Real-Time Low-Latency Cardiac Imaging Using Through-Time Radial GRAPPA

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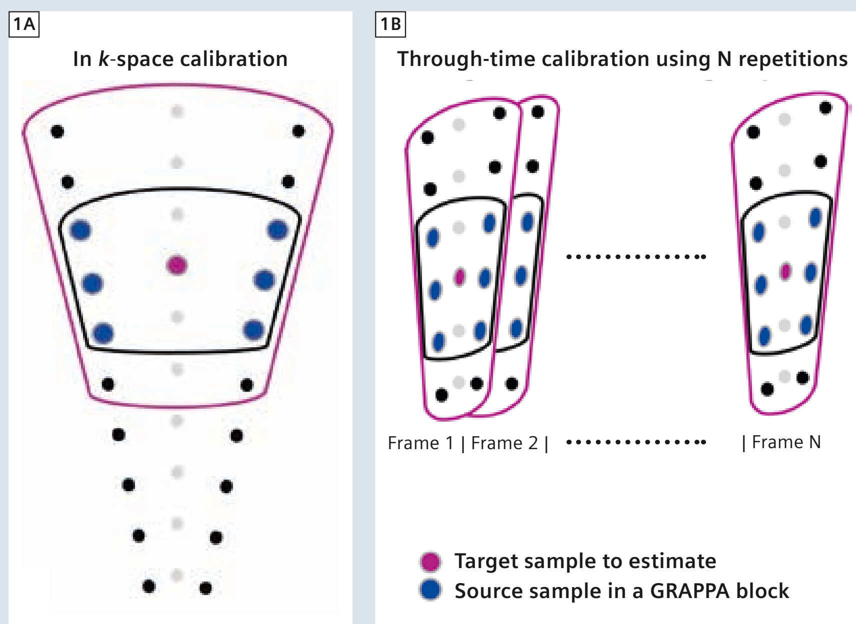
Introduction

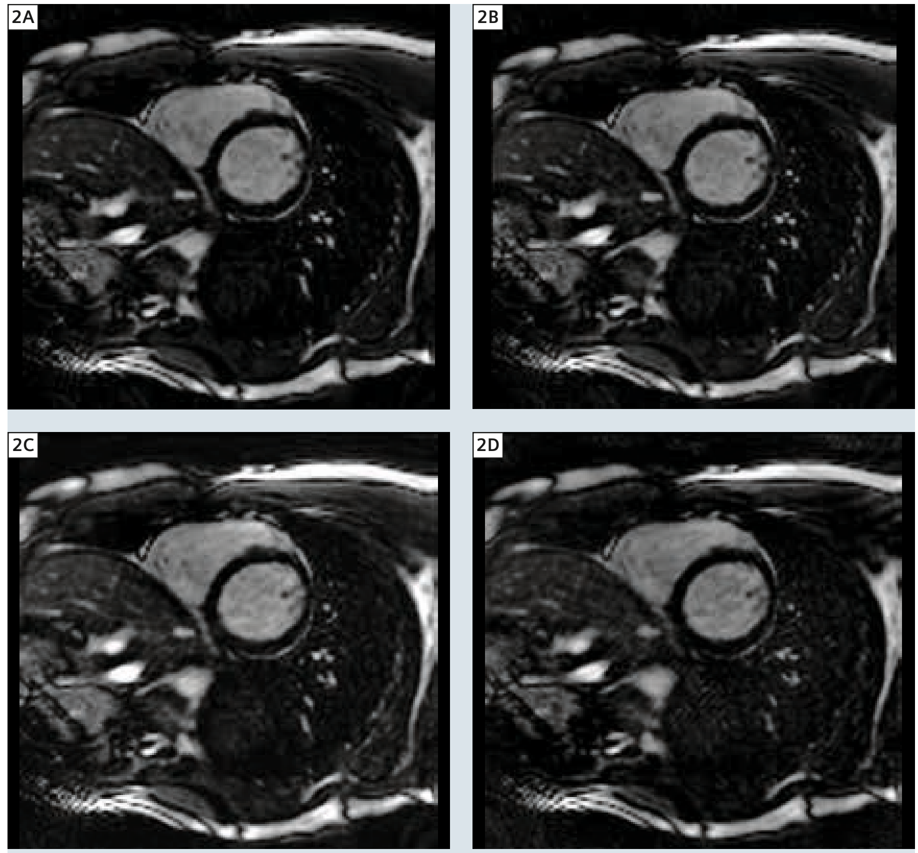
Segmented cine imaging using balanced steady state free precession (bSSFP) has been accepted as a gold standard for assessing myocardial function. However, in order to assess the entire volume of the heart, this method requires multiple breath-holds to minimize respiratory motion, which may not be possible for very ill or uncooperative patients. Additionally, due to the signal averaging in segmented cine imaging, it is difficult to achieve reliable imaging in patients with arrhythmias, and even to assess diastolic dysfunction in patients with regular sinus rhythm.

Single-shot, ungated, free-breathing real-time Cartesian MRI is currently unable to match both the temporal and spatial resolution requirements of cardiac MRI. The SCMR recommends at least 50 ms temporal resolution for a clinically acceptable cardiac function assessment [1]. However, this temporal resolution is only possible by sacrificing spatial resolution, or overall image quality, with existing Cartesian real-time MRI methods. Radial acquisitions are more tolerant to undersampling than Cartesian acquisitions due to the oversampled central *k*-space and incoherent aliasing artifacts. However, the degree of undersampling required to match the temporal resolution recommended by the SCMR for cardiac studies may still lead to significant aliasing artifacts. For this reason, several parallel imaging reconstruction strategies for accelerated radial imaging have been proposed to increase the temporal resolution without sacrificing image quality, including *k*-space domain radial GRAPPA [2, 3] and image domain iterative Conjugate Gradient SENSE [4] methods. Both methods yield good image quality with very high acceleration rates.

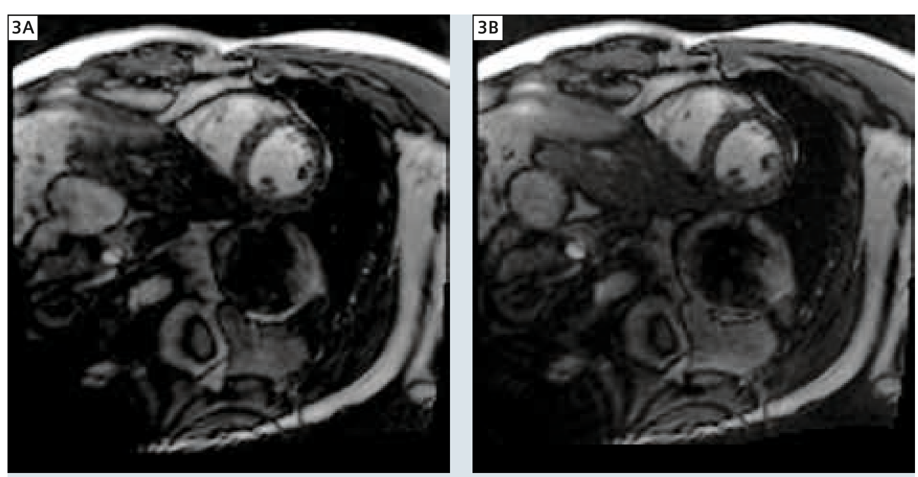


1 Depiction of the hybrid through-time/through-*k*-space radial GRAPPA calibration process. **(1A)** Through-*k*-space calibration with a small segment alone does not yield the necessary number of kernel repetitions to calculate the GRAPPA weights **(1B)** Through-time calibration, using multiple calibration frames, allows the weights to be estimated for the local geometry. The GRAPPA kernel is assumed to be uniform, and the same segment is observed through-time to obtain enough data to solve the inverse problem.

This work describes a through-time radial GRAPPA implementation capable of reconstructing images with both high temporal and spatial resolution which can be used for real-time cardiac acquisitions. Radial GRAPPA is similar to the Cartesian GRAPPA, in that missing *k*-space points are synthesized by convolving acquired points with a GRAPPA kernel. However, due to the non-uniform radial undersampling pattern in *k*-space, a single kernel cannot be used to estimate all the missing samples in the radial case. In the original formulation described by Griswold et al. [2], *k*-space is divided into small segments and reconstructed using one GRAPPA kernel per segment, where each segment was treated as a separate Cartesian GRAPPA problem. When working with the high acceleration factors needed for real-time cardiac imaging, this segmentation approach leads to errors in the GRAPPA weights as the segments no longer have the requisite quasi-Cartesian geometry. In order to generate more accurate GRAPPA weights for non-Cartesian trajectories, the through-time non-Cartesian GRAPPA can be employed [3]. In the through-time approach, individual and geometry-specific kernels are calculated for each missing sample for higher accuracy. In order to collect enough repetitions of the kernel to calculate the GRAPPA weights for the local geometry, multiple fully sampled calibration frames each exhibiting the same local geometry are acquired. For cardiac imaging, these calibration frames can be acquired as a separate free-breathing reference scan. This hybrid through-time/through-*k*-space calibration scheme is depicted in Figure 1. Using a small segment (e.g. 4 points in the readout direction and 1 point in the projection direction, or 4 × 1) combined with a long calibration scan (~30 seconds) provides the highest image quality. However, with only a nominal loss in image quality, it is possible to decrease the calibration scan time by increasing the segment size. Figure 2 shows four images reconstructed from a single undersampled dataset using different calibration configurations. Even though longer calibrations provide bet-



2 Radial GRAPPA reconstruction showing the effect of using a larger segment size to reduce the amount of calibration data required. A long calibration scan provides superior image quality, but adequate image quality can be obtained in a reasonable calibration time using a larger segment. **(2A)** Segment size 4 × 1; calibration frames 80; calibration time 30.4 seconds. **(2B)** Segment size 8 × 4; calibration frames 20; calibration time 7.6 seconds. **(2C)** Segment size 16 × 4; calibration frames 10; calibration time 3.8 seconds. **(2D)** Segment size 24 × 8; calibration frames 2; calibration time 0.8 seconds.



3 Example radial GRAPPA images with varying temporal/spatial resolutions. **(3A)** Short axis view with FOV 300 mm, image matrix 128 × 128, temporal resolution 48 ms, calibration matrix size 128 × 256, accelerated imaging matrix size 16 × 256, radial GRAPPA acceleration rate 8. **(3B)** Short axis view with FOV 300 mm, image matrix 128 × 128, temporal resolution 24 ms, calibration matrix size 128 × 256, accelerated imaging matrix size 8 × 256, radial GRAPPA acceleration rate 16.

ter quality, acceptable images can be obtained using considerably shorter calibration times (~3 seconds). Because image quality can be greatly improved by using additional through-time information, this calibration scheme was implemented for real-time acquisition and reconstruction on the scanner. Using Tim4G receiver coils, acceleration factors of 16 are achievable, resulting in a 24 ms temporal resolution with a clinically acceptable spatial resolution. Both calibration and reconstruction steps are based on a previous implementation described in Saybasili et al. [5]. The online reconstruction is multi-threaded and GPU-capable, with reconstruction times of less than 100 ms per frame. The calibration process is also multi-threaded. Figure 3 shows example short axis cardiac images acquired with radial GRAPPA acceleration rates of 8 and 16 from a normal volunteer scanned during free breathing on a 3T MAGNETOM Skyra. For assessing functional parameters such as ejection fraction, a user may choose to use lower acceleration rates and benefit from the improved image quality, whereas a higher acceleration rate with lower image quality may be preferable to appreciate detailed myocardial kinetics.

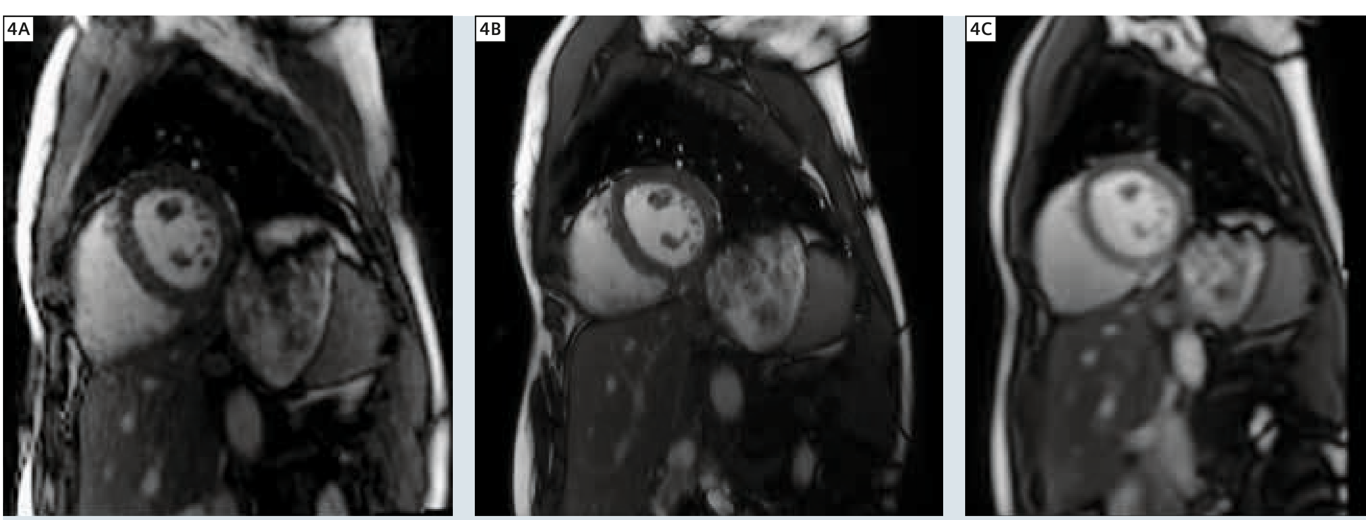
Radial GRAPPA is able to match the spatial resolution of the standard segmented bSSFP cine while providing a higher temporal resolution. Figure 4 compares short-axis cardiac images with the same spatial resolution reconstructed using radial GRAPPA, segmented cine, and Cartesian real-time sequences. While the temporal resolution of segmented cine images was 40 ms, radial GRAPPA provided 25 ms temporal resolution for the same spatial resolution. Cartesian real-time cine images could match neither the temporal or spatial resolution of the segmented cine acquisition. The radial GRAPPA images show considerable improvement compared to the standard Cartesian real-time images, both in spatial and temporal resolution. The segmented cine images are superior in image quality due to averaging, but as a result also lack the temporal fidelity during late diastole, and rely on a consistent breath-hold position.

Clinical case: Left ventricular aneurysm

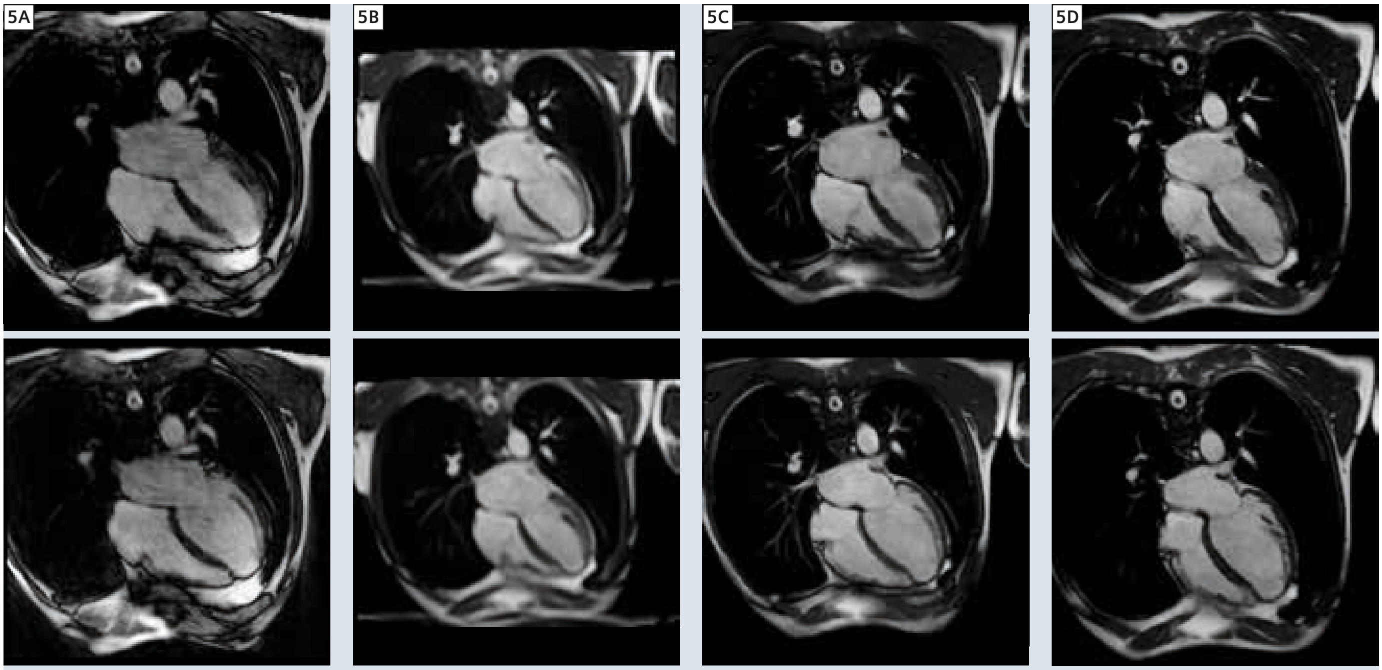
The patient is a 59-year-old male marathon runner with a past medical history of hyperlipidemia and ST-segment elevation myocardial infarction 5 months ago with symptoms starting while out for a run. The culprit lesion was in the left anterior descending coronary and the patient underwent urgent angiography with bare metal stent placement with an excellent angiographic result. Since then, the patient has resumed running and is asymptomatic, although a recent echocardiogram demonstrated moderate systolic dysfunction with an ejection fraction of 30%. The patient underwent cardiac MR imaging for assessment of ischemic cardiomyopathy. Due to the patient's intermittent arrhythmia, real-time cine imaging was employed. The chamber is enlarged, with wall motion abnormalties in the left anterior descending coronary artery territory, which is predominantly non-viable. There is an apical aneurysm without thrombus, best appreciated on high temporal resolution cine imaging (Fig. 5).

Clinical case: Diastolic dysfunction

The patient is a 64-year-old asymptomatic male with history of hypertension for which he takes two antihypertensive medications. At a routine echocardiography, he was diagnosed with grade I diastolic dysfunction as well as an aortic aneurysm. The patient was referred for cardiac MRI. Real-time cine imaging was performed due to difficulties with breathholding. Impaired myocardial relaxation (grade I diastolic dysfunction) is evident by slowed myocardial relax-



4 Mid ventricular short axis views. **(4A)** Radial GRAPPA, temporal resolution 25 ms, spatial resolution $2 \times 2 \times 8$ mm³. **(4B)** Standard product segmented bSSFP cine, temporal resolution 40 ms, spatial resolution $2 \times 2 \times 8$ mm³. **(4C)** Cartesian real-time with E-PAT factor 3, temporal resolution 50 ms, spatial resolution $2.8 \times 2.8 \times 8$ mm³.



5 **(5A)** Radial GRAPPA bSSFP cine with temporal resolution 25 ms, spatial resolution $1.7 \times 1.7 \times 8\ mm^3$, radial GRAPPA acceleration rate 16. **(5B)** Cartesian real-time bSSFP cine with E-PAT factor 3, temporal resolution 50 ms, spatial resolution $3 \times 3 \times 8\ mm^3$. **(5C)** Standard segmented bSSFP cine with temporal resolution 45 ms and spatial resolution $1.7 \times 1.7 \times 6\ mm^3$. **(5D)** High temporal resolution segmented bSSFP cine acquired in a 22 second breathhold, with temporal resolution 23 ms, and spatial resolution $1.7 \times 1.7 \times 6\ mm^3$. The top row is end diastole and the bottom row is end systole. The bulging apical aneurism is best appreciated in the high temporal resolution cine images **(5A)** and **(5D)**. The inhomogenity in (5A) is because the intensity normalization was off for the radial GRAPPA sequence and on for all other sequences.

ation on horizontal long axis cine sequences, better appreciated on the highly accelerated real-time radial GRAPPA acquisition.

Please scan the QR-Code® or visit us at **www.siemens.com/diastolic-dysfunction** to see the movies.

Conclusion

Through-time radial GRAPPA is a robust parallel MRI method capable of producing images with high spatial and temporal resolution during un-gated free-breathing real-time acquisitions. Our experiments indicate that through-time radial GRAPPA is capable of matching the spatial resolutions of segmented bSFFP cine acquisitions, while offering higher temporal resolutions, without requiring ECG gating or breath-holding. Additionally, this method outperformed Cartesian real-time acquisitions in term of both spatial and temporal resolutions. The highly optimized multi-threaded CPU implementation (and GPU implementation on supported systems) provides radial GRAPPA estimation performances of 55 – 210 ms per frame (12 – 56 ms on the GPU) for 20 – 30 coil data sets.

This work demonstrates the quality of images that are achievable using high acceleration rates with Tim 4G coils and the acquisition of separate and fully sampled reference data. The technique has the potential to directly improve patient comfort, workflow, and diagnostic potential during a cardiac exam, and deserves consideration for inclusion in current cardiac exam strategies. In addition to imaging sick or uncooperative patients, and patients with arrhythmias, the technique shows promise for assessing diastolic function, perfusion, and real time flow.

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