].
- *image-domain picture,* as represented by the original Cartesian SENSE formulation, which involves the unfolding of aliased voxels that result from undersampling [4].
- *generalized perspective,* which connects the SMASH-like and SENSE-like pictures [9-12].

Spatio-temporal correlations: Recently, parallel imaging has been combined with techniques that use spatiotemporal correlations in dynamic imaging. This is the concept behind techniques such as UNFOLD and *k-t* BLAST, all of which have been used primarily for CVMR [13, 14]. In all cases, spatial information from coil arrays can be combined with temporal information including hybrid techniques such as UNFOLD-SENSE, TSENSE, k-t SENSE [14-16].

Tradeoffs for the increased speed and efficiency of parallel MRI include the need to calibrate coil sensitivity patterns, the need to acquire training data in case of *k-t* techniques, the possibility for image artifacts when calibration or training data are inaccurate, and a reduction in SNR compared with unaccelerated imaging using the same coil array.

RF coil design: The sheer variety of CVMR applications makes it difficult to identify any single coil array design that might be considered optimal for highly accelerated CVMR. However, the following general principles apply: the selected array should have a) sufficiently high baseline SNR and depth penetration to offset anticipated SNR losses for target acceleration factors; b) a sufficiently large sensitive region to cover the cardiovascular target anatomy; c) a desirable noise amplification profile for image planes of interest; d) principal directions of sensitivity variation which match as far as possible the planned phase encoding directions to be accelerated; e) light weight design, mechanical flexibility and ease of use. Early many-element cardiac optimized coil array designs included rigid arrays arranged in contoured 2D grids with overlapped elements along the z-direction, and traditional phased array and honeycomb designs with overlapped elements as shown in Figure 1 [5, 17-19].

Parallel MRI at high magnetic field strengths: SNR losses associated with parallel MRI can rise prohibitively as the acceleration factor increases at field strengths of 1.5 T and below. It has been predicted, however, that high field strengths, in addition to increasing the baseline SNR available for accelerated studies, may also reduce noise amplification in parallel MRI [7, 20]. This development is one of the driving forces for the move towards clinical 3.0 T whole body MR systems equipped with many channel technology, which hold the promise to advance the capabilities of cardiovascular MR imaging [21].

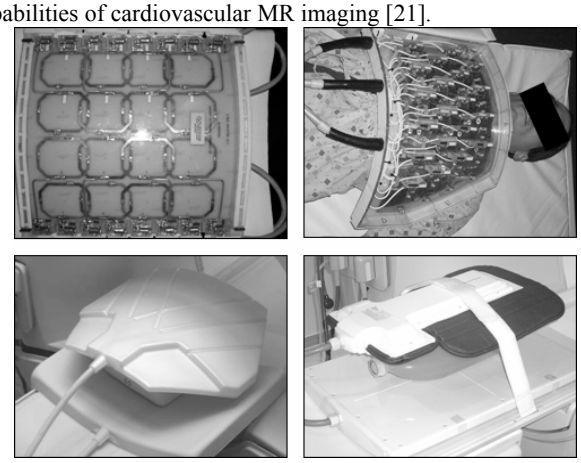

Fig. 1: Examples of 32-element coil arrays used for **top)** early feasibility studies [5, 6, 17, 18] and **bottom)** clinical routine CVMR studies [19].

III. Clinical Applications of Highly Accelerated CVMR

Imaging of cardiac anatomy and structure

Imaging of the cardiac anatomy and structure using fast spin-echo based imaging techniques benefits from highly accelerated parallel imaging, which helps to limit relaxation-related blurring by enabling reduced echo train lengths for any given acquisition time. With 8-10 slices to cover the whole heart, the conventional approach requires prolonged examination times, potentially resulting in image registration errors. Simple acceleration affords the use of longer or single shot echo trains, which substantially shortens scan times and reduces the risk of slice misregistration.

Meanwhile, high accelerated image quality is enabled by the increase in baseline SNR available at 3.0 T as opposed to 1.5 T – an SNR increase ranging from 30% in double inversion recovery (IR) prepared techniques to 75 % for triple IR fast spin-echo imaging [22].

Perhaps the greatest benefit of parallel imaging for fast spin-echo imaging at high magnetic field strength is the capability to relax total power deposition constraints by omitting phase encoding steps and corresponding RF refocusing pulses, which can be supplemented by the application of variable flip angle and hyperechoes [23, 24].

Assessement of global cardiac function

High SNR and CNR are essential for the precise assessment of global cardiac function using CINE imaging. To achieve apex-to-base coverage, the conventional approach is generally confined to 1-2 slices per breath-hold. The resulting total examination times of appr. 10-12 minutes may diminish patient compliance, and may result in appreciable slice misregistration. The improved efficiency of highly accelerated parallel acquisition strategies helps to overcome these difficulties by allowing (i) accelerated 2D CINE techniques encompassing multiple slices per breath-hold or (ii) single breath-hold whole heart coverage 3D CINE acquisitions as illustrated in Figure 2. To achieve the high accelerations required without incurring prohibitive SNR losses, spatio-temporal correlations in dynamic CINE imaging can be exploited using *k-t* approaches.

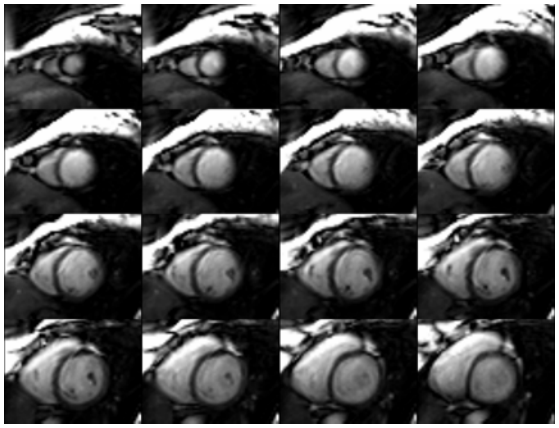

Fig. 2: Short axis views (diastole) obtained from whole heart coverage 3D CINE acquisitions using the *k-t* BLAST approach together with an acceleration factor of R=12.

The speed benefit demonstrated for CINE imaging in conjunction with highly accelerated acquisition strategies also allows the capture of an increased number of cardiac phases, resulting in an improved temporal resolution without exceeding breath-hold constraints. Such approaches should allow highly accurate wall motion tracking and tracking of small rapidly moving structures such as valve cusps throughout the cardiac cycle – a capability expected to be beneficial for the examination of valvular disease.

Detection of myocardial infarction and assessment of myocardial viability

The established CVMR assessment of ischemic heart disease includes delayed contrast-enhanced imaging [25]. Highly accelerated imaging of delayed enhancement is of clinical importance since the established unaccelerated approach, which exhibits a very limited spatial coverage of only 1 to 2 slices per breath-hold, results in prolonged examination times of 10-15 minutes with corresponding patient discomfort and decay of contrast agent concentration over the course of the exam. Highly accelerated parallel imaging can overcome these difficulties by allowing whole-heart coverage in a single breath-hold, increasing patient comfort and ensuring uniform suppression of healthy myocardium for all imaged sections.

The resulting low SNR in delayed enhancement imaging due to suppression of background and healthy myocardial signal presents a challenge for combinations with highly accelerated parallel imaging. As might be expected, this challenge can be offset by the use of many-element coil arrays in synergy with high magnetic field strengths.

Meanwhile, a phase sensitive reconstruction of inversion recovery (PSIR) technique has been shown to enhance the contrast between healthy and infarcted myocardial tissue [26]. However, this approach requires 2 R-R intervals for full magnetization recovery and hence doubles the total scan time as compared to the conventional 1 R-R interval approach. This drawback can be compensated by using the time savings inherent to accelerated

parallel imaging which facilitate short breath-hold times while achieving whole heart coverage as depicted Figure 3.

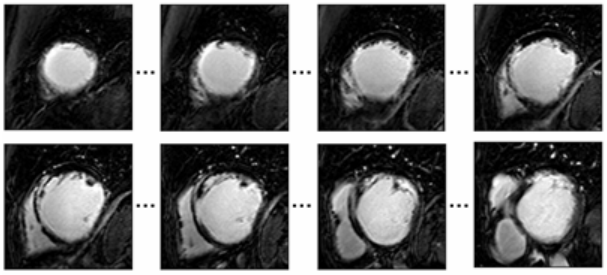

Fig. 3: Magnitude reconstructed short axis views obtained from whole heart coverage 3D delayed enhancement acquisitions using parallel imaging.

First pass myocardial perfusion imaging

Remaining obstacles to a broader clinical acceptance of first-pass perfusion MRI are (i) the limited in-plane spatial resolution resulting in Gibbs ringing artifacts [27] and (ii) the limited anatomic coverage achievable while accomplishing one- or two-heart-beat temporal resolution to track the contrast agent passage. Consequently, myocardial perfusion imaging may benefit directly from highly accelerated parallel imaging by transferring the speed advantage into enhanced spatial and/or temporal resolution. For this purpose, the *k-t* approach can be used to double the spatial coverage per unit time while preserving in-plane spatial resolution. Alternatively, *k-t* techniques can be put to use to double the in-plane matrix size without impairing the temporal resolution as illustrated in Figure 4.

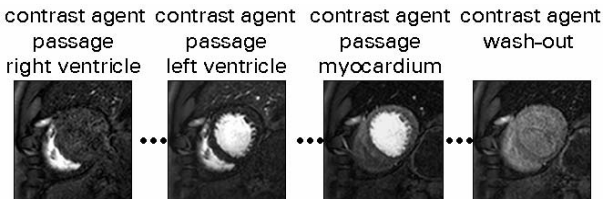

Fig. 4: Short axis view obtained from a 5-fold accelerated first pass perfusion scan using the *k-t* approach with a matrix size of 192x192 and 1 R-R interval temporal resolution.

Coronary MR angiography (CMRA)

Parallel imaging strategies provide several means of improving CMRA image quality by minimizing the impact of physiological motion [28] and by permitting an improvement in the spatial resolution and anatomic coverage [29]. The feasibility of rapid CMRA was demonstrated by combining parallel imaging with breath-held 3D SSFP imaging, covering the main branches of the coronary arterial systems in 2-3 breath-holds. The time savings of parallel imaging were translated into an enhanced spatial resolution, which resulted in an improved delineation of proximal and, most especially, distal segments of the coronary arteries [28].

Conventional CMRA studies are generally restricted to targeted thin slabs encompassing a particular segment of the coronary artery tree only. Parallel imaging allows the use of a thicker volume, which supports the visualization of long tortuous segments of the coronary arteries and offers the potential to eliminate localization scans [28]. As larger acceleration factors are explored with many-channel MR systems, the benefits of massively accelerated acquisitions are even more pronounced, allowing previously unattainable whole heart coverage CAI within a 1-2 min free breathing acquisition [30] or a single breath hold scan [18] as illustrated in Figure 5. This constitutes a significant scan time reduction which, in turn, may enable integration of CMRA into a short comprehensive cardiac examination for the detection of heart disease.

Initial 3.0T experience suggests that higher field strengths in conjunction with tailored array designs may enable accelerations factors of $R \geq 10$ and hence may provide benefits for clinical coronary MR angiography with sub-millimeter spatial resolution. Access to higher acceleration factors would allow even shorter acquisition windows, thereby further enhancing immunity to physiological motion for CAI, especially at very high heart rates, which is essential for pharmacological stress applications.

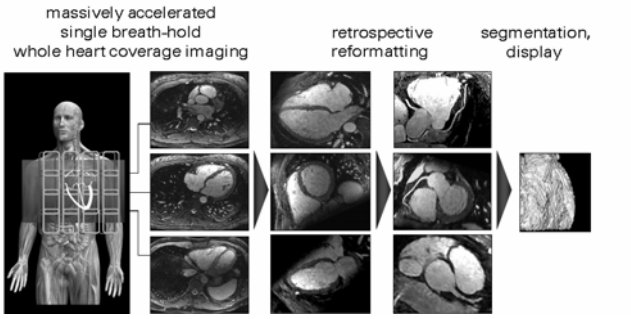

Fig. 5: Whole-heart cardiac and coronary artery imaging in a single breath-hold using 8-fold accelerated parallel imaging with a 32-receiver system and a 32-element coil array.

Vascular imaging

The conventional first pass contrast enhanced MR angiography (MRA) approach is a particularly appealing candidate for highly accelerated parallel imaging because it is comparatively rich in SNR. The comparatively short time intervals associated with the passage of contrast agents through the vascular system require rapid imaging techniques for continuous bolus tracking or appropriately timed bolus chasing [31]. The imaging speed associated with parallel MRI may be invested to improve temporal resolution in time-resolved MRA, in order to clearly distinguish arterial from venous phases or to evaluate contrast dynamics [32, 33]. Alternatively, parallel MRI may be used to improve anatomic coverage or spatial resolution in a given imaging time [34].

Twelve- to sixteen-fold accelerations have first been reported for volumetric, contrast enhanced MR angiography using 32-element arrays and a 32-receiver system [5, 6] which enabled comprehensive coverage of the vasculature at clinically useful spatial and/or temporal resolution as illustrated in Figure 6.

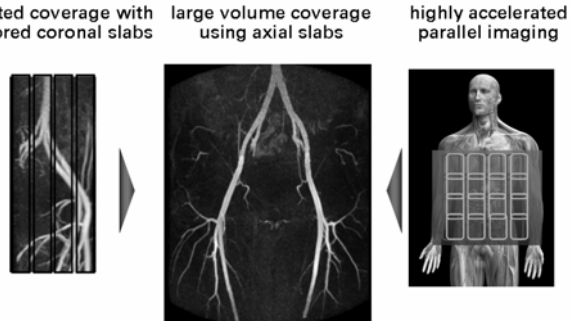

Fig. 6: MIPs reformatted from an axial, comprehensive data volume **(center)** which was obtained at high spatial resolution. An acceleration factor of R=12 was used, which reduced an impractical scan time of 4 minutes to a 20 second breath-hold.

IV. Future Directions

Highly accelerated volumetric parallel imaging strategies enable whole heart coverage acquisitions in otherwise unattainable scan

times. As high accelerations are accomplished more routinely using many-channel MR systems, the benefits of otherwise inaccessible scan times will serve to integrate CVMR into a short comprehensive examination for the detection of heart disease while improving both operator convenience and patient comfort.

The extra diagnostic value afforded by highly accelerated parallel imaging is expected to drive future technological developments. One development that is already underway is a broad move towards commercial MR systems with 32 or more receiver channels. Further image quality improvements may be expected with the use of many-element RF coil arrays tailored to cardiac fields of view. The practical design and operational requirements of clinical highly accelerated parallel imaging are also likely to motivate further advances in conductor arrangement, circuit board miniaturization, cabling methods including wireless connections, substrate material, and last but not least image reconstruction software and hardware. Another development that is already underway is a move towards commercial 3.0 T or even 7.0 T MR systems, with 32 or more receiver channels. The requirements of cardiac studies at high- or ultra-high magnetic field strengths are also likely to motivate further advances in RF coil technology. Access to high accelerations afforded by the synergy between many element coil arrays and high magnetic field strengths would serve to further enhance immunity to physiological motion, particularly at very high heart rates, and hence might facilitate pharmacological stress applications. Meanwhile, parallel imaging can help to address some of the practical limitations of high-field MRI, including susceptibility artifacts, acoustic noise and RF power deposition..

The capacity for rapid imaging promises to enhance diagnostic value not only by streamlining cardiovascular MRI for structural and functional imaging, but also by advancing targeted tissue characterization and by providing a broader access to physiologic and metabolic information. With appropriate hardware design and customized imaging techniques, one might envision compressing a comprehensive CVMR exam not merely into a span of 30-45 minutes but even into a few short breath-holds or a short period of free breathing. While this vision remains, for the moment, merely a vision, work continues apace to bring the full benefits of highly accelerated parallel acquisition to bear for the understanding and assessment of cardiovascular disease.

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