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REVIEW ARTICLE

Accelerated MRI for the assessment of cardiac function

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ABSTRACT

Heart disease is a worldwide public health problem; assessment of cardiac function is an important part of the diagnosis and management of heart disease. MRI of the heart can provide clinically useful information on cardiac function, although it is still not routinely used in clinical practice, in part because of limited imaging speed. New accelerated methods for performing cardiovascular MRI (CMR) have the potential to provide both increased imaging speed and robustness to CMR, as well as access to increased functional information. In this review, we will briefly discuss the main methods currently employed to accelerate CMR methods, such as parallel imaging, k-t undersampling and compressed sensing, as well as new approaches that extend the idea of compressed sensing and exploit sparsity to provide richer information of potential use in clinical practice.

INTRODUCTION

Heart disease is an important public health problem; it is a major source of morbidity and mortality worldwide. The mechanical pump function of the heart is a complex physiological process, requiring the co-ordination of many different kinds of systems over a wide range of scales. Many different diseases can adversely affect cardiac function, with associated loss of the patient's functional capacity. Thus, the assessment of cardiac function is an important component of the diagnosis and management of patients with heart disease. Cross-sectional imaging methods, such as echocardiography, can be used to quantitatively assess the global function of the heart, particularly through estimation of the ventricular volumes at end-diastole and end-systole, along with associated measures such as the ejection fraction. Cross-sectional imaging methods can also provide qualitative estimates of the regional wall motion, particularly through observation of the radial motion or thickening of the heart wall in the images.

MRI has been steadily gaining increased clinical acceptance as a tool to assess cardiac function, although it is still not part of routine clinical practice.[1–3] MRI can provide both static and dynamic image data on the structure and function of the heart, as well as other useful information such as imaging-based measurements related to tissue characterization, blood flow and perfusion. However, the relatively low imaging speed of cardiac MRI imposes limitations to spatial and temporal resolution, and volumetric coverage, when imaging the moving heart. During recent years, various techniques have been developed to overcome these limitations based on parallel imaging and image compressibility ideas. In this review, we will briefly summarize some fast imaging approaches to improve the performance of cardiovascular MRI (CMR) techniques and thus the assessment of cardiac function with MRI, including both well-established techniques, such as parallel imaging and k-t acceleration, and more recent ones, such as compressed sensing and extra-dimensional reconstruction.

Conventional cardiac MRI

The principles of MRI and its application to the cardiovascular system are well described in many textbooks and reviews.[1] We will here provide just a brief summary of the basic imaging concepts and the associated acquisition time requirements, as a basis for further discussion of ways being explored to accelerate the imaging process.

MRI uses magnetic fields and radio waves to encode the spatial frequencies ("k-space") of the object being imaged.[4] Conventional MRI techniques sequentially sample k-space according to the Nyquist criterion, which requires as many k-space samples as pixels to be reconstructed. The image reconstruction process in this case is very simple and robust, consisting of applying an inverse Fourier transform to the acquired data, according to the sampling trajectory. However, to achieve high spatial resolution and whole-heart coverage, a substantial amount of data needs to be acquired, which can be particularly challenging in the

presence of cardiac and respiratory motion. If the imaging is fast enough, the patient may be able to suspend respiration during the data acquisition, but this still leaves the cardiac motion to be dealt with. Speeding up the image acquisition still further, to a fraction of a cardiac cycle ("real-time imaging"),[5] can reduce the effects of cardiac motion but at the cost of reduced image quality, due to the limited amount of imaging data that can be acquired in such a short time. Alternatively, if the cardiac cycles are sufficiently similar to each other, we can synchronize the data acquisition with the cardiac cycle ("gating") and then combine the data acquired from multiple cardiac cycles in order to reconstruct "segmented" cine image sets with multiple high-quality individual sequential image frames spanning an average cardiac cycle.[6]

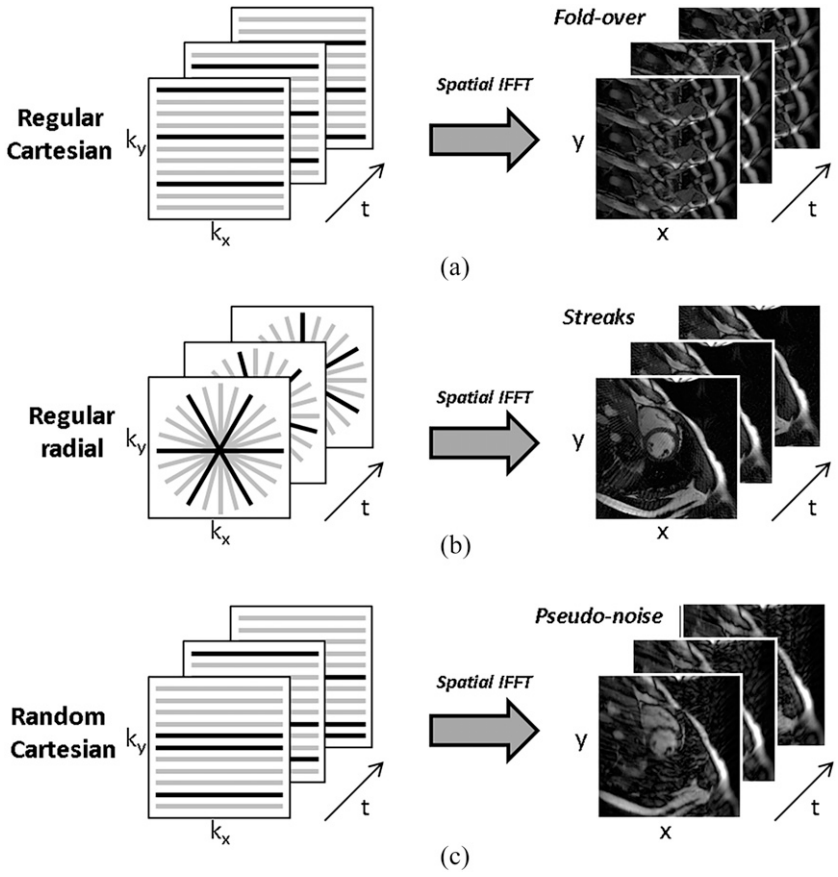
Although conventional cardiac-gated MRI can produce useful images in most subjects, there can be problems in combining the imaging data from multiple heart beats if those cardiac cycles differ significantly from each other, *e.g.* due to respiratory motion or arrhythmias (which are both common problems in patients with heart disease); the resulting inconsistency in the acquired data can lead to blurring and other image artefacts. We can reduce the problem by rejecting heart beats that differ too much from the rest, but this prolongs the imaging and may not work well with some common arrhythmias such as atrial fibrillation; we also lose potentially useful information about the abnormal beats themselves. We can further synchronize the imaging process with respiration as well, *e.g.* acquiring data for image reconstruction from only a relatively stationary portion of the respiratory cycle, in order to permit reconstructing high-quality dual-gated cine or volumetric images in the presence of free breathing. However, this prolongs the imaging process and may not work well with inconsistent breathing patterns; we also lose potentially useful information about the interaction of breathing with the cardiac cycle. We will see below how using "compressed sensing" or "sparsity-based" methods can improve MRI in the presence of breathing or arrhythmias.

Accelerated cardiac MRI

k-space undersampling

As mentioned above, conventional sampling theory tells us that in order to reconstruct an arbitrary image, we would need to sample approximately as many locations in k-space as there are reconstructed points in the image. Since the process of measuring the data in k-space takes time, this sets a basic limit

Figure 1. k-t undersampling techniques used for imaging of cardiac function. Top row (a) shows a regular Cartesian undersampling (*e.g.*, parallel imaging and k-t BLAST/SENSE), which involves (for example) acquiring one out of every four lines and results in discrete foldover artefacts in the image reconstructed with an inverse fast Fourier transform (IFFT). Middle row (b) shows uniform radial undersampling, which leads to low-value streaking artefacts. Bottom row (c) shows random Cartesian undersampling, which leads to noise-like artefacts. The last two sampling schemes are appropriate for the application of compressed sensing.



as to how fast we can acquire the image data. One approach that has been used to reduce the data acquisition time is to use modified magnetic field gradients to enable sampling data on alternative trajectories in k-space. For example, spiral trajectories can enable single-shot (or reduced number) data acquisitions for imaging.[7] However, this approach has other associated technical challenges, and it has not been widely used clinically.

The other approach, which is the main topic of this review, is to reduce the amount of k-space data acquired and to exploit constraints and prior information to reconstruct images with full information from the undersampled data. With conventional Cartesian sampling of k-space, if we attempt to shorten the data acquisition time by making fewer measurements and decreasing the density of the sampled locations, we will decrease the size of the region that can be unambiguously reconstructed and thus introduce "spatial aliasing" of the images, with folding over into the other side of the reconstructed image and superimposition on the "true" image of any structures that extend beyond this region (Figure 1a). With radial imaging, simply decreasing the number of different directions measured in k-space in order to reduce acquisition time will also lead to related aliasing artefacts, which manifest as low-intensity streaks (Figure 1b). By taking random samples on a Cartesian grid, the aliasing artefacts take the form of noise-like interference that adds incoherently to the original image (Figure 1c). The last two approaches are said to be incoherent, since the overall image features are preserved and the undersampling artefacts take on low-intensity values and are spread out over the whole image without replicating image components. If we seek to accelerate MRI through reduction in the amount of data acquired, we must also correct for the effects of the "missing" data; simply substituting zeroes for the missing data usually has poor results. Current approaches (described further below) used to correct for the missing data in image reconstruction include: (1) parallel imaging that makes use of multiple simultaneous acquisitions with different coils to remove regular aliasing, (2) k-t acceleration exploits image sparsity in the temporal frequency domain to reduce the degree of regular aliasing and (3) compressed sensing exploits image compressibility ("sparsifiability" with a suitable transform) to remove irregular aliasing artefacts. Both k-t acceleration and compressed sensing exploit image compressibility/sparsity, but in different ways. The former approach uses regular undersampling with a linear reconstruction approach that is solved by inverting a matrix, whereas the latter uses irregular/incoherent undersampling with a non-linear reconstruction that is effectively accomplished by using a thresholding operation to remove noise-like aliasing artefacts.

Parallel imaging

The receivers used to detect the MR signal are typically composed of arrays of individual coil elements. The additional effective spatial information that can be provided by the different spatial sensitivity patterns of the different coil element permits the use of image reconstruction methods that can produce images without associated aliasing, even in the presence of some degree of undersampling of k-space. This approach, called parallel imaging,[8,9] can be used to speed-up

Figure 2. Parallel imaging principle. Regularly undersampled multicoil data can be reconstructed without the aliasing seen in the original separate coil images (top row), using the corresponding coil sensitivity information (bottom row). The maximum acceleration (or undersampling) is determined by the number of independent coils along the accelerated dimension and is limited by noise amplification in the inverse reconstruction problem, due to overlapping of coil sensitivities.

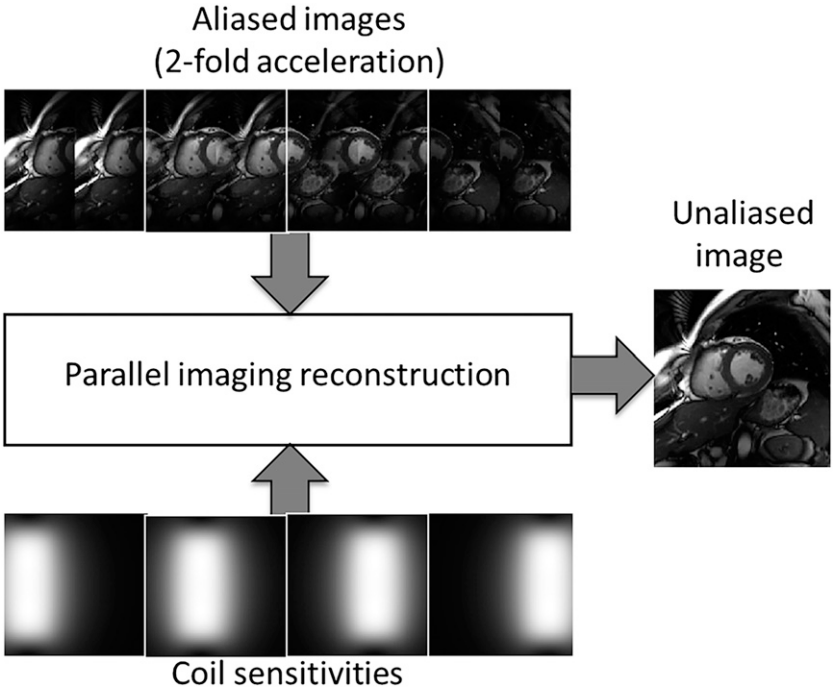


image acquisition and is widely used in conventional cardiac MRI (Figure 2). There are two principal approaches that have been used for implementing parallel imaging: (1) image-based [*e.g.* sensitivity encoding (SENSE™) method] and (2) k-space type [*e.g.*, generalized autocalibrating partially parallel acquisitions (GRAPPA) method]. The basic principle of the use of parallel imaging in the image domain is that while the use of inadequate density of sampled locations in the k-space will lead to aliasing of the resulting image, the separate images reconstructed from the signals detected with the different coil elements will have different relative intensities of the aliased component of the images. SENSE[9] uses this property to separate the aliased components from the underlying true structures in the image, enabling a corrected reconstruction of the full region being imaged. When applied in the k-space domain, we can use the varying spatial response patterns of the coil elements to better estimate the corresponding different contributions to the "missing" data points from the neighbouring measured k-space data and then use the expanded data set to reconstruct the full imaged region. GRAPPA[10] estimates a convolution kernel in k-space using fully-sampled low resolution data, which is then used to reconstruct each non-sampled k-space point. SENSE requires the explicit estimation of coil sensitivities, which is usually performed using a separate low resolution acquisition or by fully sampling the centre of k-space. GRAPPA performs a data-to-data fitting, which does not require the explicit calculation of coil sensitivities. The main difference between SENSE and GRAPPA is in the size of the reconstruction kernel in k-space. The image space reconstruction performed by SENSE effectively uses a full k-space reconstruction kernel, which is accurate but very sensitive to noise amplification. GRAPPA uses a finite k-space reconstruction kernel (usually limited to a few neighbouring k-space points), which increases the robustness to noise at the expense of data reconstruction errors.

The maximum acceleration factor in parallel imaging is limited to the number of independent coils along the phase-encoding dimension. Any spatial overlap between the spatial sensitivity patterns of the coils will introduce noise amplification in the reconstruction. This is commonly known as the "g-factor" and represents the major limitation for parallel MRI, which cannot be removed even for the case of a large number of coils.

Temporal SENSE[11] and temporal GRAPPA[12] combine the undersampled k-space data from adjacent frames in dynamic imaging to obtain a fully sampled reference for coil sensitivity calibration without the need of acquiring a separate reference or a fully sampled central k-space region. In this case, the k-space sampling pattern is shifted over time to acquire complementary information that can be combined along the time dimension to obtain the fully sampled reference.

Parallel imaging techniques can benefit from moving to higher magnetic fields, such as 3 T, which provide higher baseline signal-to-noise ratio (SNR) that can be traded off for acceleration. For example, SENSE with three-fold acceleration was found to provide a better contrast-to-noise ratio at 3 T

Figure 3. Accelerated cardiac cine imaging using (top) two-dimensional (2D) acquisition with two-fold GRAPPA acceleration and (bottom) three-dimensional (3D) acquisition with four × two = eight-fold 2D-GRAPPA acceleration. The 2D acquisition was performed during seven breath-holds and the 3D acquisition during a single breath-hold due to the increased acceleration factor.

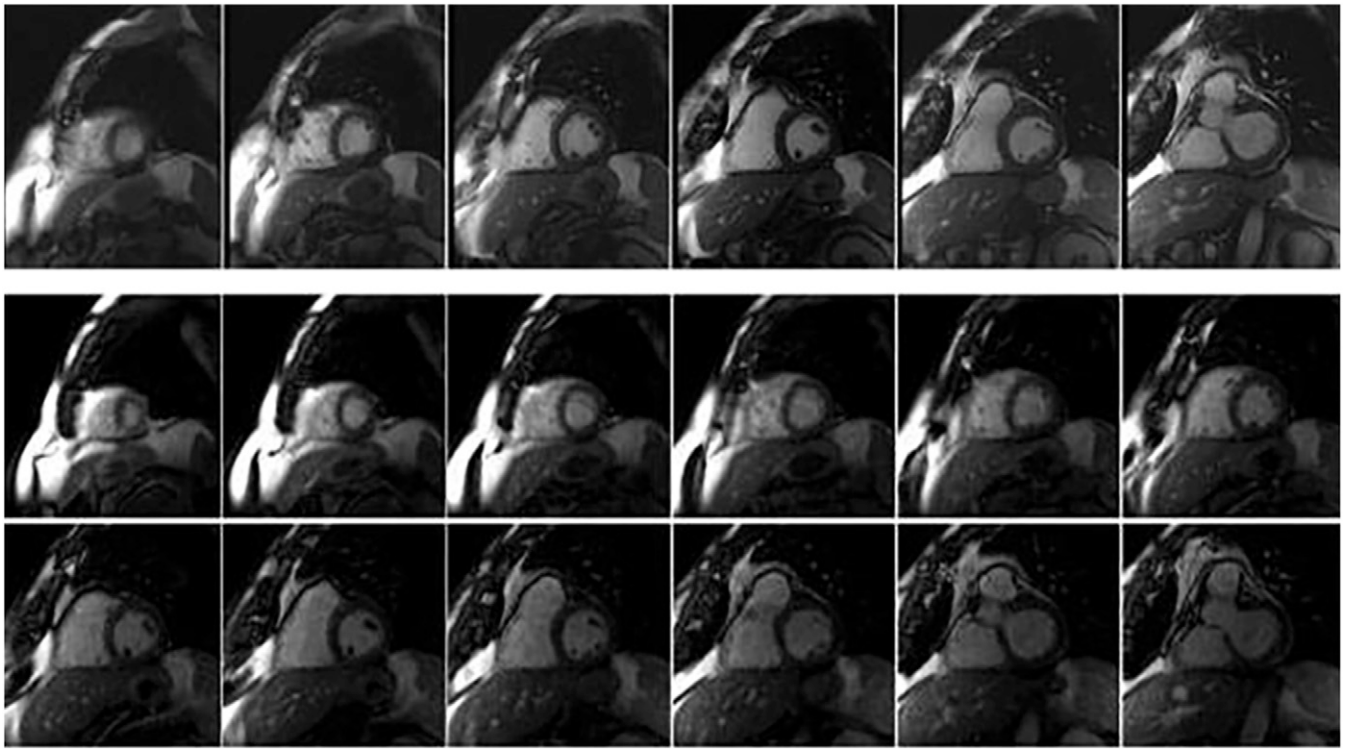
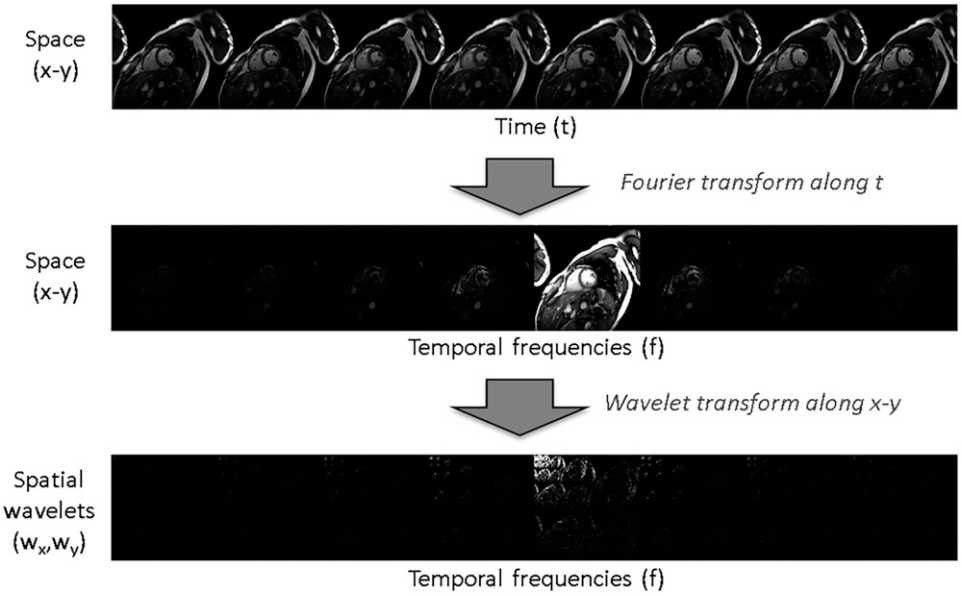


Figure 4. Cardiac cine data sets are very compressible or sparse after appropriate transformations. For example, applying a temporal Fourier transform produces a sparse representation in the *x-y-f* domain, where *f* is the temporal frequency, since cardiac motion is quasiperiodic. Additional sparsity can be introduced by using a spatial transform, *e.g.* wavelets, that exploits correlation between pixels.



than at 1.5 T on steady-state free precession (SSFP) cardiac cine imaging.[13] Three-dimensional (3D) acquisitions are particularly well suited for the application of parallel imaging, since they offer higher baseline SNR and enable the use of two-dimensional (2D) acceleration along the two phase-encoding dimensions, which significantly reduces g-factor noise amplification as compared with the same one-dimensional acceleration factor. GRAPPA with four × two-fold acceleration has enabled 3D cardiac cine imaging with whole-heart coverage within a single breath-hold (Figure 3).[14]

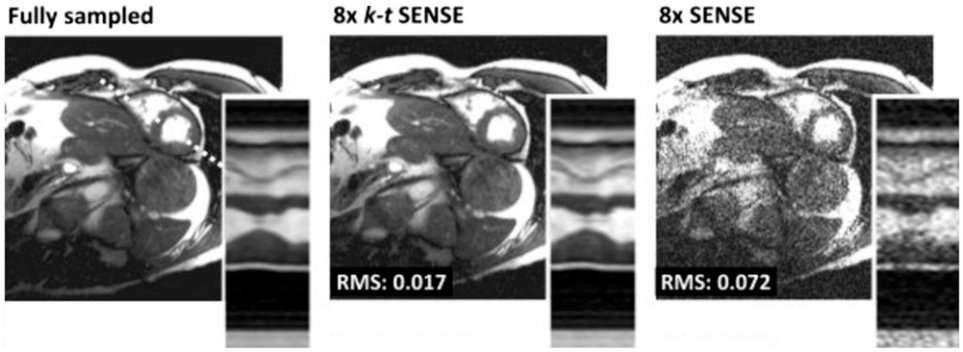
k-t acceleration

The introduction of k-t methods represented the first attempt to exploit the extensive temporal correlations in dynamic cardiac MRI. Such dynamic image series are sparse in an appropriate transform domain, such as the temporal frequency domain, where the significant information is captured in a few coefficients while most of the rest are zero or close to zero and can be discarded safely (Figure 4). This is the main principle used for data compression, and it enables the reconstruction of images from undersampled data, since the effective number of unknowns is reduced. k-t acceleration methods[15] sample k-t space in such a way that signal overlap is minimized in a suitable transform domain, where the object is known to be sparse. One example is the combined spatial domain and temporal frequency domain (*x-y-f*), where the dynamic heart image data set is sparse, since only the pixels corresponding to the heart require full temporal bandwidth, whereas most of the other pixels require only a few frequency components. The reconstruction first estimates the sparse representation in the transform domain and then uses a linear filter to recover the unaliased representation. For example, k-t broad use linear acquisition speed-up technique (BLAST)[16] uses a shifted regular undersampling pattern at each point, as shown in Figure 1 (top row), to minimize signal foldover in the *x-y-f* space and removes the remaining aliasing by using a previously estimated sparse representation (obtained from a series of fully sampled low spatial resolution acquisitions). k-t SENSE[16] extends this idea to include coil sensitivities in the linear filter. k-t GRAPPA replaces the SENSE-based reconstruction by a GRAPPA-based reconstruction which does not need to explicitly compute coil sensitivities.[17] k-t principal component analysis[18] replaces the temporal Fourier transform by a temporal principal component (principal component analysis) operation to improve sparsity of representation. Figure 5 shows the improved performance of k-t SENSE over SENSE for a highly accelerated cardiac cine example.

Compressed sensing and sparsity-based methods

Compressed sensing[19,20] also exploits sparsity in a transform domain (such as the combined temporal frequency and spatial wavelet domain in Figure 4) but in a different way than k-t methods. Instead of reducing the overlap in the transform domain, compressed sensing uses incoherent sampling and non-linear reconstruction, where k-t space is sampled in such a way that the aliasing artefacts add incoherently with low value to the image representation, without replicating information, and the reconstruction algorithm effectively thresholds out the low-value incoherent aliasing artefacts, to keep only the coefficients with significant image information.[21,22] Random Cartesian and uniform radial undersampling schemes (Figure 1) are examples of incoherent sampling. For the case of dynamic MRI, a different k-space sampling pattern must be used for each temporal frame in order to introduce incoherence along the temporal

Figure 5. Fully sampled and eight-fold accelerated cardiac cine images, using k-t SENSE and SENSE. The x-t profiles (insets) correspond to the dotted line in the fully sampled image. k-t SENSE significantly improves signal to noise ratio without introducing significant temporal degradations (see the x-t profiles), when compared with SENSE. Adapted from Tsao et al[15] with permission from John Wiley and Sons.



domain and to enable the exploitation of temporal sparsity. A clear advantage of compressed sensing over k-t methods is that the sparse representation does not need to be known *a priori*. The only assumption compressed sensing makes is that the image is sparsifiable, but there is no need to know just how sparse the image is or the location of the pixels with significant information. We can further accelerate the image acquisition process by combining the sparsity approach with parallel imaging, taking advantage of the additional spatial information provided by the different receiver coil elements and building this directly into the reconstruction process, using joint multicoil sparsity rather than coil-by-coil sparsity.[23–25] Figure 6 shows an example of the application of such a combined approach for real-time cardiac cine imaging with high temporal resolution.[26] An image data acquisition approach of particular utility for MRI of cardiovascular and other dynamically changing structures is to use continuous radial sampling acquisitions, with successive "golden angle" incrementation of the direction of sampling in k-space so that it never repeats any particular direction, yet, the density of the sampling remains approximately uniform.[27] The golden-angle radial sampling scheme is particularly suitable for sparsity-based reconstruction, since it enables incoherence along all spatial and temporal dimensions.[28] The data points at the centre of k-space contain information about the total strength of the signal. The repeated sampling of the centre of k-space that the radial acquisition approach provides allows us to use this data to monitor the changing signal intensities due to the cardiac and respiratory cycles; this can be used for "self-gating" and to assign a particular cardiac and respiratory cycle phase to each set of radially sampled data. We can now sort the continuously acquired data into "bins" corresponding to different combinations of cardiac and respiratory phases (Figure 7). The amount of such data that can be acquired in each bin in a reasonable image acquisition time would be inadequate for independent reconstruction of good quality individual image frames with conventional image reconstruction methods. However, with sparsity-based approaches, we can treat the whole data set as a multidimensional "object" to be

Figure 6. Representative images from real-time cardiac cine MRI with in-plane spatial resolution of 2.5 mm and temporal resolution of 40 ms, using k-t SPARSE-SENSE (combination of compressed sensing and parallel imaging based on Cartesian k-space sampling) with eight-fold acceleration.

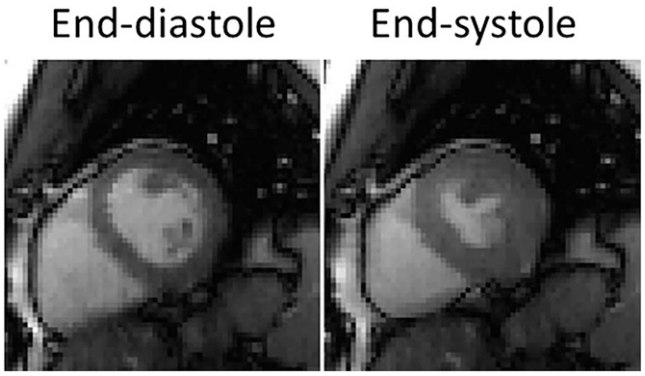


Figure 7. Respiratory and cardiac motion signals may be derived directly from two-dimensional and three-dimensional radial data sets, using temporal evolution of the central k-space position, which reflects the total detected signal. Separation of respiratory and cardiac motion is feasible by using signals from different coils.

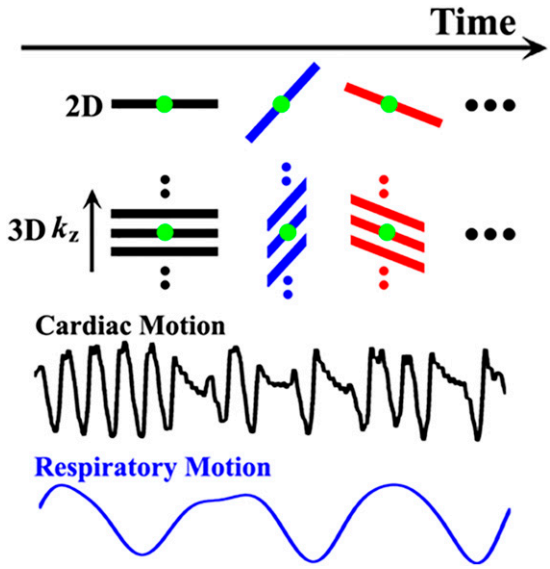
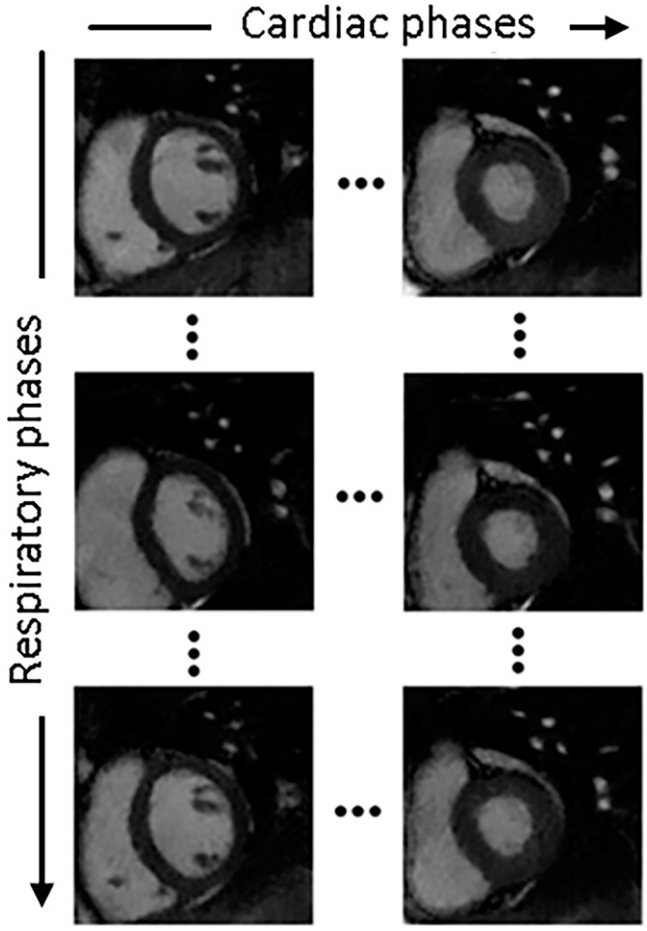


Figure 8. XD-GRASP sorts the acquired golden-angle radial data into undersampled cardiac and respiratory motion dimensions and performs a multidimensional sparse reconstruction to resolve unaliased images of different cardiac and respiratory phases.



reconstructed; the relatively high degree of correlation expected along these different dimensions makes it possible to perform a high-quality joint reconstruction of the multidimensional image. Extra dimensional golden angle radial sparse parallel MRI (XD-GRASP) was recently introduced to as a means to reconstruct additional cardiac and respiratory dimensions from a continuously acquired data set by exploiting multidimensional sparsity[29] (Figure 8). Many patients with heart disease have difficulty suspending respiration, which significantly degrades conventional CMR images; this new XD-GRASP approach permits acquisition of better quality images in such patients. The improved tolerance to respiratory motion of the new approach also permits the acquisition of large data sets (*e.g.* 3D angiographic images) that would not be possible within a breath-hold with conventional imaging. In conventional imaging, respiratory motion is usually dealt with by only acquiring data within a relatively narrow portion of the respiratory cycle; the new approach permits acquiring and using all of the data. Many patients with heart disease also have arrhythmias, which can significantly degrade conventional images; we can use a similar approach to also reconstruct high-quality images in the presence of arrhythmias (Figure 9). XD-GRASP thus permits not only acceleration of conventional imaging, through permitting image reconstruction from smaller data sets, but also allows reaching other goals such as incorporating motion compensation into the image reconstruction. The resulting images also permit new kinds of image analyses, such as separation of the effects of cardiac and respiratory motion.

New methods that extend the idea of sparsity to matrices, such as the low-rank plus sparse matrix decomposition,[30] can be directly applied to dynamic cardiac MRI to separate the relatively static background component from the physiological dynamic component. These methods can accommodate even a moving background and self-learn motion fields.

Applications of accelerated cardiac MRI to cardiac function evaluation

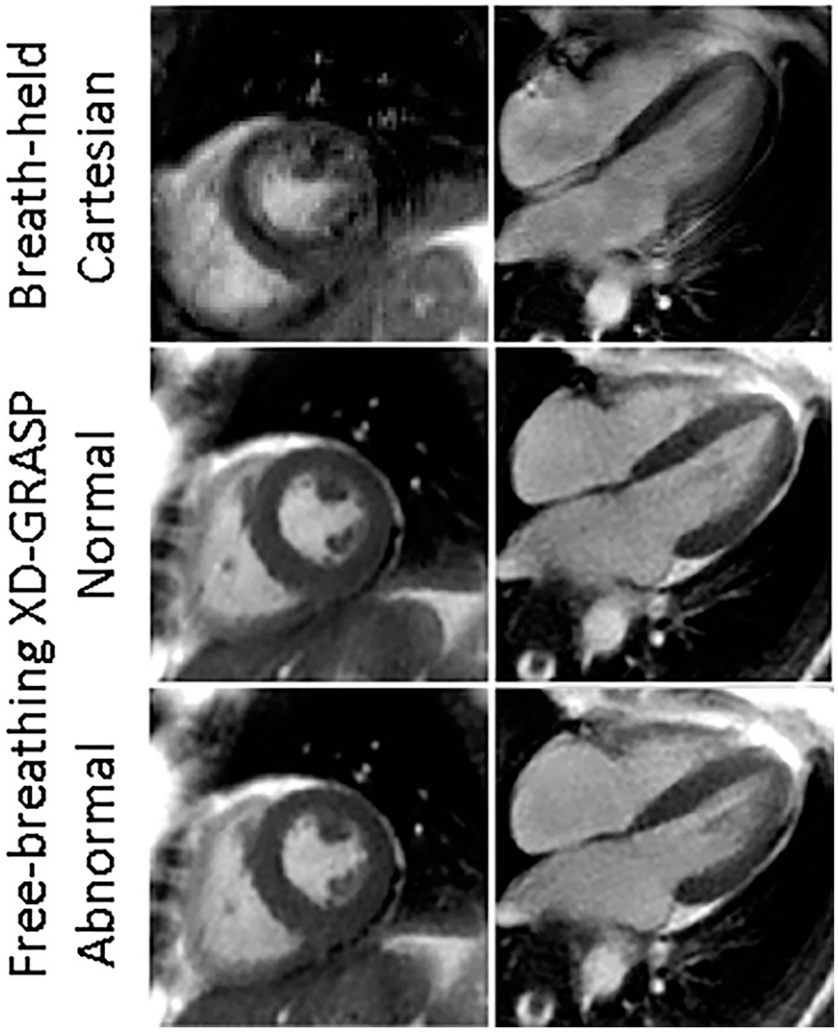
The ability to perform cardiac functional imaging faster, using the accelerated methods described above, provides a way to shorten the imaging time, which is better from the points of view of both patient comfort and imaging system utilization. Another useful direction is to use the acceleration to gather more information per unit time, *e.g.* to increase spatial resolution and volumetric coverage. These two directions are already producing clinically useful advances and are the main reason for the current worldwide use of parallel imaging in cardiac MRI and the ongoing active development of compressed sensing techniques for cardiac MRI applications.

Parallel imaging is already routinely used in clinical practice with 2D scans and has been fundamental to reduce the number of required breath-holds in cardiac MRI. Furthermore, it has enabled promising new applications, such as improved real-time 2D imaging[31] and 3D imaging with whole-heart coverage within a single breath-hold.[14]

Compressed sensing has demonstrated higher performance than parallel imaging in several initial cardiac imaging studies.[26,32–34] However, it is not yet widely used in clinical practice, which is due, in part, to the current lack of fast image reconstruction approaches and to the need to specify additional reconstruction parameters, such as the weight of the sparsity constraint relative to the data consistency constraint. Thus, there is still only limited information on how they will perform in real-world clinical settings; for example, a compressed-sensing-based single-breath-hold MRI method for assessment of left ventricular (LV) volumes and function has been found to have very good agreement with conventional multi-breath-hold MRI.[35] However, with ongoing advances in the development of more powerful but affordable computer power and with more experience in the design of reconstruction approaches for cardiac MRI, compressed sensing approaches are likely to play an increasing role in clinical CMR.

The more recent sparsity-based imaging methods for cardiac MRI can also potentially add new value for the assessment of cardiac function. For example, XD-GRASP is able to capture clear cine

Figure 9. Short-axis and long-axis views of a representative systolic phase from cardiac cine image sets in a patient with premature ventricular contractions (PVCs), using conventional breath-held Cartesian MRI (top row) and free-breathing XD-GRASP with reconstruction of respiratory and cardiac motion dimensions. XD-GRASP both eliminates blurring and enables separate visualization of the dynamics of normal (middle row) and PVC (abnormal; lower row) beats.



images even in the presence of free breathing and to provide tolerance to arrhythmia, through the joint reconstruction of an extended cardiac image set with additional physiological "dimensions". Although there has not yet been a systematic evaluation of the degree of improvement that will be found in practice with a routine mix of clinical patients, breathing and arrhythmias are common enough problems in clinical CMR that the greater robustness of these new imaging methods is likely to provide a significant clinical advantage beyond simple acceleration of the imaging. Furthermore, the separate resolution of respiratory and cardiac cycle phases in the expanded reconstructed image sets provides novel information on the interaction of the cycles, such as the associated interaction of the right and left ventricles during respiration, which is likely to provide novel insights into physiology and pathophysiology (Supplementary Video A).

Extending the accelerated imaging methods to the acquisition of fully cardiorespiratory-gated 3D data sets is now possible in reasonable time. Although still under development, this could provide significant improvement in MR angiography, with the potential of even providing image quality comparable with CT angiography but without the need for radiation or contrast agent administration.

The extension of the sparsity-based methods to MRI velocity imaging is still in its early stages, but the potential of bringing the associated imaging time down into a more practical range would open up the possibility of using this kind of functional imaging more widely.

CONCLUSION

CMR is already a clinically useful imaging method for assessing cardiac function. In particular, it has become generally considered the effective "gold standard" method for global cardiac function measurements. However, the associated time required for imaging and the associated vulnerability to image artefacts

from breathing and arrhythmias with conventional CMR are still factors limiting the broader utilization of MRI for the assessment of cardiac function.

New accelerated MRI methods are now being developed that promise to provide more imaging speed, superior tolerance to motion artefacts and even the potential for deriving new kinds of functional data. It is hoped that these new methods will lead to an expanded utilization of MRI for the assessment of cardiac function.

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