Research Promises for Functional Assessment: Free-Breathing / Real-Time / Non-Gated Cardiac Imaging

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Highlights

- Radial k-space acquisition improves motion robustness and enables free-breathing exams
- Iterative reconstruction provides sufficient imaging speed for real-time scans without ECG gating
- Self-navigated parametric reconstruction allows freezing respiratory or cardiac motion retrospectively

Introduction

While MRI offers excellent image-contrast properties and avoids use of ionizing radiation, it has two major limitations: 1) the data acquisition is slow compared to other imaging techniques and 2) it is very sensitive to motion. Both properties pose a particular challenge for cardiac examinations, where two concurrent types of motion occur: a) fast-paced and mostly periodic cardiac motion and b) slower but potentially irregular respiratory motion. Therefore, conventional cardiac MRI techniques use an external ECG signal to identify time points with consistent cardiac phase, which enables combining data from multiple heartbeats. In addition, acquisitions are performed during suspended respiration. In clinical practice, however, this approach fails quite often. On the one hand, it can be difficult to derive a stable ECG signal. Furthermore, the synchronization tends to fail if the patient has arrhythmia. On the other hand, many patients - in particular those in need of cardiac examination - are unable to properly hold breath, which frequently results in non-diagnostic images. As consequence, the volume of clinically requested cardiac MRI scans is still relatively low compared to other clinical MRI applications. The purpose of this presentation is to discuss several technical concepts that help to overcome these limitations and promise to improve the reliability of functional cardiac MRI.

Radial Sampling of k-Space

The pronounced motion sensitivity of MRI results from the conventionally used phase-encoding principle, which spatially resolves the object along one direction only using signal phase offsets. According to the shift property of the Fourier transformation, spatial translation of the object leads to phase modulation in the Fourier space. Thus, if the object moves during the acquisition, spurious phase offsets are added to the k-space signal that disturb the phase encoding and result in the appearance of ghosting artifacts (due to local Nyquist violation). This can be avoided by using non-Cartesian trajectories such as radial sampling, in which k-space is acquired in a spoke-wheel-like fashion. As a direct result of this sampling geometry, appearance of ghosting artifacts is impossible. Furthermore, the overlap of spokes in the k-space center results in a data-averaging effect. Thus, simply by switching the k-space acquisition to a radial scheme, the motion sensitivity of MRI is reduced significantly and it becomes possible to perform examinations during continued breathing [1]. Although this concept has been known for many years, radial MRI sequences have only recently become reliable enough for clinical scanning, in particular due to the higher technical requirements such as precise gradient timing [2,3].

In addition to providing higher motion robustness, radial sequences offer further advantages. Because a phase-encoding direction does not exist, the number of k-space lines ("spokes") can be selected independently from the desired base resolution. If only few spokes per image are acquired, the acquisition time is short but streak-alike undersampling artifacts appear. On the contrary, if the number of spokes is large, images are free from streaking but represent the time average over a relatively long acquisition window (comparable to a photograph with long exposure time). Hence, by modifying the number of spokes, a trade-off can be made between imaging speed and image quality while the underling spatial resolution remains largely unchanged.

Of particular interest in this context is the golden-angle acquisition scheme proposed by Winkelmann et al [4], in which the angle of the spokes is continuously increased by 111.25 degrees. This value corresponds to 180 degrees multiplied by the golden ratio and ensures that the next to-be-acquired spoke falls into the largest angular gap of the already acquired spokes, regardless of the number of acquired spokes. Therefore, any set of sequentially sampled spokes covers k-space quite uniformly and can be combined into an image (with the level of streaking depending on the spoke count). This means that the k-space data can be acquired continuously and that the desired temporal resolution can be adjusted solely by varying the width of the reconstruction window, i.e. without changing any acquisition parameter.

Iterative Reconstruction with Temporal Constraint

While the motion robustness achieved with radial sampling is (in most cases) sufficient to handle continued respiration, the acquisition speed is often not high enough to properly capture the (much faster) cardiac motion. When used in a real-time manner, i.e. without ECG synchronization and with fastest possible gradient switching, radial sequences with conventional gridding-based reconstruction provide acceptable image quality in the diastolic phase [5]. However, in the systolic phase, the image quality is often compromised due to the too large temporal footprint of the k-space data, which results in blurry depiction of the cardiac wall. The situation can be improved by reducing the number of spokes, which gives a higher effective frame rate but comes at the expense of stronger streak artifacts (which, at a certain level, make exact localization of the wall difficult). Bauer et al concluded that it is possible to use images obtained with this strategy for quantitative functional assessment, but noted that it would be preferable to achieve higher temporal resolution without streaks [6]. Because the maximum acquisition speed is restricted due to risk of peripheral nerve stimulation (PNS), further improvement in temporal resolution can only be achieved using advanced image reconstruction techniques.

The latter is feasible for radial sampling owing to the characteristic streak-alike undersampling artifacts. When employing a scheme that acquires a different set of spokes for each sequential frame, such as the golden-angle scheme, the streaks appear with varying orientation in each frame. Thus, when displaying the undersampled frames rapidly as a movie, the streaks show as heavy random-alike flickering. The underlying true object, in contrast, changes only "slightly" from frame to frame. Hence, by exploiting the fact that the true object information is correlated across frames whereas the undersampling leads to rapid incoherent flickering, it is possible to separate the artifacts from the true object information and to recover images without streaking artifacts. This concept is also known as compressed sensing (CS) [7,8,9]. Most

CS techniques for dynamic MRI use an iterative reconstruction scheme that enforces consistency with the measured k-space data and penalizes flickering along time in the images ("regularization"). This is achieved by formulating the reconstruction mathematically as inverse problem in the form:

$$\Phi(x) = \| \mathbf{A}x - y \|^2 + \lambda \, | \mathbf{TV}_t(x) | \tag{1}$$

where x is the image frame (or frames) to be estimated, **A** is an operator that synthesizes hypothetical k-space data from the given image estimate x, y is the actually measured k-space data, $\mathbf{TV}_t(x)$ is a temporal regularization operator (usually the temporal total variation), and λ is a scaling factor. A solution is found by minimizing the equation numerically with an iterative optimization algorithm, such as the conjugate gradient (CG) algorithm [10]. During each iteration, the solution is improved until sufficient reconstruction quality is achieved. For this reason, iterative reconstruction approaches take much longer than conventional MRI reconstructions.

Many of the existing CS methods for dynamic MRI share this basic equation, but differ in the details regarding how the temporal correlation between frames is incorporated. In the methods described by Adluru et al [11] and Feng et al [12,13], the regularization is applied to all time points simultaneously by penalizing the L1- or L2-norm after applying a temporal difference operator (thus, subtracting all adjacent frames and summing over their magnitude values). The method described by Uecker et al [14,15] instead applies the regularization only to one preceding time point (followed by median filtering over 5 preceding time points). While potentially less efficient, incorporating only retrospective samples allows that results can be displayed in real-time while the acquisition is still running (assuming that the reconstruction can be performed sufficiently fast, e.g. using GPUs [16,17]), which promises that cardiac MRI exams can be done interactively in an ultrasound-alike fashion in the near future. The majority of cardiac CS techniques additionally incorporate the parallel-imaging concept to achieve higher scan speed, i.e. they make use of the spatial encoding capabilities of the receive coils. Based on equation (1), it is relatively simple to integrate parallel imaging following the CG-SENSE formalism described by Pruessmann et al [18], by including a multiplication with the coil profiles into the operator **A**. Coil sensitivity profiles can be estimated from the imaging data itself as the k-space center is heavily oversampled by radial trajectories. Seiberlich et al described that a similar technique can also be realized for k-space-based parallel imaging (GRAPPA) by making use of temporal correlations during the calibration of the GRAPPA coefficients ("through-time radial GRAPPA") [19,20].

By combining radial sampling with temporally-constrained iterative reconstruction and parallel imaging, streaking artifacts can be suppressed up to a quite high level of undersampling, which directly translates into short acquisition time per image frame. Several groups have reported imaging speed of up to 20-40 ms per frame [14,13,19], which for most patients is sufficiently fast to image the heart in real-time without ECG gating (and breath holding). This does not only eliminate the lengthy procedure of setting up the ECG electrodes but also provides reliable imaging during severe arrhythmia, which often disturb conventional gated imaging sequences (despite existing arrhythmia-detection mechanisms). It should be noted, however, that the reported frame rates hold only true if the imaged object fulfills the assumption about the type of motion that is embedded in the reconstruction equation, i.e. that subtracting adjacent frames leads to sparse representation of the object. If this assumption is violated, e.g. by abrupt translation of the bulk object, the image quality breaks down and streaks appear comparable to conventional gridding reconstruction. However, in clinical practice such bulk movements appear rarely over longer periods of time, and successful applications of radial real-time sequences have been described with FLASH [21] as well as bSSFP contrast [22,23].

Self-Navigation and Extra-Dimensional Reconstruction

An inherent complication of cardiac real-time imaging without breath-hold consists in the varying location of the heart due to the patient's respiration. While tolerable for visual qualitative inspection of the exam, the changing position can pose a significant problem when evaluating images quantitatively for functional assessment. Therefore, it is necessary to perform image registration prior to the analysis [24], which, however, can only correct for in-plane motion. As a second problem, free-breathing exams lead to inconsistencies in multi-slice scans, because it cannot be guaranteed that the different slices are acquired in the same respiratory phase. Therefore, the heart position usually jumps (including the through-plane position) when scrolling through the slice stack.

Due to the continuous acquisition of the k-space center, radial sequences can be used to solve this problem. Because the (dark) lung volume that is visible in the images changes during respiration, also the total image power changes (i.e. the sum over all pixel intensities), which is represented by the signal value at the k-space center. Thus, by looking at the central sample of sequentially acquired spokes, which all pass through k-space center, it is possible to generate a respiration curve that shows the patient's breathing pattern during the exam [25]. This curve is typically noisy and needs to be properly filtered [26], but it often provides a more reliable breathing detection than external sensors such as respiration bellows [27]. In addition to estimating the respiratory motion, the same principle can also be used to simultaneously detect cardiac motion. This can be achieved by analyzing the signal from only individual localized receive-coil elements [28]. Thus, by using the signal from a coil element located above the diaphragm it is possible to detect respiration, whereas the signal received by an element located above the heart allows detecting contraction of the heart. Suited coil elements can be identified automatically by analyzing the frequency spectrum and selecting coils with typical frequencies for respiratory and cardiac motion. Of note, both the respiration and cardiac curves are obtained simultaneously with the imaging data, without increasing the scan or patient-preparation time ("self-navigation").

Once the two motion states are available, the information can be incorporated into the image reconstruction for motion compensation. When following a conventional gating-type approach, i.e. accepting only data with consistent respiratory and cardiac state, very long acquisition time would be needed to collect sufficient data for each gate. However, it is again possible to use a combination of compressed sensing and parallel imaging for improving scan efficiency, as recently described by Feng et al [29,30]. In the first step, the sequentially acquired spokes are sorted into data bins according to their estimated respiratory and cardiac state, which will give a two-dimensional array of k-space data bins, with each entry corresponding to a different combination of a respiratory and cardiac motion state (r,c). In most cases, the k-space data in each individual bin is highly undersampled. Because correlations exist between the individual motion states (e.g., across different cardiac phases), it is possible to apply the same iterative-reconstruction principle as described in the previous section for removal of the streak artifacts. In this case, however, the regularization is not applied along time (as for real-time imaging) but along the two motion-state dimensions. Thus, instead of reconstructing a dataset with dimensions (x,y,t), this approach will create a 4D dataset (x,y,r,c) with 2 parametric motion dimensions (ranging from end-inspiratory to end-expiratory position, and from diastolic to systolic phase).

When the iterative reconstruction has been finished, the respiratory and cardiac curves can be used to map the parametric frames back to the original time dimension, yielding an image series comparable to a real-time scan. However, because data from distant time points are grouped in the reconstruction (thus, removing the need to acquire the data as fast as possible), higher spatial resolution can be obtained. Also, higher temporal fidelity can be achieved for resolving the cardiac cycle, because the temporal footprint of each frame can be (theoretically) as small as one TR cycle. Most importantly, however, it is possible to retrospectively freeze individual components of the motion [31,32]. By mapping only the cardiac dimension back to the time domain and keeping the respiratory state invariant, a cardiac CINE movie is obtained without respiration-related movement of the heart (although the acquisition was done during free breathing), which eliminates the need for later image registration. Furthermore, it is also possible to freeze the cardiac motion while playing out the respiratory motion. This enables to analyze how the heart is deformed during the respiration cycle, in particular the interventricular septum, which is not possible with conventional cardiac MRI sequences.

Because a parametric respiratory dimension is available, also sequential multi-slice acquisitions can be retrospectively displayed with consistent location of the heart in all slices, which enables whole-heart free-breathing non-gated cardiac exams. However, it is even possible to go one step further and perform self-navigated scans using 3D volumetric sequences with isotropic resolution. For this application, 3D sphere-shaped radial trajectories need to be used [33], so that an independent self-navigation signal can be derived for every spoke (stack-of-stars trajectories would be too slow to capture the cardiac motion). Several options exist for ordering the spokes on the sphere, including the spiral phyllotaxis scheme described by Piccini et al [34], which has demonstrated convincing results with self-navigated radial bSSFP sequences. The key advantage of extending the self-navigation approach to 3D consists in the simplification of the acquisition workflow. Because the spatial resolution is isotropic, the orientation can be selected arbitrarily during the acquisition, and desired views can be generated from the 5D image set (x,y,z,r,c) via retrospective multi-planar reconstruction (MPR). This eliminates the need of identifying correct scan orientations, such as the short-axis or 4-chamber view, during the exam and makes the procedure less error prone. Furthermore, because data can be acquired over a long period of time with the self-navigated approach, it is possible to achieve sufficiently high spatial resolution for also imaging the coronary anatomy [35,36]. Hence, in the future many of the cardiac protocols that are currently acquired as individual sequential scans may be replaced by a single free-breathing non-gated continuous acquisition over several minutes, from which functional as well as anatomical information can be extracted in multiple orientations and for varying respiration states.

Conclusion

Several technical developments were discussed that can be combined in a modular fashion to improve the robustness of cardiac MRI. The use of radial sampling reduces the overall motion sensitivity and allows for flexible retrospective reconstruction if combined with golden-angle ordering. Iterative reconstruction with temporal regularization provides high scan speed by exploiting correlations in images series. Additional acceleration is achieved by integrating self-calibrated parallel imaging, which enables imaging the heart without ECG synchronization. Finally, by extracting motion information on the respiratory and cardiac state from the k-space center, it is possible to reconstruct self-navigated extra-dimensional image sets that allow freezing respiratory and/or cardiac motion during the display of the images. Currently, all of these techniques are still at a research stage and not clinically available, but their feasibility has been demonstrated using standard MRI hardware, so that clinical translation could be possible within the next few years.

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