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Free-breathing cine DENSE MRI using phase cycling with matchmaking and stimulated-echo image-based navigators

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Abstract

Purpose—This study aimed to develop a self-navigated method for free-breathing spiral cine displacement-encoding with stimulated echoes (DENSE), a myocardial strain imaging technique that uses phase-cycling for artifact suppression. The method needed to address two consequences of motion for DENSE: striping artifacts from incomplete suppression of the T1-relaxation echo and blurring.

Methods—The method identifies phase-cycled spiral interleaves at matched respiratory phases by minimizing the residual signal due to T1 relaxation after phase-cycling subtraction. Next the method reconstructs image-based navigators from matched phase-cycled interleaves that are comprised of the stimulated echo (ste-iNAV). Ste-iNAV is used for motion estimation and compensation of k-space data. The method was demonstrated in phantoms and compared to diaphragm-based navigator (dNAV) and conventional iNAV (c-iNAV) methods for the reconstruction of free-breathing volunteer datasets (N=10).

Results—Phantom experiments demonstrated that the proposed method removes striping artifacts and blurring due to motion. Volunteer results showed that respiratory motion measured by ste-iNAV was better correlated than c-iNAV to dNAV data ($R^2 = 0.82 \pm 0.03$ vs. 0.70 ± 0.05 , $P < 0.05$). Match-making reconstructions of free-breathing datasets achieved lower residual T1-relaxation echo energy (1.04 ± 0.01 vs. 1.18 ± 0.04 for dNAV and 1.18 ± 0.03 for c-iNAV, $P < 0.05$), higher apparent signal-to-noise ratio (11.93 ± 1.05 vs. 10.68 ± 1.06 for dNAV and 10.66 ± 0.99 for c-iNAV, $P < 0.05$), and better phase quality (0.147 ± 0.012 vs. 0.166 ± 0.017 for dNAV, $P = 0.06$, and 0.168 ± 0.015 for c-iNAV, $P < 0.05$) than dNAV and c-iNAV methods.

Conclusion—For free-breathing cine DENSE, the proposed method addresses both types of breathing-induced artifacts and provides better quality images than conventional dNAV and iNAV methods.

Keywords

cardiac MRI; cine DENSE; free-breathing; self-navigating; image-based navigator

Introduction

Cine displacement encoding with stimulated echoes (DENSE) (1) is a myocardial strain imaging method that is accurate (2), reproducible for both global and regional measurements (3), and amenable to rapid displacement and strain analysis (4). With these properties, the clinical applications of cine DENSE are expanding. For example, Auger et al (5) recently showed in heart failure patients that cine DENSE can quantify late mechanical activation and predict treatment response, Mangion et al (6) showed the prognostic value of cine DENSE in acute myocardial infarction, and Jing et al (7) showed the detection of subclinical contractile dysfunction in childhood obesity. Like many cardiac MRI acquisitions, cine DENSE is generally performed during breath-holding. However, in patient populations such as heart failure, acute myocardial infarction, children, and others, multiple breath-holds can be taxing. In addition, performing multi-breath-hold protocols can be complex for technologists. Self-navigated free-breathing methods could overcome these problems.

While diaphragm-based navigator (dNAV) methods (8), including those for cine DENSE (9), are available, a paradigm shift is occurring in cardiac MRI where self-navigation with motion estimation and motion correction is superseding dNAV-based methods for free-breathing acquisitions. Self-navigated methods have the advantages that they do not require complex dNAV setup procedures and they are more efficient than dNAVs because, with motion estimation and correction, they use data acquired during much or all of the respiratory cycle, whereas in dNAV-based methods data acquisition is restricted to a narrow band of the respiratory cycle. Self-navigated techniques have previously been developed for multiple cardiac MRI applications including cine imaging (10–12), late-gadolinium-enhanced imaging (13), coronary artery imaging (14–16), and T1 mapping (17), however they have not yet been developed for strain imaging methods such as cine DENSE.

For cine DENSE imaging, two echoes are generally present in the acquisition window (1), namely the desired displacement-encoded stimulated echo and an echo due to T1 relaxation that can cause image artifacts. A two-point phase cycling method is typically used to suppress the T1-relaxation echo, wherein two acquisitions comprised of stimulated echoes of opposite signs and T1-relaxation echoes of the same sign are subtracted (1). While phase cycling (used in conjunction with through-plane dephasing (18)) effectively suppresses the T1-relaxation echo for breath-hold DENSE protocols, this subtraction-based method can be ineffective for free-breathing scans because phase-cycled interleaves may be acquired at different respiratory positions where tissues contribute differently to the T1-relaxation signals. Insufficient suppression of the T1-relaxation echo leads to striping artifacts (18), which represents a unique and major challenge for free-breathing self-navigated cine DENSE. In addition to creating challenges for suppression of the T1-relaxation echo, respiratory motion induces blurring of the stimulated-echo image, as it does for other MR images. In Fig. 1 we demonstrate both types of motion-related artifacts using spiral cine DENSE data acquired from a phantom placed at two different positions. Subtraction of phase-cycled data acquired at mismatched positions leads to a strong residual T1-relaxation echo in k-space (Fig. 1e) and striping artifacts in the corresponding image (Fig. 1f). After subtraction of phase-cycled data from matched positions, image reconstruction that combines post-subtraction stimulated echoes from different positions leads to blurring (Fig.

1g). These types of artifacts are observed for free-breathing in vivo cine DENSE, as shown in Fig. 1h, and can lead to unsuccessful imaging of patients with imperfect breath-holding, as previously reported (19, 20). The purpose of the present study was to develop an effective method for free-breathing self-navigated cine DENSE, and the proposed approach involved suppression of the T1-relaxation echo as a first step, followed by the use of image-based navigators (iNAVs) for motion estimation and correction as a second step.

Methods

Free-breathing cine DENSE framework using match-making and stimulated-echo image-based navigators (ste-iNAVs)

We propose a self-navigated framework for free-breathing spiral cine DENSE that (a) selects phase-cycled spiral interleaves at matched respiratory phases, (b) performs subtraction of matched phase-cycled interleaves, (c) reconstructs image-based navigators (iNAVs) from post-subtraction interleaves (ps-interleaves) that are primarily comprised of the stimulated echo (termed ste-iNAVs), (d) performs ste-iNAV-based motion estimation to account for motion between ps-interleaves, and (e) applies rigid motion correction in k-space for image reconstruction. The first part of this method, which selects phase-cycled interleaves at matched respiratory phases, is termed “match-making”. The proposed framework is illustrated in Fig. 2a and is shown in contrast to conventional respiratory-gated navigator strategies such as dNAVs or conventional iNAVs (c-iNAVs) (Fig. 2b).

We propose to perform match-making of phase-cycled interleaves acquired during free breathing by evaluating the residual energy of the T1-relaxation echo after complex subtraction of those phase-cycled interleaves. This approach is based on the concept that the residual T1-relaxation echo energy will be minimized when the phase-cycled interleaves are acquired at matched respiratory phases, and will be greater otherwise. Since the approximate location in k-space of the T1-relaxation echo is determined by the displacement-encoding frequency, k_e , the residual T1-relaxation echo energy can be estimated by summing data over a predetermined region of k-space, i.e., $k > k_e/2$. Along with match-making to suppress the T1-relaxation echo, we propose to also use localized generation of stimulated echoes, so that ste-iNAVs can be focused to the heart, a reduced field of view (FOV) can be used, and automated motion estimation is facilitated.

DENSE Pulse Sequence

To experimentally investigate free-breathing cine DENSE imaging using the match-making framework with motion compensation, we modified a previously-described spiral cine DENSE pulse sequence (9), which supports two-point phase-cycling, to include golden angle rotation (21, 22) through time frames within the cardiac cycle and localized generation of stimulated echoes, as shown in Fig. 3. Golden angle rotation facilitates the reconstruction of iNAVs by utilizing consecutively acquired interleaves. In the current design, each fully sampled iNAV frame consisted of eight consecutively acquired interleaves, i.e. four consecutive frames with golden angle rotation between them and two interleaves per frame with uniform rotation. Localized generation of stimulated echoes was implemented by applying slice selection for all RF pulses that contribute to the stimulated echo such that

stimulated echoes were generated only in the region where the RF pulse profiles intersect (23, 24). We note that, with this pulse sequence, while the stimulated echo is localized to the heart region, the T1-relaxation echo originates from the entire slice. The cine DENSE pulse sequence also supported acquisition of a dNAV at end-diastole, as previously described (9). All DENSE scans employed multicoil acquisitions, and multi-channel data were adaptively combined to reconstruct complex images with sensitivity maps estimated from the data itself, as previously described.(25)

Reconstruction using the match-making framework

As illustrated in Fig. 2a, phase-cycled spiral interleaves at matched respiratory phases were selected using the match-maker criterion, specifically the minimal residual T1-relaxation echo energy. Matched interleaves must have the same displacement encoding and k-space trajectory, and they could be selected from any respiratory phase, without limitation. The residual T1- relaxation echo energy was averaged over all cardiac frames within each heartbeat. We assume that multiple averages of all interleaves are acquired. Of the available pairs of interleaves to choose from, the one pair (one average) with the lowest residual T1-echo energy (the match) is selected for the reconstruction, and all other data are discarded. After match-making, subtraction of matched interleaves was performed and ste-iNAV's were reconstructed. Multiple ste-iNAV's were reconstructed per heartbeat, specifically one ste-iNAV was reconstructed using eight spiral interleaves, and a sliding window was not used. Two-dimensional translations were estimated using the ste-iNAV's automatically, without manual identification of a region, using two-dimensional cross-correlation. Motion estimation was performed separately for different cardiac phases. The resulting motion estimation was used for motion compensation of the selected segmented k-space data.(8) The resulting motion-corrected k-space data underwent density-weighted nonuniform fast Fourier transform (26) to reconstruct final cine DENSE images.

Reconstruction using conventional dNAV gating

As illustrated in Fig. 2b, the conventional dNAV reconstruction method accepted data acquired within a dNAV window centered at end-expiration and rejected data outside that window. Specifically, in our protocol, we acquired a fixed number of averages, and in a retrospective reconstruction, we accepted one average of data that were within the narrowest window at end-expiration based on the dNAV position. This method was chosen to ensure a fair comparison between the various reconstructions.

Reconstruction using conventional iNAV gating

For the c-iNAV reconstruction, c-iNAV's were reconstructed using the methods described in the Appendix. Since c-iNAV's were reconstructed for each individual heartbeat, their reconstruction did not employ subtraction of phase-cycled interleaves. Instead, suppression of the T1-relaxation echo for the c-iNAV's was performed by separating the stimulated echo and T1-relaxation echoes using principal component analysis (PCA), and applying a PCA filter to the iNAV's (Appendix). An early systolic c-iNAV was used and 2D translation was estimated by 2D cross-correlation for displacement-based retrospective gating. Similar to dNAV-gating, one average of data within a narrow window around end expiration defined by the c-iNAV position were accepted, as described in Fig. 2b.

Experimental design

Phantom experiments were conducted to demonstrate the use of matching phase-cycled interleaves using the residual T1-echo energy and using localized ste-iNAVs for motion estimation and correction. All phantom imaging was performed on a 3T MRI system (Magnetom Prisma, Siemens Healthcare, Erlangen, Germany) with a 32-channel phased-array spine coil. Specifically, a phantom was scanned and cine DENSE datasets were acquired six times. In between each acquisition the phantom was moved toward the head direction in 5 mm increments to create a range of translations. For each phantom position, a coronal slice, a transverse slice and an oblique slice between the coronal and transverse planes were scanned. The motions seen by these three slices were in-plane translation, through-plane motion and a combination of in-plane and through-plane motion, respectively. Cine DENSE datasets were acquired with the following parameters: FOV = $260 \times 260 \text{ mm}^2$, 10 spiral interleaves, spiral readout length of 2.8 ms, in-plane spatial resolution of $3.4 \times 3.4 \text{ mm}^2$, 2 spiral interleaves per heartbeat, TR = 15 ms, TE = 1.08 ms, and slice thickness = 8 mm. The displacement encoding frequency was 0.10 cycles/mm, and the through-plane dephasing frequency was 0.04 cycles/mm. The T1 of the phantom was approximately 150 ms. DENSE imaging was performed with a simulated RR interval of 1000 ms. Ten frames were imaged for the phantom experiment. The trigger time of the images used for data analysis was 150 ms. For analysis, we correlated the residual T1-echo energy with the amount of phantom motion and we demonstrated the ability to perform motion estimation and compensation using ste-iNAVs.

In addition, free-breathing cine DENSE datasets were acquired from 12 healthy volunteers (7 male, 27.3 ± 2.1 years old) who were scanned in accordance with protocols approved by our institutional review board after providing informed consent. All volunteer imaging was performed on 3T systems (Magnetom Trio and Magnetom Prisma; Siemens Healthcare, Erlangen, Germany) with a phased-array body coil (6-channel for Magnetom Trio and 18-channel for Magnetom Prisma) and a 32-channel spine coil. After the acquisition of localizer images, a mid-ventricular short-axis slice was acquired during both breath-holding and free-breathing acquisitions with the following parameters: FOV = $160 \times 160 \text{ mm}^2$, thickness of localized stimulated echo = $80 - 100 \text{ mm}^2$, 6 spiral interleaves per image, 2 interleaves per heartbeat, spiral readout length of 3.4 ms, in-plane spatial resolution of $3 \times 3 \text{ mm}^2$, slice thickness = 8 mm, TR = 15 ms, TE = 1.08 ms, and temporal resolution of 30 ms. Ramped flip angles with a final flip angle of 15° were employed to achieve a consistent signal-to-noise ratio (SNR) through the cardiac cycle.(27) Fat suppression was employed by applying a fat saturation pulse immediately after ECG triggering as previously described(9, 28). Depending on the heart rate of the subject, 22–30 frames were acquired, covering approximately 80% of the RR interval. The rest of the RR interval was used to acquire the dNAV and allow for variation in the RR interval. The total scan time was 18 heartbeats (corresponding to one average) for breath-hold acquisitions and 54 heartbeats (corresponding to the acquisition of each interleave three times, and implemented using the averaging loop) for free-breathing acquisitions. The DENSE loop structure, from inner to outer, looped through spiral interleaves, averages, phase-cycling pairs, and displacement-encoding dimensions, which included reference, x-encoded and y-encoded acquisitions.(29) The temporal and spatial resolutions were chosen based on protocols that have been reported

in clinical studies to provide a balance of SNR, temporal resolution, and total scan time.(30) Additionally, for 5 subjects, a 15-average dataset (270 heartbeats in duration) was acquired and these data were used to demonstrate the relationships between ste-iNAV and c-iNAV motion estimation and dNAV data. All 3-average datasets were reconstructed offline three ways in MATLAB (Mathworks, Natick, MA) using: (a) the conventional dNAV method, (b) the c-iNAV method and (c) the match-making framework.

Evaluation of the match-making framework

We used the volunteer data to evaluate intermediate steps of the match-making framework as applied to in vivo imaging. Specifically, we computed the correlation between the residual T1-echo energy and the difference in the dNAV positions for all phase-cycling interleave pairs from free-breathing acquisitions. These data could demonstrate that low residual T1-echo energy of ps-interleaves indicates that the phase-cycled interleave pair were acquired at matched respiratory phases, and vice versa. We also compared ste-iNAVs with c-iNAVs by assessing the correlation of motion estimated from iNAVs with respiration measured by dNAVs using the 15-average acquisitions. Specifically, for each of the first 15 heartbeats, the best phase-cycling match was found from subsequent heartbeats. Then ste-iNAVs were reconstructed and used to estimate respiration-induced heart motion (2D translations) between the ste-iNAVs. The translations were then correlated to the dNAV positions of the first 15 heartbeats. Correlations were analyzed for both x- and y-translations, and for all encoding dimensions. For comparison, translations were also estimated using c-iNAVs for the first 15 heartbeats of the same datasets and correlated to the dNAV positions. The Signed Rank test was used to test for statistically significant differences in correlations with significance level set at 0.05. In addition, the motion estimation algorithm was applied to ste-iNAVs reconstructed from the breath-holding datasets to demonstrate that negligible motion estimates are obtained in these conditions. The range of motion from breath-holding ste-iNAVs was compared to that estimated from free-breathing datasets.

Comparison of the match-making framework with the conventional dNAV and c-iNAV methods for reconstructing free-breathing cine DENSE images

Finally, free-breathing cine DENSE magnitude and phase images reconstructed using dNAV, c-iNAV, and match-making framework were compared. Each of the volunteer datasets was reconstructed using all three methods. Because factors that affect intrinsic SNR such as number of averages, voxel size, and readout time were constant for all reconstruction methods, but breathing artifacts can lead to an apparent SNR reduction by effecting both the myocardial and background signals, we compared the different reconstruction methods using the apparent SNR. The apparent SNR was measured from magnitude-reconstructed images using a region of interest (ROI) that included all of the myocardium within a slice and a large background ROI. The apparent SNR was calculated as the mean of the myocardial ROI divided by the standard deviation of the background ROI, and the correction for the Rician distribution of the magnitude signal was applied. (27, 31) In addition, phase quality (the variance of the local 2D spatial derivative of the phase image) (32, 33) was measured from all of the manually-segmented myocardium within each slice. Phase quality was calculated for background phase-corrected phase images after phase unwrapping. Also, for each reconstruction method, the residual T1-echo energy was computed from the

corresponding raw data. Given that k-space energy varies among subjects and scans, for each dataset the residual T1-echo energy was normalized to a baseline value estimated from early systole (the minimal residual T1-echo energy within 300 ms after the displacement-encoding pulses) of the best-matched phase-cycling interleaves and the normalized value is referred as relative residual T1-echo energy. In this way, the residual T1-echo energy can be compared both among reconstruction methods and among subjects. Apparent SNR, phase quality and the relative residual T1-echo energy were averaged over all cardiac phases.

The total acceptance windows and the inter-phase-cycling motion for accepted data were also compared for each reconstruction method. The total acceptance windows were computed using the corresponding dNAV data defined as the range of dNAV positions for accepted heartbeats. The inter-phase-cycling motion was quantified as the difference in dNAV positions between the two interleaves of each accepted phase-cycling pair. All quantifications are presented as mean $\pm$ standard error. One-way repeated-measures ANOVA (or one-way repeated-measures ANOVA with ranks if the normality test failed) was used to test for statistical significance with significance level set at 0.05. Lastly, circumferential strain was computed (33) using a single-slice six-segment model for each reconstruction method. Bland-Altman plots were used to analyze agreement of strain values from free-breathing acquisitions with those from breath-holding acquisitions.

Results

Demonstration of the match-making framework with phantom experiments

We acquired DENSE data from a phantom positioned at different locations to demonstrate the reduction of striping and blurring artifacts using matching of phase-cycled interleaves and ste-iNAV motion correction. Example k-space domain signals after subtraction of phase-cycled interleaves sampled along a spiral trajectory are illustrated in Fig. 4a. In one case (black line) the phase-cycled interleaves were acquired at matched locations and in the other case (red line) the phase-cycled interleaves were acquired at mismatched locations. For matched locations, the echo due to T1 relaxation is well suppressed, whereas for mismatched locations it is not (arrows). Multiple peaks corresponding to the T1-relaxation echo are observed because the spiral trajectory intersects the T1-relaxation echo multiple times, as shown in Fig. 4b. Experiments were performed where the phantom was moved between 0 – 25 mm with 5 mm increments, and Fig. 4c–e demonstrate that the residual T1-echo energy after subtraction of phase-cycled interleaves is linearly related to the distance the phantom was moved between the acquisitions of the phase-cycled interleaves. This finding holds for in-plane motion (Fig. 4c), through-plane motion (Fig. 4d), and a combination of in-plane and through-plane motion (Fig. 4e). These results show that the residual T1-echo energy is an indicator of the amount of motion between acquisitions of phase-cycled interleaves, and that very low residual T1-echo energy can be used to select phase-cycled interleaves acquired at matched locations (match-making). For the case of in-plane motion, Fig. 4g–h shows that striping artifacts are removed from the DENSE image when phase-cycled interleaves from matched locations are selected and subtracted, but image blurring still occurs when ps-interleaves from different locations are combined for the reconstruction. By using the ste-iNAV of each ps-interleave for motion estimation, k-space

domain motion correction can be applied to compensate for the blurring induced by in-plane motion (Fig. 4i), and the images corrected for in-plane motion compare favorably to corresponding images from data acquired at a single position (Fig. 4f). The example images for the cases of through-plane motion and combined motion are shown in the Supporting Fig. S1. Together, these results demonstrate the use of match-making and ste-iNAV-based motion estimation to compensate for motion-induced artifacts.

Evaluation of the match-making framework in volunteers

For in-vivo evaluation, two datasets were excluded from analysis due to extremely low SNR and extensive artifacts in images reconstructed by dNAV, c-iNAV, and match-making methods. Fig. 5 demonstrates the use of the residual T1-echo energy as an effective criterion for matching phase-cycled interleaves for in vivo imaging. The respiratory pattern of a volunteer as measured by the dNAV signal is shown in Fig. 5a, and the respiratory phases of three interleaves are annotated. Specifically, interleave A (Int-A) and interleave B (Int-B) are a pair of phase-cycled interleaves acquired at different respiratory phases, while Int-B and Int-C are phase-cycled interleaves acquired at a similar respiratory phase. Fig. 5b shows the k-space domain data after subtraction of the two pairs of phase-cycled interleaves and demonstrates suppression of the residual T1-echo for interleaves acquired at matched respiratory phases and substantial residual T1-echo signal for interleaves acquired at mismatched respiratory phases. Fig. 5c shows that the residual T1-echo energy remains low throughout the cardiac cycle for the phase-cycled interleaves acquired at similar respiratory phases, but increases for the phase-cycled interleaves acquired at different respiratory phases. For all phase-cycled interleave pairs from this acquisition, the relative residual T1-echo energy (averaged over all cardiac frames) was highly correlated with the difference in the corresponding dNAV positions, dNAV, with R^2 of 0.71. The average R^2 for all subjects was 0.61 ± 0.04 ($N = 10$). These results demonstrated that the relative residual T1-echo energy was an indicator of respiratory motion between phase-cycled interleaves.

Match-maker ste-iNAVs assess respiration-induced heart motion better than conventional iNAVs

Fig. 6 shows (a) a c-iNAV reconstructed using a simple low-pass filter to suppress the T1-relaxation echo, (b) a c-iNAV reconstructed using a simple low-pass filter and PCA filtering, and (c) a match-maker ste-iNAV. The ste-iNAV is localized to heart and depicts the heart more clearly than the c-iNAVs. Note that Fig. 6 shows navigator images, not reconstructed DENSE images. Fig. 6 also shows the correlation between respiration-induced heart motion as estimated by iNAVs and diaphragm motion as measured by dNAVs for both c-iNAVs (with low-pass and PCA filtering) and ste-iNAVs. As shown in Fig. 6g, the correlation for ste-iNAVs was significantly higher than that of c-iNAVs for the same datasets, with an R^2 of 0.82 ± 0.03 vs. 0.70 ± 0.05 ($P < 0.05$). This result supports the premise that motion estimation was more accurate using ste-iNAVs compared to using c-iNAVs. Also, we found that the overall range of heart motion due to respiration estimated from breath-holding ste-iNAVs was negligible (0.62 ± 0.20 mm, $N = 5$) compared to the range of heart motion estimated from the free-breathing ste-iNAVs (6.75 ± 3.33 mm, $N = 5$).

Comparison of cine DENSE reconstructions using the match-making framework with the conventional c-iNAV and dNAV methods

Example cine DENSE magnitude and phase images for the dNAV, c-iNAV, and matchmaker reconstruction methods applied to the same raw data are shown in Fig. 7 for both systolic and diastolic cardiac frames. Magnitude reconstructed images using the dNAV and c-iNAV methods had striping artifacts due to residual T1-relaxation echoes (yellow arrows). However, for the match-making framework, the magnitude reconstructed image had less artifact, higher apparent SNR, and less blurring. The phase images of the match-maker framework had a smoother appearance within the myocardium. The relative residual T1-echo energy, apparent SNR, and phase quality are summarized for all volunteer data in Fig. 8a–c. The relative residual T1-echo energy of the match-making framework was significantly lower than that of the dNAV and c-iNAV methods, demonstrating that the match-making framework better suppressed the T1 relaxation echoes. The apparent SNR of the match-making framework was higher than for both the dNAV and c-iNAV methods, and the phase quality was lower or trended to be lower than that of the dNAV and c-iNAV methods, demonstrating better image quality.

Fig. 8d–e compares the total acceptance windows (as measured by the dNAV positions) and the motion within each accepted phase-cycled interleave pair (as measured by the dNAV positions) for the dNAV and c-iNAV methods and for the match-making framework. The match-making framework had a larger total acceptance window than the conventional dNAV method, indicating that it accepted data from a wider range of respiratory phases. The motion within selected phase-cycled interleave pairs was smaller for the match-making framework compared to the c-iNAV method.

Fig. 9 shows the Bland-Altman plots of circumferential strain comparing agreement between free-breathing and breath-holding acquisitions for all subjects and all segments. The match-making framework provided better agreement with breath-holding acquisitions than the dNAV and c-iNAV methods.

Discussion

In this study, we developed and evaluated a framework for self-navigated free-breathing cine DENSE MRI that addresses two consequences of motion - striping artifacts due to incomplete suppression of the T1-relaxation echo and blurring. While a conventional iNAV approach is complicated by the presence of the T1-relaxation echo, we showed that low post-subtraction residual T1-echo energy is a simple and useful metric to indicate whether phase-cycled DENSE interleaves were acquired at matched respiratory phases. While low residual T1-echo energy was shown to be effective for matching phase-cycled interleaves, this metric alone does not provide information about the absolute position of the heart and cannot be used for motion compensation of post-subtraction data. However, we showed that ste-iNAVs reconstructed from interleaves acquired at matched locations are localized, not contaminated by T1-relaxation echo artifacts, and can be used to accurately and automatically estimate in-plane heart motion due to respiration. Indeed, we showed that ste-iNAV motion estimation correlated better than conventional iNAV motion estimation with dNAV-measured respiratory motion, and our results further showed that the match-making

framework reconstructions provided higher apparent SNR and a trend toward better phase quality for free-breathing cine DENSE than did the dNAV or c-iNAV reconstructions applied to the same raw data.

Both in-plane and through-plane motion can lead to changes in the complex T1-relaxation echo and, subsequently, to an increase of the residual T1-echo energy after subtraction of phase-cycled interleaves. In-plane displacement causes a phase shift of the k-space domain data. For through-plane motion, different tissue contributes to the different T1-relaxation echoes. Both types of motion lead to residual signal after subtraction of the phase-cycled interleaves. Although the underlying motion mechanisms leading to reduced T1-echo energy are different for in-plane and through-plane motion, in both cases low values of residual T1-echo energy identify phase-cycled interleaves acquired at matched locations.

Respiratory motion estimated by the ste-iNAVs correlated well with dNAV motion, as shown in Fig. 6g, whereas respiratory motion estimated by c-iNAVs had an overall lower correlation across all subjects. Furthermore, motion estimation using the ste-iNAVs was completely automatic, without needing manual definition of a region of interest. These results were obtained because the ste-iNAVs were designed to have suppression of the T1-relaxation echo and localized generation of stimulated echo. In addition, because c-iNAVs are reconstructed from data prior to phase-cycling subtraction, they consist of signal from both the stimulated echo and the T1-relaxation echo. Even with PCA-based filtering and/or low-pass filtering, our experience showed that these iNAVs can still be corrupted by the T1-relaxation echo and are not well-localized to the heart. Therefore, the c-iNAVs are poorly-suited for respiratory motion estimation for cine DENSE. With these results, the match-making framework accepts data from any respiratory position and uses motion estimation and motion correction, while the dNAV and c-iNAV methods use retrospective gating but do not employ motion estimation and correction.

The total acceptance window, as defined by the full range of diaphragm positions for all accepted data, was greater for the match-making framework and trended to be larger for the c-iNAV method than for the conventional dNAV method. However, the motion between phase-cycled interleaves, as measured by the corresponding diaphragm positions, was lower for the match-making framework compared to the c-iNAV method. The lower amount of motion between phase-cycled interleaves led to a lower residual T1-echo energy and high quality ste-iNAVs for the match-making framework. Even though the total acceptance window was large, the high-quality ste-iNAVs provided good motion estimation and compensation, and altogether the match-making framework with motion estimation and compensation produced higher apparent SNR and better phase quality in human subjects than the c-iNAV method. This further demonstrated that the c-iNAV method was not suitable for self-navigation for free-breathing cine DENSE imaging.

While the simple method for displacement encoding was used in this study, another option would have been to use the balanced displacement-encoding method.⁽²⁹⁾ With simple encoding, for the phase reference acquisition, the stimulated echo and T1-relaxation are overlaid in k-space, which is non-ideal for matchmaking (although matchmaking does still work for this case). The balanced displacement encoding method more naturally separates

the stimulated echo and T1 relaxation echo in k-space for all displacement-encoding dimensions and avoids the overlay problem. In the present study, the simple method was chosen because it leads to less phase wrapping.(29) Nonetheless, in the future balanced encoding may be better suited for use with matchmaking, perhaps when used in combination with lower displacement-encoding frequencies or more effective phase-unwrapping algorithms.

Having established that the residual T1-echo energy is an effective metric for identifying spiral phase-cycled interleaves acquired at matched locations, in the future this metric may be used to develop an adaptive data acquisition strategy for efficient free-breathing self-navigated cine DENSE. Similar to the diminishing variance algorithm that was previously applied to conventional navigator data (34), an adaptive strategy would be to acquire an initial complete set of spiral interleaves, compute all the residual T1-echo energies in real time, and then to reacquire interleaves with the highest residual T1-echo energy until all interleaves have an acceptably low residual T1-echo energy. Such an approach may provide high-quality free-breathing cine DENSE images with improved time efficiency.

A limitation of the current approach was that an off-resonance deblurring correction for spiral imaging was not employed due to the fact that the field map acquisition was not localized to the heart and therefore the reduced field-of-view was not applied for field map acquisitions. However, the spiral readout was shortened to largely account for the effects of off-resonance. In the protocol employed in this study, the repetition time was not set to its shortest possible value, as using the minimum TR would have led to a lower SNR. Instead, TR = 15ms was selected in order to maintain an SNR similar to prior studies.(30)

In addition, the present motion estimation and compensation methods only considered two-dimensional in-plane translation. Combining stimulated echoes with differing through-plane motions may lead to suboptimal images, and methods to reject, accept, and/or correct for through-plane motion may need to be developed in the future. Another limitation of the study is that only healthy volunteers were scanned. The method will be applied in patients after implementation of the adaptive acquisition strategy in order to acquire data more efficiently. Presently all image reconstruction was performed offline. In the future, we will implement an online version of the match-making framework. Lastly, the measured improvements in apparent SNR, phase quality and strain compared to the dNAV and c-iNAV methods were modest. It is likely that the improvements were not greater because our experiments involved the acquisition of only three averages and used a predefined acquisition order, which limited the degree to which respiratory phases could be closely matched and to which the residual T1-echo energy could be fully minimized. The envisioned real-time adaptive approach to match-making is expected to overcome this limitation, may provide good suppression of the T1-relaxation echo for all interleaves, and may provide greater advantages compared to conventional navigator methods.

The match-maker iNAV concept for free-breathing scans may be generalizable to other MRI acquisitions that utilize phase-cycled subtractions to suppress signals, such as myocardial tagging using complementary spatial modulation of magnetization (35, 36), localized spectroscopy (37), and T1rho imaging (38) with phase cycling.

In conclusion, the match-making framework with motion estimation and compensation addresses both the striping and blurring effects of respiratory motion in free-breathing cine DENSE and provides advantages compared to conventional dNAV and c-iNAV methods. In the future, adaptive acquisition strategies based on the match-making framework as well as compensation for through-plane motion may enable efficient and high-quality free-breathing cine DENSE imaging with simple setup procedures in clinically-applicable scan times.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix

Principle component analysis (PCA) to separate signals for improved conventional cine DENSE iNAVs

In this study, we assessed respiratory motion estimation using the match-maker ste-iNAV method and a conventional iNAV method. When implementing a simple conventional iNAV method for cine DENSE, we found that the T1-relaxation echo led to very poor quality iNAVs and very poor motion estimation performance. To get improved performance, we applied PCA to the iNAV data to separate the stimulated-echo and T1-relaxation-echo signals, and we reconstructed iNAVs after removal of the main T1-relaxation-echo component.

As shown in Supporting Fig. S2a, preliminarily iNAVs were organized into a spatiotemporal Casorati matrix, S , where each column represents the pixels from each iNAV.(39) PCA was performed to decompose the matrix, S , into spatial and temporal bases. Supporting Fig. S2b–g shows the first and second spatial bases in the image and k-space domains, and also shows their temporal bases, respectively. The first spatial basis in the image and k-space domains and the first temporal basis were found to predominantly represent the T1-relaxation-echo signal (Supporting Fig. S2, b–d). The second spatial basis in the image and k-space domains and the second temporal basis were found to predominantly represent the stimulated-echo signal (Supporting Fig. S2, e–g). After the first principal component was removed and a low-pass filter was applied to the k-space data to further suppress the residual T1-relaxation-echo signal, iNAVs were reconstructed from the k-space data.

Demonstration of the effect of PCA-based and low-pass filtering on the iNAVs is shown in Supporting Fig. S3. Without filtering, the iNAV has a strong T1 relaxation signal outside the heart (predominantly fat signal from chest wall in this example) (Supporting Fig. S3a, white

arrow), while the iNAV reconstructed with filtering shows better suppression of the signal outside the heart (Supporting Fig. S3c). By using manually-tracked iNAVs as a reference, we showed that automatic motion estimation using cross-correlation applied to iNAVs with PCA-based and low-pass filtering had better performance for estimating motion of the heart due to respiration, whereas motion estimation applied to iNAVs without PCA-based filtering had worse performance (Supporting Fig. S3, e,f).

References

1. Kim D, Gilson WD, Kramer CM, Epstein FH. Myocardial tissue tracking with two-dimensional cine displacement-encoded MR imaging: development and initial evaluation. *Radiology*. 2004; 230(3): 862–71. [PubMed: 14739307]
2. Young AA, Li B, Kirton RS, Cowan BR. Generalized spatiotemporal myocardial strain analysis for DENSE and SPAMM imaging. *Magnetic resonance in medicine*. 2012; 67(6):1590–9. [PubMed: 22135133]
3. Lin K, Meng L, Collins JD, Chowdhary V, Markl M, Carr JC. Reproducibility of cine displacement encoding with stimulated echoes (DENSE) in human subjects. *Magnetic resonance imaging*. 2017; 35:148–53. [PubMed: 27569367]
4. Gilliam AD, Epstein FH. Automated motion estimation for 2-D cine DENSE MRI. *IEEE transactions on medical imaging*. 2012; 31(9):1669–81. [PubMed: 22575669]
5. Auger DA, Bilchick KC, Gonzalez JA, Cui SX, Holmes JW, Kramer CM, et al. Imaging left-ventricular mechanical activation in heart failure patients using cine DENSE MRI: Validation and implications for cardiac resynchronization therapy. *Journal of Magnetic Resonance Imaging*. 2017
6. Mangion K, Carrick D, Carberry J, Mahrous A, McComb C, Gao H, et al. Comparative prognostic value of myocardial strain derived from DENSE CMR: the British Heart Foundation MR-MI study. *The Lancet*. 2017; 389:S66.
7. Jing L, Binkley CM, Suever JD, Umasankar N, Haggerty CM, Rich J, et al. Cardiac remodeling and dysfunction in childhood obesity: a cardiovascular magnetic resonance study. *Journal of Cardiovascular Magnetic Resonance*. 2016; 18(1):28. [PubMed: 27165194]
8. Ehman RL, Felmlee JP. Adaptive technique for high-definition MR imaging of moving structures. *Radiology*. 1989; 173(1):255–63. [PubMed: 2781017]
9. Zhong X, Spottiswoode BS, Meyer CH, Kramer CM, Epstein FH. Imaging three-dimensional myocardial mechanics using navigator-gated volumetric spiral cine DENSE MRI. *Magnetic resonance in medicine*. 2010; 64(4):1089–97. [PubMed: 20574967]
10. Larson AC, White RD, Laub G, McVeigh ER, Li D, Simonetti OP. Self-gated cardiac cine MRI. *Magnetic Resonance in Medicine*. 2004; 51(1):93–102. [PubMed: 14705049]
11. Uribe S, Muthurangu V, Boubertakh R, Schaeffter T, Razavi R, Hill DL, et al. Whole-heart cine MRI using real-time respiratory self-gating. *Magnetic Resonance in Medicine*. 2007; 57(3):606–13. [PubMed: 17326164]
12. Usman M, Atkinson D, Odille F, Kolbitsch C, Vaillant G, Schaeffter T, et al. Motion corrected compressed sensing for free-breathing dynamic cardiac MRI. *Magnetic resonance in medicine*. 2013; 70(2):504–16. [PubMed: 22899104]
13. Kellman P, Larson AC, Hsu LY, Chung YC, Simonetti OP, McVeigh ER, et al. Motion-corrected free-breathing delayed enhancement imaging of myocardial infarction. *Magnetic resonance in medicine*. 2005; 53(1):194–200. [PubMed: 15690519]
14. Stehning C, Börner P, Nehrke K, Eggers H, Stuber M. Free-breathing whole-heart coronary MRA with 3D radial SSFP and self-navigated image reconstruction. *Magnetic resonance in medicine*. 2005; 54(2):476–80. [PubMed: 16032682]
15. Henningsson M, Koken P, Stehning C, Razavi R, Prieto C, Botnar RM. Whole-heart coronary MR angiography with 2D self-navigated image reconstruction. *Magnetic resonance in medicine*. 2012; 67(2):437–45. [PubMed: 21656563]

16. Lai P, Larson AC, Bi X, Jerecic R, Li D. A dual-projection respiratory self-gating technique for whole-heart coronary MRA. *Journal of Magnetic Resonance Imaging*. 2008; 28(3):612–20. [PubMed: 18777542]
17. Chow K, Yang Y, Shaw P, Kramer CM, Salerno M. Robust free-breathing SASHA T1 mapping with high-contrast image registration. *Journal of Cardiovascular Magnetic Resonance*. 2016; 18(1): 47. [PubMed: 27535744]
18. Zhong X, Spottiswoode BS, Cowart EA, Gilson WD, Epstein FH. Selective suppression of artifact-generating echoes in cine DENSE using through-plane dephasing. *Magnetic resonance in medicine*. 2006; 56(5):1126–31. [PubMed: 17036303]
19. Goto Y, Ishida M, Takase S, Sigfridsson A, Uno M, Nagata M, et al. Comparison of Displacement Encoding With Stimulated Echoes to Magnetic Resonance Feature Tracking for the Assessment of Myocardial Strain in Patients With Acute Myocardial Infarction. *The American Journal of Cardiology*. 2017; 119(10):1542–7. [PubMed: 28335982]
20. Kihlberg J, Haraldsson H, Sigfridsson A, Ebberts T, Engvall JE. Clinical experience of strain imaging using DENSE for detecting infarcted cardiac segments. *Journal of Cardiovascular Magnetic Resonance*. 2015; 17(1):50. [PubMed: 26104510]
21. Winkelmann S, Schaeffter T, Koehler T, Eggers H, Doessel O. An optimal radial profile order based on the Golden Ratio for time-resolved MRI. *IEEE transactions on medical imaging*. 2007; 26(1):68–76. [PubMed: 17243585]
22. Kim YC, Narayanan SS, Nayak KS. Flexible retrospective selection of temporal resolution in real-time speech MRI using a golden-ratio spiral view order. *Magnetic resonance in medicine*. 2011; 65(5):1365–71. [PubMed: 21500262]
23. Mills P, Chew W, Litt L, Moseley M. Localized imaging using stimulated echoes. *Magnetic resonance in medicine*. 1987; 5(4):384–9. [PubMed: 3683170]
24. Aletras AH, Balaban RS, Wen H. High-resolution strain analysis of the human heart with fast-DENSE. *Journal of Magnetic Resonance*. 1999; 140(1):41–57. [PubMed: 10479548]
25. Walsh DO, Gmitro AF, Marcellin MW. Adaptive reconstruction of phased array MR imagery. *Magnetic Resonance in Medicine*. 2000; 43(5):682–90. [PubMed: 10800033]
26. Fessler JA, Sutton BP. Nonuniform fast Fourier transforms using min-max interpolation. *IEEE Transactions on Signal Processing*. 2003; 51(2):560–74.
27. Wehner GJ, Suever JD, Haggerty CM, Jing L, Powell DK, Hamlet SM, et al. Validation of in vivo 2D displacements from spiral cine DENSE at 3T. *Journal of Cardiovascular Magnetic Resonance*. 2015; 17(1):5. [PubMed: 25634468]
28. Fahmy AS, Ibrahim E-SH, Osman NF. Spectrally-Presaturated Modulation (SPM): An efficient fat suppression technique for STEAM-based cardiac imaging sequences. *Magnetic resonance imaging*. 2017; 37:209–15. [PubMed: 27826082]
29. Zhong X, Helm PA, Epstein FH. Balanced multipoint displacement encoding for DENSE MRI. *Magnetic resonance in medicine*. 2009; 61(4):981–8. [PubMed: 19189288]
30. Bilchick KC, Kuruvilla S, Hamirani YS, Ramachandran R, Clarke SA, Parker KM, et al. Impact of mechanical activation, scar, and electrical timing on cardiac resynchronization therapy response and clinical outcomes. *Journal of the American College of Cardiology*. 2014; 63(16):1657–66. [PubMed: 24583155]
31. Constantinides CD, Atalar E, McVeigh ER. Signal-to-noise measurements in magnitude images from NMR phased arrays. *Magnetic Resonance in Medicine*. 1997; 38(5):852–7. [PubMed: 9358462]
32. Ghiglia DC, Pritt MD. Two-dimensional phase unwrapping: theory, algorithms, and software. Wiley New York: 1998.
33. Spottiswoode BS, Zhong X, Hess AT, Kramer C, Meintjes EM, Mayosi BM, et al. Tracking myocardial motion from cine DENSE images using spatiotemporal phase unwrapping and temporal fitting. *IEEE transactions on medical imaging*. 2007; 26(1):15–30. [PubMed: 17243581]
34. Sachs TS, Meyer CH, Irarrazabal P, Hu BS, Nishimura DG, Macovski A. The diminishing variance algorithm for real-time reduction of motion artifacts in MRI. *Magnetic resonance in medicine*. 1995; 34(3):412–22. [PubMed: 7500881]

35. Axel L, Dougherty L. MR imaging of motion with spatial modulation of magnetization. *Radiology*. 1989; 171(3):841–5. [PubMed: 2717762]
36. Axel L, Dougherty L. Heart wall motion: improved method of spatial modulation of magnetization for MR imaging. *Radiology*. 1989; 172(2):349–50. [PubMed: 2748813]
37. Knight-Scott J, Shanbhag DD, Dunham SA. A phase rotation scheme for achieving very short echo times with localized stimulated echo spectroscopy. *Magnetic resonance imaging*. 2005; 23(8):871–6. [PubMed: 16275426]
38. Li X, Han ET, Ma CB, Link TM, Newitt DC, Majumdar S. In vivo 3T spiral imaging based multi-slice T1ρ mapping of knee cartilage in osteoarthritis. *Magnetic resonance in medicine*. 2005; 54(4):929–36. [PubMed: 16155867]
39. Lingala SG, Hu Y, DiBella E, Jacob M. Accelerated dynamic MRI exploiting sparsity and low-rank structure: kt SLR. *IEEE transactions on medical imaging*. 2011; 30(5):1042–54. [PubMed: 21292593]

Fig. 1.

Illustration of motion-induced striping and blurring artifacts in cine DENSE imaging. In this experiment, fully-sampled cine DENSE images were acquired with the phantom located at position 1 and also at position 2. Motion, simulated by combining phase-cycling pairs from positions 1 and 2, induces insufficient suppression of the T1-relaxation echo (panel e, white arrow) and corresponding striping artifacts in the images (panel f). If phase-cycled data at matched positions are subtracted (panels a, c), but motion occurs between k-space segments after successful suppression of the T1-relaxation echo (panel b, d), then blurring artifact occurs when combining data from different segments (panel g). In this example, half of the k-space data was taken from each of the two positions. In vivo example images demonstrating both blurring and striping artifacts due to respiratory motion are also shown. (Panel h, BH: breath-holding; FB: free-breathing.)

a. The proposed strategy using match-making and ste-iNAV based motion compensation.

b. Conventional gating strategy using dNAV or c-iNAV.

Fig. 2.

(a) Diagram of the proposed match-making framework for free-breathing cine DENSE imaging. First, match-making is applied to identify phase-cycled interleave pairs acquired at matched respiratory positions to compensate for striping artifacts. The two blue circles identify a matched phase-cycling pair and the two green circles identify another matched pair. Phase-cycling subtraction is performed using the identified phase-cycled interleaves and ste-iNAV are reconstructed from post-subtraction data. Lastly, ste-iNAV based in-plane motion estimation and correction is performed to compensate for blurring artifacts. (b) Diagram of the conventional respiratory gating strategy using dNAVs or conventional iNAVs (c-iNAVs), where data within a narrow window around end-expiration are accepted.

Fig. 3.

Diagram of the pulse sequence used for free-breathing cine DENSE. Fat saturation (FS) is applied after each ECG trigger, followed by displacement encoding (DE) pulses, spiral acquisitions (ACQ) and the diaphragm navigator (dNAV). Localized generation of stimulated echoes is performed by applying slice selection for all RF pulses, including those in the displacement encoding module. Data acquisition uses a segmented spiral trajectory with golden angle rotation of the trajectory through cardiac frames. Each iNAV frame consists of four cine DENSE frames (i.e., eight consecutive spiral interleaves).

Fig. 4.

Results of the phantom experiment demonstrating the match-maker method. (a) Intensities of k-space data along a post-subtraction spiral interleave (ps-interleave) from subtraction of matched phase-cycled interleaves (black curve) and mismatched phase-cycled interleaves (red curve). Strong residual T1-relaxation echo signal remains in the ps-interleave from the mismatched subtraction (arrows). (b) Illustrative trajectory of the ps-interleave in (a). (c–e) Correlation between the residual T1-relaxation echo energy of the ps-interleave and the amount of translation between interleaves for in-plane motion (c), through-plane motion (d), and a combination of both in-plane and through-plane motion (e), respectively. (f–i) Demonstration of applying the match-maker framework for the cases of in-plane. (f)

Motion-free reference images. (g) Images reconstructed using ps-interleaves of mismatched phase-cycled interleave pairs have strong striping artifacts and blurring. (h) The images from ps-interleaves with matched phase-cycling but with motion between ps-interleaves show removal of striping artifacts but still have blurring. (i) Using the match-making framework with motion compensation, blurring artifacts due to in-plane motion were also removed.

Fig. 5.

Phase-cycled cine DENSE data acquired during free breathing were processed to show that the relative residual T1-relaxation echo energy from phase-cycled interleave pairs correlates with the difference in the diaphragm positions of the interleave pairs for in vivo imaging. (a) dNAV-based monitoring of respiration is shown, along with the annotated acquisitions of phase-cycled interleaves. (b) Magnitudes of post-subtraction interleaves for interleave pairs at similar (Int(B) – Int(C)) and different (Int(A) – Int(C)) respiratory positions. (c) The relative residual T1-relaxation echo energies of the two phase-cycling pairs at each cardiac frame. (d) The relative residual T1-relaxation-echo energy summed over all cardiac frames is highly correlated to the difference in the diaphragm positions, with $R^2 = 0.71$.

Fig. 6.

Comparison of conventional iNAV and ste-iNAV. Example iNAV are shown for (a) an iNAV reconstructed from pre-subtraction data with low-pass filtering, (b) an iNAV reconstructed with PCA-based and low-pass filtering, and (c) an ste-iNAV from matched ps-interleave data, which is localized to the heart region and provides higher spatial resolution. Panel (d) shows the dNAV positions for 15 consecutive heartbeats, and panel (e) shows heart motion estimated from ste-iNAV for the same 15 heartbeats. Panel (f) provides an example showing that the correlation of iNAV-measured heart motion to dNAV position measured by ste-iNAV is higher than for conventional iNAV (c-iNAV). Panel (g) shows the R^2 values

for all five subjects and for both x- and y-translations and all encoding dimensions (median and interquartile range values are displayed).

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Fig. 7.

Example end-systolic (top box) and diastolic (bottom box) DENSE images reconstructed using the conventional dNAV method, the c-iNAV method and the match-making framework for the same free-breathing volunteer raw data. The magnitude reconstructed images of the match-making method demonstrate lower artifact level, higher apparent SNR and better edge definition. The phase images of the match-making method have smoother phase in the myocardial ROI (arrows), and this is reflected in the better phase quality maps.

Fig. 8.

Quantitative comparisons for DENSE reconstructions using the match-making framework (MM) and the conventional dNAV and c-iNAV methods. (a) The relative residual T1-relaxation echo energy was lower for MM (* $P < 0.05$ vs. dNAV; # $P < 0.05$ vs. iNAV). (b) The apparent SNR of magnitude reconstructed images was higher for MM. (c) The phase quality of phase images was better for MM compared to c-iNAV and trended to be better compared to the dNAV method (\$ $P = 0.06$ vs. dNAV). (d) The match-making framework had a larger total acceptance window than the dNAV method, indicating that it accepted data from a wider range of respiratory phases (% $P = 0.08$ vs. dNAV). (e) The motion within phase-cycled interleave pairs was smaller for MM than for the c-iNAV method (& $P < 0.05$ vs. iNAV, one-way repeated measures ANOVA on ranks), indicating that the match-making framework identified phase-cycled interleaves at closer respiratory phases.

Fig. 9.

Comparison of agreement of circumferential strain from free-breathing acquisitions with that from breath-holding acquisitions for each reconstruction method. The match-making framework (MM, panel c) provided better agreement of strain with breath-holding acquisitions (BH) than the conventional dNAV and c-iNAV methods (panels a, b)