Published in final edited form as:

MAGMA. 2018 February ; 31(1): 49–59. doi:10.1007/s10334-017-0655-7.

2D XD-GRASP provides better image quality than conventional 2D cardiac cine MRI for patients who cannot suspend respiration

Eve Piekarski, MD, Teodora Chitiboi, PhD, Rebecca Ramb, PhD, Larry A Latson Jr, MD, Puneet Bhatla, MD, Li Feng, PhD, and Leon Axel, PhD, MD

Abstract

Object—Residual respiratory motion degrades image quality in conventional cardiac cine MRI (CCMR). We evaluated whether a free-breathing (FB) radial imaging CCMR sequence with compressed sensing reconstruction (eXtra-Dimension (e.g. cardiac and respiratory phases) Golden-angle RAdial Sparse Parallel, or XD-GRASP) could provide better image quality than a conventional Cartesian breath-held (BH) sequence, in an unselected population of patients undergoing clinical CCMR.

Material and Methods—101 patients who underwent BH and FB imaging in a mid-ventricular short-axis plane at a matching location were included. Visual and quantitative image analysis was performed by two blinded experienced readers, using a 5-point qualitative scale to score overall image quality and visual signal-to-noise ratio (SNR) grade, with measures of noise and sharpness. End-diastole (ED) and end-systole (ES) left-ventricular areas were also measured and compared for both BH and FB images.

Results—Image quality was generally better with the BH cines (overall quality grade BH vs FB: 4 vs 2.9, $p < 0.001$; noise 0.06 vs 0.08 $p < 0.001$; SNR grade: 4.1 vs 3, $p < 0.001$), except for sharpness ($p = 0.48$). There were no significant differences between BH and FB images regarding ED or ES areas ($p = 0.35$ and 0.12). 18 of the 101 patients had impaired BH image quality (grades 1 or 2). In this subgroup, image quality of the FB images was better ($p = 0.0032$), as was the SNR grade ($p = 0.003$), but there were no significant differences regarding noise and sharpness ($p = 0.45$, $p = 0.47$).

Corresponding Author: Leon Axel, PhD, MD, NYU Medical Center, New York, New York United States.

There is no overlap of our study with previously published works.

We confirm that we have solely submitted our work to Magnetic Resonance Materials in Physics, Biology and Medicine.

COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of potential conflicts of interest

Conflict of Interest: The authors declare that they have no conflict of interest.

Research involving Human Participants and Informed consent

This retrospective study was approved by our institutional review board and was performed according to standards of the Health Insurance Portability and Accountability Act. Documentation of consent was waived.

AUTHOR'S CONTRIBUTION

EP participated in the data collection and the data analysis, and redacted the manuscript.

TC participated in the data collection, in the data analysis and reviewed the manuscript.

RR participated in the data analysis and reviewed the manuscript.

LL participated in the data collection and reviewed the manuscript.

PB participated in the data collection and reviewed the manuscript.

LF participated in the protocol development and reviewed the manuscript.

LA designed the project development, participated in the data analysis and redacted and reviewed the manuscript.

Conclusion—Although FB XD-GRASP CCMR was visually inferior to conventional BH cardiac cine in general, it provided improved image quality in the subgroup of patients presenting respiratory motion-induced artifacts on breath-held images.

Keywords

Cardiac MRI; Free-breathing; XD-GRASP; Radial MRI; Compressed sensing

INTRODUCTION

Cardiac MRI (CMR) has become a key tool for the evaluation of many cardiovascular diseases [1,2]. This modality is non-invasive, allows study of both anatomical and functional parameters, and provides information about myocardial tissue composition, volume and contractility. It is a complementary tool to echocardiography, in that it is not operator-dependent, allows access to the entire heart volume (including the apex), and provides unique combination of information about the heart tissue, including regional function, late gadolinium enhancement, T1 and T2 properties (including mapping), and diffusion.

Due to the limited encoding speed of conventional MRI, k-space lines may be acquired in different respiratory motion states during free-breathing in conventional Cartesian acquisitions, resulting in ghosting or aliasing artifacts, as well as spatiotemporal blurring in the reconstructed images. The simplest approach to avoid such respiratory motion effects is to have patients suspend respiration during acquisitions. Although this approach is widely used in routine clinical MRI exams [3,4], breath-holding capabilities and capacities are limited for a significant number of patients undergoing CMR. Therefore, the quality of many CMR examinations suffers from respiratory motion-induced blurring or artifacts. These artifacts are related to both incomplete breath-holds (inability to perform or maintain breath holding) and drifts in the breath-holding position. They become even more severe in the presence of arrhythmias due to associated k-space data inconsistency, and this affects a large proportion of patients undergoing CMR. Possible approaches to reduce the effects of respiratory motion - and avoid breath-holding during the MR measurement - include either prospective gating or triggering based on a navigator with a fixed acceptance window, or extended data acquisition with retrospective gating of respiratory and cardiac phases. However, these approaches reduce data sampling efficiency and generally result in prolonged imaging times. To retain scan efficiency and still reduce the effects of respiratory motion artifacts without breath-holding, several groups [5] have explored rapid continuous free-breathing MRI radial acquisition schemes with compressed sensing reconstruction, for several types of MRI (including cardiac, as well as liver and brain MRI) [6–8]. However, those studies have primarily focused on providing a proof-of-concept demonstration of the feasibility of the proposed imaging strategy. There is thus still a need for a larger scale validation of these techniques, in order to evaluate their potential clinical utility and robustness.

The purpose of our study was to compare image quality between a free-breathing (FB) radial imaging cine CMR sequence in combination with a multidimensional compressed sensing reconstruction approach (eXtra-Dimension (e.g., cardiac and respiratory phases) Golden-

angle RAdial Sparse Parallel or XD-GRASP [6]) and a conventional Cartesian breath-held (BH) sequence (here considered as our reference method), in an unselected population of patients undergoing clinical CMR.

MATERIALS AND METHODS

Study Population

This retrospective study was approved by our institutional review board (IRB) and was performed according to standards of the Health Insurance Portability and Accountability Act. Documentation of consent was waived and was approved by the IRB. An additional short-axis (SAX) FB cine acquisition was performed in 111 patients who underwent clinical CMR at our center between October 2015 and February 2016. 10 patients were excluded, due to the absence of a gold-standard reference BH acquisition. Hence, 101 patients were included in total. Demographic characteristics are shown in Table 1.

Breath-Held Cardiac Cine Imaging

The reference method was a conventional Cartesian cine CMR sequence, with breath-hold acquisition using a balanced steady-state free precession (bSSFP) readouts. Imaging was performed on a whole-body 1.5T MRI system (Avanto, Siemens Healthcare GmbH, Erlangen, Germany) with retrospective ECG-gating. Relevant acquisition parameters included: GRAPPA acceleration factor = 2, flip-angle = 70° , bandwidth = ~ 900 Hz/pixel, TR/TE $\approx 4.5/1.2$ ms, FOV = 320×320 mm², slice thickness = 8 mm, spatial resolution ≈ 1.6 mm $\times$ 1.6 mm, number of acquired phases = 25 (one cardiac cycle). Acquisition time was between ~ 15 –20 seconds for each slice.

Free-Breathing Cardiac Cine Imaging

FB imaging was performed on a whole-body 1.5T scanner (Avanto, Siemens Healthcare GmbH, Erlangen, Germany) without any external gating or triggering. A 2D bSSFP sequence with golden-angle radial acquisition scheme ($\sim 111.25^\circ$, [9,10]) was employed for data acquisitions. One mid-ventricular SAX slice was acquired in each patient, with the slice position matching that of the corresponding BH acquisition. The acquisition parameters included: flip angle = 40° , bandwidth = ~ 1100 Hz/pixel, TR/TE = $2.8/1.4$ ms, FOV = 320×320 mm², slice thickness = 8 mm, spatial resolution 2 mm $\times$ 2 mm (320 readout points in each spoke including 2-fold oversampling). Acquisition time was 23 seconds for each slice.

XD-GRASP reconstruction was performed in each radial dataset. The reconstruction algorithm was used as described in the proof-of-concept study for XD-GRASP cine CMR [6], enforcing sparsity by constraining the total variation [11–13], separately along the cardiac and the respiratory dimensions. Since frame-to-frame similarities are higher between adjacent cardiac phases than compared to adjacent respiratory states, a higher penalty weight was chosen for the cardiac dynamics. For more details about XD-GRASP, please see ref 6. From the k-space central data that was repeatedly sampled in each k-space readout, we extracted quasi-periodic [14, 15] cardiac and respiratory motion-related signal evolutions, one from each coil element. As previously described in [6], the best cardiac and respiratory motion signals were selected according to the frequency range of the quasi-periodic signal,

with the highest peak in the frequency range of 0.5–2.5 Hz representing the cardiac motion and the highest peak in the frequency range of 0.1–0.5 Hz representing the respiratory motion). The acquired k-space data were then binned according to different cardiac and respiratory motion states followed by multidimensional compressed sensing reconstruction [16–21]. The number of reconstructed cardiac phases was ~25 to match that in the reference method. For the purpose of current study, only the end-expiratory phase was used for comparison with corresponding BH images that were also acquired at end-expiration.

Comparison of Free-Breathing and Breath-Held Images

To compare FB XD-GRASP cine images with corresponding reference BH cine images, one experienced cardiologist and one experienced radiologist (with 5 and 4 years of experience, respectively) blinded to the type of images (FB or BH) and relevant clinical information reviewed all images after randomization. This was performed using a custom program in Matlab (R2015a, The Mathworks, Natick, MA, USA), which displayed the cine images and allowed qualitative and quantitative evaluation.

The first step in the readers' analysis was a qualitative visual assessment of the overall image quality, using a 5-point grading scale. Grade 1 corresponded to non-diagnostic image quality, grade 2 to poor, grade 3 to average, grade 4 to good, and grade 5 to excellent quality. Then, the readers graded the visual SNR using the same 5-point grading scale (SNR grade). The next step was a set of quantitative measurements on the end-diastolic and end-systolic frames from each cardiac cine set. Specifically, two regions of interest (ROI) were drawn by the readers in homogeneous regions, one inside the left ventricle (LV) cavity and the other one inside the interventricular septal (IVS) wall, at both end-diastole and end-systole. Average pixel value, standard deviation, and size of ROI were recorded for analysis. To evaluate sharpness, lines were drawn by the readers normal to the mid IVS, and corresponding intensity profiles were recorded for analysis.

We used a surrogate measure of normalized noise: the ratio of the standard deviation to the average pixel intensity value for each ROI. To evaluate sharpness, we analyzed the rise-distance (10 to 90% of the peak value) [22] of the intensity changes across IVS edges. Finally, the readers interactively drew endocardial contours to measure LV areas on ED and ES images, to compare LV areas measured on BH vs. FB cines.

Subgroup analysis: Breath-Held images of poor quality (grade 1 or 2)

After the readers' analyses, the likely patient-related causes of the BH cines considered of poor quality (grade 1 or 2) were classified as: 1) respiratory motion (blurring seen both above and below the diaphragm), 2) arrhythmias (blurring principally affecting the images of the heart alone), or 3) both.

Intra- and inter-observer variability

The intra-observer reproducibility was evaluated by showing a subset of the free-breathing or breath-held cines (total of 27 cines) repeatedly to the readers, keeping them blinded to that information. Inter-observer variability was evaluated for both qualitative and quantitative results.

Analysis of potential factors impacting the Free-Breathing images quality

In order to assess the origin of the artifacts in the FB cine images considered to be of poor quality (grade 1 or 2), we reviewed the patients' characteristics, noted any MRI findings that might affect the quality of reconstruction (such as wall motion abnormalities, including akinesia or hypokinesia), visually assessed the self-gating signal for the quality of cardiac and respiratory motion detection, and catalogued the artifacts encountered.

Statistical evaluation

For the analysis of qualitative and quantitative results, we used a paired Student's t-test for the entire population, and a Wilcoxon signed-rank test for the subgroups. For inter- and intra-observer variability, we used linear weighted Cohen's kappa for the analysis of qualitative results, and a Bland-Altman analysis with intra-class correlation coefficients and variability coefficients for the analysis of quantitative results. To assess associations of different potential factors to specific types of artifacts related to poor FB quality, we performed univariate and multivariate linear regression.

RESULTS

Comparison of Free-Breathing and Breath-Held Images

Regarding the FB cines, 34/101 (33.6%) were graded 1–2, 25/101 (24.8%) graded 3 and 42/101 (41.6%) graded 4–5; regarding the BH cines, 18/101 (18%) were graded 1–2, 8/101 (8%) graded 3 and 75/101 (74%) graded 4–5. For the entire group of 101 included patients, BH cines had significantly better overall image quality ($p < 0.001$), higher SNR grading ($p < 0.001$) and lower noise measurements ($p = 0.002$) than FB cines (Table 2). There were no significant differences in terms of sharpness ($p = 0.24$) (Table 2), nor of ED and ES areas ($p = 0.35$ and 0.12) (Table 2).

Subgroup analysis: Breath-Held images of impaired quality (grade 1 or 2)

For the subgroup of 18 patients who presented poor image quality (grades 1 or 2) of the BH cines, the FB cines provided improved image quality, in regard to overall image quality grade ($p = 0.0032$, Table 3) and SNR grade ($p = 0.003$). No significant differences were found regarding noise and sharpness ($p = 0.45$ and 0.47 , Table 3).

Within this subgroup, 8 patients had blurred images due to arrhythmia, 5 due to respiratory motion (incomplete breath-holds), and 4 due to a combination of both arrhythmia and respiratory motion. The highest FB quality was found in the respiratory motion subgroup (average FB grade 2.9 for the respiratory motion subgroup vs 2.5 and 2 for the arrhythmia and the combined arrhythmia with respiratory motion subgroups, respectively) (Table 3, Fig 1). The observed respiratory motion-induced artifacts were mainly related to incomplete breath-holds rather than drifts in the breath-holding position.

Inter- and intra-observer variability: qualitative analysis

The inter-observer reproducibility of the qualitative assessments was good (linear weighted kappa = 0.62; Table 4). The intra-observer reproducibility was good for both readers (linear weighted kappa = 0.66 for reader 1, linear weighted kappa = 0.69 for reader 2; Table 4).

Inter-observer variability: quantitative analysis

The inter-observer reproducibility was acceptable for the ROI, the profile measures, and very good for ED and ES area measurements (intra-class coefficients were 0.5, 0.48, 0.94 and 0.95, respectively; Table 4). Corresponding Bland-Altman graphs are presented in Fig 2.

Analysis of potential factors impacting the Free-Breathing images quality

For the FB images of poor quality (grade 1 or 2, 29 patients in total), we analyzed the associations with the patient characteristics and the results of our reconstruction algorithm, to assess for potential factors explaining the reduced quality of the FB cines in the overall population. The results of our univariate and multivariate analyses are presented in Table 5.

The main image artifact encountered (in 29 of the 29 patients with impaired FB image quality) in FB images was radially oriented streak artifacts (Fig 3 and 4), to which radial imaging is particularly prone [23–25]. The radially oriented streak artifacts generally did not contaminate the entire image, but could be classified as: 1) radially oriented streaks located at the borders of the patient, and 2) radially oriented streaks located inside or contaminating the region of the heart.

1. The streaks located at the borders of the patient did not affect the analysis of the region of the heart. They typically emerged from hyperintense structures, such as subcutaneous fat (Fig 3). As seen in Table 5, the patient's BMI is not generally associated with impaired FB quality, since it is mostly responsible for streaks at the border of the patient, which don't contaminate the region of the heart. Off-resonance artifacts (to which bSSFP is very sensitive [26]) were also encountered as potential factors explaining streaks located at the border of the patient.
2. The second type of streak artifact (radially oriented streaks located inside or contaminating the region of the heart) were present in all of the patients with impaired FB image quality (29 of 29 patients with grade 1 or 2 FB cines). Those cardiac-associated streaks were found to be associated with 2 major factors: 1) Hyperintense structures, such as mediastinal or epicardial fat, may be located in the region of the heart; in case of prominent through-plane motion of this type of fat, streaks were likely to be present. 2) bSSFP sequences are prone to flow artifacts [27], when the associated « dark band artifact » passes through moving blood; this can be seen as a hypointense irregular linear structure inside the right or left ventricle.

Finally, when analyzing the self-gating cardiac motion signal curves obtained from data, we found a significant number of patients that presented either noisy (n=2 of 72 patients with average and good quality FB cines and n=4 of 29 patients with poor FB cines) or strongly modulated (for example, respiratory modulation of the cardiac signal) motion-related signal curves. This was found for both the average and good quality FB cines (46 of 72 patients, 64%) and the poor FB cines (18 of 29 patients, 62%; $p=0.87$).

DISCUSSION

Comparison of Free-Breathing and Breath-Held Images

Our study showed that image quality was better in BH bSSFP Cartesian cardiac cine MRI compared to 2D FB XD-GRASP in the overall, unselected population of 101 patients imaged.

Subgroup analysis: Breath-Held images of impaired quality (grade 1 or 2)

However, in the subgroup of 18 patients, where image quality of BH was impaired by motion artifacts, the FB acquisitions actually provided improved image quality, due to resolving the combined motion states.

18% of unselected patients undergoing routine clinical CMR exhibited poor BH image quality in the reference SAX cine acquisition; half of these patients appeared to have image degradation by respiratory motion. As we only graded one cine set for each patient, it is likely that there would be a higher number of patients with poor quality images if other images were also graded. Furthermore, these patients were all undergoing routine outpatient imaging; it is likely that a higher frequency of respiratory motion artifacts will be encountered in inpatient examinations, where the patients are generally sicker. Thus, the relatively high frequency of motion artifacts encountered in conventional BH cine imaging emphasizes the need for the development of reliable and robust free-breathing imaging sequences.

Analysis of potential factors impacting the Free-Breathing images quality and potential limitations of our study

As described above, radially oriented streak artifacts were the main artifacts encountered in radial imaging. Radial MRI is known to be generally sensitive to streaks [23–25]; however, such findings were not described in the initial proof-of-concept report on XD-GRASP due to the limited number patients [6]. While the use of radial k-space sampling has some potential advantages over Cartesian sampling, the tendency to generate streak artifacts in the presence of undersampling is a major limitation. However, the same principle of treating the cardiac and respiratory cycle phases as additional dimensions for reconstruction of free-breathing acquisitions using multidimensional compressed sensing approach can also be extended to Cartesian sampling. Thus, the encouraging results found here for imaging of patients with poor quality conventional cine images are also encouraging for the prospects for clinical utility of such Cartesian approaches using the same « extra-dimension » FB imaging approach.

Another source of image degradation in the FB images was the presence of banding artifacts in bSSFP imaging due to field inhomogeneities. Banding artifacts that occurred within the heart gave rise to streaks in the region of the heart. The FB images analyzed in this retrospective study were just acquired as a quick « add-on » in the end of clinical CMR examinations, without any attempt to optimize the magnetic field homogeneity in the region of the heart so as to minimize these artifacts. Thus, it is likely that the use of additional field

shimming and frequency adjustment steps prior to imaging will alleviate this problem and significantly improve the FB images.

Also, we note that FB and BH images were acquired with different acquisition parameters in this initial technical sequence development stage, including different TR, TE and particularly different spatial resolution parameters ($2 \times 2 \text{ mm}^2$ vs $1.6 \times 1.6 \text{ mm}^2$), which could have favored BH image quality. These parameters could be adjusted more consistent in future works.

In the current work, a single-slice FB image-series was acquired in each patient as a first development and clinical testing of the FB sequence. Thus, further studies are needed to validate its use for both multislice 2D and 3D acquisitions. Nevertheless, given that there were no significant differences for ED and ES areas, the FB imaging could possibly reliably evaluate LV volumes and therefore estimate LV ejection fraction in multiple 2D-cines acquired from LV base to LV apex.

The FB images were reconstructed with multiple respiratory phases. Since different respiratory motion states might modify the pre-load LV conditions by modifying intra-thoracic pressure, therefore producing less reproducibility between FB and BH images, we selected the FB images at end-expiratory phase only for comparison with the BH images, which were also acquired at end-expiration. We used the same reconstruction algorithm here as in the initial proof-of-concept report on the XD-GRASP technique [6]. Specifically, we used a total variation constraint, relying primarily on high temporal correlation, to handle the relatively undersampled imaging data. Choosing another sparsifying transform, or a combination of sparsifying transforms, including relying more on spatial correlation, could potentially further improve our results. The issue of k-space data undersampling artifacts may have explained some of the poor-quality FB cines. This general area could be more extensively evaluated in a future study, for example, systematically evaluating the effect of different choices of temporal resolution and acquisition times, and different associated sparsifying functions.

Even though we found a significant proportion of cardiac signal curves modulated by respiratory motion, this did not seem to differ between average and good FB cines vs. impaired FB quality cines. In most cases, even though the signal appeared modulated, after a simple filtering step (using threshold values of ratios of surrounding maxima to the detected minima, to exclude spurious minima), minimas and maximas were correctly detected. However, it has been noted that the approach used to extract respiratory and cardiac motion signal is relatively simplistic. For instance, it is prone to errors by replying the selection process on a single frequency peak. Meanwhile, irregular breathing patterns also add more challenges in signal selection. We are currently developing a more reliable algorithm to extract physiological motion signals from a pre-reconstructed real-time image series. The assessment of this new approach is currently underway and will be validated in patient studies in future works. In addition, the motion detection can also be improved in 3D imaging, where a self-navigation readout can be periodically inserted during data acquisitions for motion detection, as previously demonstrated in [28]. These potential directions will be further explored in future work.

A significant limitation of our study was the small effective sample size: 18 subjects with poor quality conventional BH cine images. Thus, these findings will need to be confirmed on a larger sample of patients undergoing clinical CMR examinations.

Finally, although we found improved image quality with FB compared with BH in the subgroup of patients with poor BH quality, the fact that our objective measurements did not reproduce the findings of the readers' qualitative grading is a potential limitation. This could be explained by the relatively poor inter-reader reproducibility regarding ROI and profile measures. Thus, we will want to reconsider the procedures used for making the quantitative measurements in any future studies (e.g., fixed positioning of ROI or profile measurements).

Perspectives

A potential further development of FB XD-GRASP cardiac cine imaging is its use in arrhythmic patients, as was initially demonstrated in a limited number of patients [6, 29]; we did not incorporate this capability in the image reconstructions studied here. The ability to obtain a cardiac motion-related signal during image acquisition allows us to further obtain a surrogate signal for the successive RR intervals from the cardiac motion signal [30]; that surrogate signal can be used to sort patients into non-arrhythmic patients and arrhythmic patients, using the global variation of RR intervals [31, 32]. We can then incorporate this data into the reconstruction process, effectively using a total of 5 dimensions (2 spatial and 3 physiologic, including an additional dimension corresponding to the preceding RR interval for each cardiac cycle acquired), with an associated improvement in the reconstructed image quality. As more than half of the patients with poor BH image quality also showed evidence of arrhythmias, these patients would then be expected to have further image quality improvement with the FB imaging.

The self-gating property of the radial sampling MRI method used permits us to reliably retrieve both cardiac and respiratory motion-related signals from the imaging data. Hence, it allows for reconstruction of images along both respiratory and cardiac cycle dimensions, for example, offering the possibility to track septal wall motion along the phases of the respiratory cycle, at fixed phases of the cardiac cycle. The ability to separately reconstruct images along the phases of the physiologic cardiac cycle and the respiratory cycle dimensions could potentially allow us to more thoroughly study interventricular coupling and the relation between pre-load and septal motion, as they vary during the respiratory cycle; this has been initially assessed in some studies using real-time breath-held cardiac cine MRI [33].

Another potential area for further development of this self-gated multidimensional MRI approach could be for application to pediatric and fetal imaging, since breath-held imaging cannot be reliably performed in this population; for fetal imaging, in particular, cardiac gating cannot be done with conventional ECG monitoring.

In conclusion, although free-breathing XD-GRASP cine CMR did not achieve image quality as good as conventional breath-held cine CMR overall, for a group of unselected patients undergoing clinical CMR examinations, it provided improved image quality in the subgroup of patients who had motion-related artifacts on the conventional cine images, particularly

those related to respiratory motion. Thus, the current version of the FB XD-GRASP reconstruction could potentially be used as an alternative clinical imaging method for patients unable to hold their breath, although some further improvements will be needed before it is suitable for use in all patients. However, there are promising approaches available to further pursue such imaging improvements. There is also the potential to extend these imaging methods to higher spatial dimensions, e.g., for free-breathing MR angiography and cardiac function applications, and to other applications, such as imaging of arrhythmic patients or pediatric and fetal patients.

Acknowledgments

Funding: This study was funded by the NIH (grant number NIH R21-EB109595-01).

References

1. Pennell DJ, Sechtem UP, Higgins CB, et al. Clinical indications for cardiovascular magnetic resonance (CMR): Consensus Panel report. *Eur Heart J.* 2004; 25(21):1940–65. [PubMed: 15522474]
2. Hundley WG, Bluemke DA, Finn JP, et al. American College of Cardiology Foundation Task Force on Expert Consensus Documents. ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. *J Am Coll Cardiol.* 2010; 55(23):2614–62. [PubMed: 20513610]
3. Ferreira PF, Gatehouse PD, Mohiaddin RH, Firmin DN. Cardiovascular magnetic resonance artefacts. *J Cardiovasc Magn Reson.* 2013; 15:41. [PubMed: 23697969]
4. Saloner D, Liu J, Haraldsson H. MR physics in practice: how to optimize acquisition quality and time for cardiac MR imaging. *Magn Reson Imaging Clin N Am.* 2015; 23(1):1–6. [PubMed: 25476668]
5. van Heeswijk RB, Bonanno G, Coppo S, Coristine A, Kober T, Stuber M. Motion compensation strategies in magnetic resonance imaging. *Crit Rev Biomed Eng.* 2012; 40(2):99–119. [PubMed: 22668237]
6. Feng L, Axel L, Chandarana H, Block KT, Sodickson DK, Otazo R. XD GRASP: Golden-Angle Radial MRI with Reconstruction of Extra Motion-State Dimensions Using Compressed Sensing. *Magn Reson Med.* 2016; 75(2):775–88. [PubMed: 25809847]
7. Chen C, Li Y, Axel L, Huang J. Real time dynamic MRI by exploiting spatial and temporal sparsity. *Magn Reson Imaging.* 2016; 34(4):473–82. [PubMed: 26578303]
8. Wech T, Pickl W, Tran-Gia J, Ritter C, Beer M, Hahn D, Köstler H. Whole-Heart Cine MRI in a Single Breath-Hold – A Compressed Sensing Accelerated 3D Acquisition Technique for Assessment of Cardiac Function. *Rofo.* 2014; 186(1):37–41. [PubMed: 23996623]
9. Weber, MA. *Magnetic Resonance Imaging of the Skeletal Musculature.* Springer-Verlag; Berlin Heidelberg: 2013.
10. Glover GH, Pauly JM. Projection Reconstruction Techniques for Reduction of Motion Effects in MRI. *Magn Reson Med.* 1992; 28(2):275–89. [PubMed: 1461126]
11. Rudin LO, Osher S, Fatemi E. Nonlinear total variation based noise removal algorithms. *Physica D.* 1992; 60(1–4):259–268.
12. Adluru G, Awate SP, Tasdizen T, Whitaker RT, Dibella EV. Temporally Constrained Reconstruction of Dynamic Cardiac Perfusion MRI. *Magn Reson Med.* 2007; 57(6):1027–36. [PubMed: 17534924]
13. Block KT, Uecker M, Frahm J. Undersampled Radial MRI with Multiple Coils. Iterative Image Reconstruction Using a Total Variation Constraint. *Magn Reson Med.* 2007; 57(6):1086–98. [PubMed: 17534903]

14. Lustig, M., Santos, M., Donoho, D., Pauly, JM. k-t SPARSE: High frame rate dynamic MRI exploiting spatio-temporal sparsity. Conference: 13th Annual Meeting of ISMRM; 06–12 May 2006; Seattle, Washington, USA: Washington State Convention & Trade Center; 2006.
15. Thompson RB, McVeigh ER. Cardiorespiratory-resolved magnetic resonance imaging: measuring respiratory modulation of cardiac function. *Magn Reson Med*. 2006; 56(6):1301–1310. [PubMed: 17058205]
16. Lustig M, Donoho D, Santos J, Pauly JM. Compressed Sensing MRI. *IEEE Signal Process Mag*. 2008; 25(2):72–82.
17. Lustig M, Donoho D, Pauly JM. Sparse MRI: The Application of Compressed Sensing for Rapid MR Imaging. *Magn Reson Med*. 2007; 58(6):1182–95. [PubMed: 17969013]
18. Babacan SD, Peng X, Wang XP, Do MN, Liang ZP. Reference-guided sparsifying transform design for compressive sensing MRI. *Conf Proc IEEE Eng Med Biol Soc*. 2011:5718–5721. [PubMed: 22255638]
19. Smith DS, Li X, Abramson RG, Quarles CC, Yankeelov TE, Welch EB. Potential of compressed sensing in quantitative MR imaging of cancer. *Cancer Imaging*. 2013; 13(4):633–44. [PubMed: 24434808]
20. Zibetti MV, De Pierro AR. Improving compressive sensing in MRI with separate magnitude and phase priors. *Multidimens Syst Signal Process*. 2016
21. Candes EJ, Wakin MB. An introduction to compressive sampling. *IEEE Signal Process Mag*. 2008; 25(2):21–30.
22. Ahmad R, Ding Y, Simonetti OP. Edge sharpness assessment by parametric modeling: Application to Magnetic Resonance Imaging. *Concepts Magn Reson Part A Bridg Educ Res*. 2015; 44(3):138–149. [PubMed: 26755895]
23. Xue Y, Yu J, Kang HS, Englander S, Rosen MA, Song HK. Automatic coil selection for streak artifact reduction in radial MRI. *Magn Reson Med*. 2012; 67(2):470–6. [PubMed: 21656562]
24. Chan RW, Ramsay EA, Cheung EY, Plewes DB. The influence of radial undersampling schemes on compressed sensing reconstruction in breast MRI. *Magn Reson Med*. 2012; 67(2):363–77. [PubMed: 21656558]
25. Riffel P, Zoellner FG, Budjan J, et al. “One-Stop Shop”: Free-Breathing Dynamic Contrast-Enhanced Magnetic Resonance Imaging of the Kidney Using Iterative Reconstruction and Continuous Golden-Angle Radial Sampling. *Invest Radiol*. 2016; 51(11):714–719. [PubMed: 27299581]
26. Lin W, Huang F, Simonotto E, Duensing GR, Reykowski A. Off-Resonance Artifacts Correction With Convolution in k-Space (ORACLE). *Magn Reson Med*. 2012; 67:1547–1555. [PubMed: 21993985]
27. Wei Li W, Storey P, Chen Q, Li BSY, Prasad PV, Edelman RR. Dark Flow Artifacts with Steady-State Free Precession Cine MR Technique: Causes and Implications for Cardiac MR Imaging. *Radiology*. 2004; 230:569–575. [PubMed: 14752195]
28. Pang J, Sharif B, Fan Z, et al. ECG and navigator-free four-dimensional whole-heart coronary MRA for simultaneous visualization of cardiac anatomy and function. *Magn Reson Med*. 2014; doi: 10.1002/mrm.25450
29. Contijoch F, Iyer SK, Pilla JJ, et al. Self-gated MRI of Multiple Beat Morphologies in the Presence of Arrhythmias. *Magn Reson Med*. 2016; doi: 10.1002/mrm.26381
30. Piekarski E, Chitiboi T, Ramb R, Feng L, Axel L. Use of self-gated radial cardiovascular magnetic resonance to detect and classify arrhythmias (atrial fibrillation and premature ventricular contraction). *J Cardiovasc Magn Reson*. 2016; 18(1):83. [PubMed: 27884152]
31. Huang RY, Dung LR. Measurement of heart rate variability using off-the-shelf smart phones. *BioMed Eng OnLine*. 2016; 15:11. [PubMed: 26822804]
32. Ruan, X., Liu, C., Li, P. Detection of Atrial Fibrillation Using R-R Interval Signal. Conference: 4th International Conference on Biomedical Engineering and Informatics, BMEI 2011; October 15–17, 2011; Shanghai, P. R. China. Shanghai, China: 2011.
33. Francone M, Dymarkowski S, Kalantzi M, Bogaert J. Real-Time Cine MRI of Ventricular Septal Motion: A Novel Approach to Assess Ventricular Coupling. *J Magn Reson Imaging*. 2005; 21(3): 305–9. [PubMed: 15723377]

Fig 1.
Example of improved image quality with FB XD-GRASP acquisition (left image) in the presence of respiratory-motion blur in the BH acquisition (right image)

Fig 2.

Bland-Altman plots show inter-observer variability for quantitative measurements (Top: ROI on the left, profiles on the right; Bottom: ED LV areas on the left, ES LV areas on the right): averages are plotted against differences. Each grey lozenge represents the differences between a measure for one given patient made by reader 1 and the same measure made by reader 2.

The solid line represents the mean difference (bias), and the dotted lines show 2 SD of differences.

Fig 3.

FB cine showing radially oriented streaks located:

- at the border of the patient (white arrow heads, subcutaneous fat)
- inside the right ventricle region (red arrows, mediastinal fat)

Fig 4. FB cine showing radially oriented streaks contaminating the region of the heart in the presence of flow artifacts (hypointense dark line indicated by the red arrows)

Table 1

Demographic characteristics of the population

Total number of patients		101
Age (years)	Average (max-min)	50 (9–82)
Sex	Women/Men	38 (38%)/63 (62%)
Reason for referral for MRI	Cardiomyopathies	71
	Arrhythmia	27
	Valvular disease	5
	Aortic disease	1
	Pericardial disease	3
	Cardiac mass	1

Table 2

Comparison between FB and BH cines (whole group)

	FB		BH		Paired Student's t-test
	Average	SD	Average	SD	p value
Image Quality Grade	2.9	0.96	4	1.14	< 0.001 *
SNR Grade	3	0.89	4.1	0.91	< 0.001 *
Noise	0.08	0.04	0.06	0.02	< 0.001 *
Rise Distance	5.04	1.75	4.96	1.72	0.48 (mean difference -0.08; IC 95[-0.29, 0.14])
LV ED Area (mm ²)	105	31	114	56	0.35
LV ES Area (mm ²)	63	26	67	39	0.12

* statistically significant

Table 3
Comparison between FB and BH cines for the impaired BH quality population
(18 patients)

	FB		BH		Wilcoxon signed-rank test p value
	Average	SD	Average	SD	
Image Quality Grade	2.4	0.93	1.77	0.43	0.0032 *
Subgroup RM ^a	2.9	1.12	1.88	0.35	
Subgroup A ^b	2.5	0.87	1.83	0.39	
Subgroup RM+A ^c	2	0.82	1.71	0.49	
SNR Grade	2.57	0.83	1.79	0.42	0.003 *
Noise	0.09	0.04	0.07	0.02	0.45
Rise Distance	4.4	0.9	4.5	0.9	0.47

^aRM: respiratory motion,

^bA: arrhythmia,

^cRM+A: combined respiratory motion and arrhythmia

* statistically significant

Table 4

Inter- and intra-observer variability

Inter-observer variability		
Cine grading	Linear weighted kappa	0.62
	Observed concordance	0.53
ROI	Variability Coefficient	0.32
	Intra-Class Correlation Coefficient	0.5
Profiles	Variability Coefficient	0.18
	Intra-Class Correlation Coefficient	0.48
ED LV Area	Variability Coefficient	0.4
	Intra-Class Correlation Coefficient	0.94
ES LV Area	Variability Coefficient	0.51
	Intra-Class Correlation Coefficient	0.95
Intra-observer variability: grading		
Reader 1	Linear weighted kappa	0.66
	Observed concordance	0.85
Reader 2	Linear weighted kappa	0.69
	Observed concordance	0.74

Table 5

Univariate and Multivariate regression analysis of potentially limiting factors and artifacts related to impaired FB quality (grades 1, 2)

Univariate analysis (Student's t-test)			
	Number of patients	Percentage	p value
Patient characteristics			
BMI ^a >30	9	26.50%	0.71
HR ^b > 100 bpm	0		
h/o cardiac surgery	1	3%	0.8
Arrhythmia	9	26.50%	0.03 [*]
MRI results			
LVEF 30–40%	5	17%	0.43
LVEF 40–55%	6	20%	0.31
Wall motion abnormalities	6	20%	0.3
Reconstruction			
Incorrectly detected cardiac motion	18	62%	0.1
Incorrectly detected respiratory motion	4	13.7%	0.93
Artifacts			
Streaks related to intrathoracic fat (Fig 3)	21	72.4%	0.04 [*]
Streaks related to flow artifacts (Fig 4)	9	31%	0.04 [*]
Off-resonance artifacts at borders	8	27.6%	0.98
Multivariate analysis (multivariate regression analysis)			
		Coefficient	p value
Factors associated with poor FB results (grades 1, 2)			
Streaks related to flow artifacts (Fig 4)		−1.44	2 × 10^{−17} [*]
Arrhythmia		−0.8	0.003 [*]
Factors associated with good FB results (grades 4, 5)			
Wall motion abnormalities		0.62	0.02 [*]

^aBMI = Body Mass Index,

^bHR = Heart rate,

* statistically significant