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B₀ Mapping using Rewinding Trajectories (BMART)

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Abstract

Purpose—To create a B₀ map and correct for off-resonance with minimal scan time increase for 2D or 3D non-Cartesian acquisitions.

Methods—Rewinding trajectories that bring the zeroth gradient moment to zero every TR were used to estimate the off-resonance with a center-out 3D cones trajectory, which required an increase in the minimum TR by 5%. The off-resonance estimation and correction was implemented using an algorithm based on binning and object-domain phase correction. B₀ maps using BMART (B₀ Mapping using Rewinding Trajectories) were compared to maps obtained using separate scans with multiple TE in a phantom and human brain.

Results—Excellent agreement between BMART and the multiple-TE method were observed, and images corrected with BMART were deblurred.

Conclusion—BMART can correct for off-resonance without requiring an additional scan, and can be easily applied to center-out or projection trajectories (2D or 3D).

Introduction

Non-Cartesian trajectories such as spirals or projections have numerous advantages, including short TE, rapid acquisition, and benign motion artifacts. However, their widespread use has been hampered by their off-resonance behavior which manifests as blurring. These issues can be addressed with the aid of a B₀ map [1,2], which typically requires an extra scan. In addition to the longer total scan time required, motion occurring between the acquisition of the imaging data and B₀ map can lead to misregistration. There has been significant effort toward correcting off-resonance using self-calibrated approaches with autofocus techniques [3-8]. However, many of these methods require some user input which limits clinical applicability, or perform piecewise linear estimations of the B₀ map which may introduce errors. The ORACLE method allows self-calibration for radial trajectories via clever arrangement of projections [9], but this form of self-calibration cannot be easily generalized to other trajectories (e.g., interleaved spiral).

In this work, B₀ Mapping using Rewinding Trajectories (BMART) is proposed to correct for off-resonance effects for 3D (or 2D) non-Cartesian acquisitions in a fully automatic manner without requiring an extra scan or making any linear approximations. A B₀ map is self-

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acquired by comparing the normally acquired signal to signal acquired during a rewind portion of the trajectory that returns the zeroth gradient moments to zero. In pulse sequences that use balanced gradients, such as balanced SSFP (bSSFP), this method requires negligible scan time and TR increases. Even in cases where rewind gradients are not normally used, a small TR increase for the rewinders is likely merited since the B_0 map is inherently self-registered to the normally acquired data, and the total scan time increase is much less than for an additional B_0 map scan. Any trajectory that repeatedly samples the center of k-space (e.g., spiral or projection) can likely be easily adapted for BMART. In this work, BMART is validated using a 3D cones trajectory [10] in both a phantom and human brain.

Methods

BMART

The basic principle behind BMART is to use the rewind portion of the trajectory to reconstruct an image that is acquired at a later effective TE compared to the normally acquired images. Then, the B_0 map (in rad/s) is just the relative phase between the two images divided by the difference in TE. Therefore, this approach ideally requires that all the rewind portions of the trajectory taken together fully sample k-space. A projection or center-out trajectory (e.g., interleaved spirals) is naturally suited to BMART, because a low-resolution central region can be fully sampled by the rewind portion of the trajectory (Fig. 1).

Before computing a B_0 map, the raw k-space data (both normally acquired, k_{NORM} , and rewind, k_{REW}) is first gridded to a Cartesian sampling pattern at 2x the nominal FOV and multiple receiver channels are combined using sensitivity maps obtained with ESPIRiT [11]. After gridding, the effects of concomitant gradient fields are corrected using an object-domain method similar to one proposed by Cheng [12]. This is an important step prior to computing a B_0 map because phase accrued by concomitant gradient fields will be different between the normal and rewind portions of the trajectory. Multiple-TE methods do not have this issue.

Notably, the acquisition delay between k_{NORM} and k_{REW} varies depending on k-space position. For center-out trajectories, the central k-space regions have a larger delay than the outer regions. BMART accounts for the nonuniform acquisition delays by using the algorithm illustrated in Fig. 2a, where the B_0 map is built up using a multi-resolution approach. N bins of k-space samples are identified based on the mean effective delay between the normal and rewind parts of the acquisition at each k-space position, t_i (Fig. 2b). Bin $i = 1$ corresponds to the bin centered at $k=0$, and increasing i corresponds to increasing distance of the bin from the k-space origin (i.e., while the members of each bin are defined based on acquisition time, the order they are processed is based on the mean distance from the k-space origin). This ordering is used because it results in the most accurate B_0 estimates at low spatial frequencies, which is typically the dominant component of B_0 inhomogeneity. For non-Cartesian trajectories, multiple samples with potentially different acquisition times can contribute to each gridded k-space sample. Therefore, the average acquisition time for each gridded k-space position is used for binning. For each bin, the B_0 map is estimated using

$$B_{0i} = \text{angle} \left(\text{LPF} (S_{REW}) \text{LPF} (S_{NORM}^*) \right) / (\gamma \Delta t_i) - B_0^{\text{error}} \quad [1]$$

where LPF is a low-pass filter operation (Hanning window) to suppress residual undersampling artifacts, $\{S_{NORM}, S_{REW}\}$ is the object-domain data, and $B_0^{\text{error}} = ax + by + cz$ is a linear correction for phase from eddy currents and/or gradient amplifier nonlinearity. The coefficients $\{a, b, c\}$ can be determined by performing a least-squares fit to the difference in B_0 estimated by BMART (with $B_0^{\text{error}} = 0$) and a multiple-TE method in a large, well-shimmed phantom (required for any specific trajectory). Then, B_{0i} is used to advance the phase in bin i to be consistent with the acquisition time in bin $i+1$,

$$\begin{aligned} S_{NORM}' &= S_{NORM} e^{j\gamma B_{0i} \tau_{NORM,i}} \\ S_{REW}' &= S_{REW} e^{j\gamma (B_{0i} \tau_{REW,i} + B_0^{\text{error}} (\Delta t_{i+1} - \Delta t_i))} \end{aligned} \quad [2]$$

where $\tau_{NORM,i}$ and $\tau_{REW,i}$ are the mean time delays between bins i and $i+1$ for the normal and rewind portions of the trajectory, respectively (Fig. 2b). Also note that $\tau_{NORM,i} - \tau_{REW,i} = t_i - t_{i+1}$, and the B_0^{error} term accounts for erroneous phase that has accrued between acquisition of the k_{NORM} and k_{REW} . Finally, S_{NORM}' and S_{REW}' are inverse Fourier transformed, and the k-space samples from bins 1 to i are inserted into k_{NORM} and k_{REW} to start processing of the next bin. Accordingly, at the end of the processing of any bin i , bins 1 to i have been B_0 corrected (i.e., the phase accumulation from B_0 is consistent between all k-space samples). Also, each subsequent bin provides a higher resolution estimate of B_0 (i.e., B_{0i}) compared to the previous bin. After processing all N bins, the images S_{NORM} and S_{REW} are inherently B_0 corrected, and B_{0N} is the final B_0 map.

Notably, the full extent of k-space is used in Eq. 1,2 for every i . While the acquisition times of the bins larger than i are not consistent with bins 1 to i , the sharp discontinuity created by only using the k-space samples from bins 1 to i in the equations creates more error (via Gibb's ringing) than keeping the data at the larger i .

Simulation

A one-dimensional simulation was performed to validate the ability to BMART to account for variable acquisition time delays. The acquisition consisted of two center-out readouts with rewinds (128×1 matrix size) and infinite slew rates were assumed. The object was a rect function with randomly generated fine features, and the ground truth B_0 was generated by slightly low pass filtering a set of random values in the range $[0, 0.02\pi]$ radians per k-space sample.

Acquisitions

Three-dimensional acquisitions using spoiled gradient echo 3D cones [10] were performed in a phantom and in the brain of a volunteer with informed, signed consent on a 1.5 T GE Signa Excite. The 3D cones trajectory uses spiral trajectories played out along conic surfaces to efficiently fill k-space, and the rewinds are designed to return to the k-space

origin as quickly as possible (Sup. Fig. S1). Each conic surface contains several spiral interleaves, and the rewinds are similar to a 3D projection trajectory. For a center-out trajectory with 1.2 mm isotropic resolution, the rewinds are fully sampled to a radius approximately 1/5 the full extent of k-space (i.e., fully sampled resolution ~ 6 mm isotropic) (Sup. Fig. S1). Note that all of the rewind data, including regions of k-space that were undersampled, were used in the BMART algorithm, and undersampling artifacts were reduced using the Hanning low-pass-filter described in the Methods. The 3D cones parameters were: TR = 10.5 ms, TE = 0.6 ms, flip 30°, BW = 250 kHz, FOV = 28 × 28 × 14 cm³, 1.2 mm isotropic resolution, 9137 readouts (scan time = 1.6 min), readout duration = 2.8 ms. The extra time required to return both the gradients and their zeroth moment to zero before gradient spoiling compared to only bringing the gradients to zero was 0.3 ms every TR (minimum TR with rewinds = 5.6 ms compared to 5.3 ms without). The Hanning window used in the BMART computations was heuristically chosen to give an effective isotropic resolution of 4 mm. While this is a finer resolution than the fully sampled extent of the rewinds (6 mm), undersampling artifacts were fairly benign because of the similarity of k_{REW} to a 3D-projection trajectory. Gradient delays from eddy currents were corrected separately for the normal and rewind portions of the trajectory by directly measuring gradient waveforms in a calibration scan and comparing them to the desired output (only required once) [13]. B_0^{error} (Eq. 1,2) was estimated using a 30 cm diameter spherical phantom.

For validation, five additional scans with equally spaced TE ranging from 1.3 ms to 4.1 ms were acquired (all other parameters identical to above). The multiple scans were aligned using rigid body registration [14]. A reference B_0 map, B_0^{MTE} , was computed using the multi-TE data without using any rewind data. The cones trajectory was used to create the reference B_0 map (rather than a different trajectory) because it ensures that contributions to the B_0 map from eddy currents are similar for the BMART and reference B_0 maps.

Results

In the simulation, good agreement between B_0^{BMART} and the true B_0 map was observed; however, errors were observed in regions with phase wrapping (Fig. 3a). At least 10 bins were required to achieve accurate results (Fig. 3b). Agreement between B_0^{BMART} and B_0^{MTE} was also observed in the phantom and brain tissue when 50 bins were used (Fig. 4a). However, some phase-wrap errors can be observed in the fat, where the off-resonance due to chemical shift was large. BMART failed to produce an accurate B_0 map when only one bin was used, and objects with very large inhomogeneity suffered from phase wrap artifacts (Sup. Fig. S2). The root-mean-squared-difference of BMART in the brain with a varying number of bins compared to case with 100 bins shows that increasing the number of bins beyond 50 resulted in little change in B_0^{BMART} (Fig. 4b).

Off-resonance-corrected images that were reconstructed using the BMART algorithm for a deshimmied phantom and brain showed improved resolution of fine features compared to the result when no B_0 correction was applied (Fig. 5). In regions where there was negligible inhomogeneity, the algorithm did not impact the final image.

Discussion

B_0 maps constructed using gradient rewinds agreed well with those obtained using standard multiple-TE methods, and images corrected using BMART exhibited reduced blurring from magnetic field inhomogeneity. For the cones center-out trajectory used here with spoiled gradient echo imaging, the only disadvantages of utilizing BMART are the extra time required to ensure that both the gradients and their zeroth moment return to 0 every TR (0.3 ms) and the additional reconstruction time. BMART is likely directly applicable to other center-out trajectories or projection imaging (including 2D trajectories), because the rewind parts of the cones trajectory are essentially projections. In fact, projection imaging trajectories could contain three effective TEs (using the pre-phasing gradients, center of projection, and rewind), which could allow better robustness to phase wrapping. Interestingly, there is theoretically no pulse sequence cost for using BMART with balanced sequences (e.g., bSSFP) that already implement rewind gradients and center-out trajectories. Another notable advantage of BMART is that the B_0 map is inherently self-registered to the imaging data.

The way in which images are corrected with BMART is similar to the ORACLE method [9]; however, ORACLE uses convolution in k-space rather than multiplication in object space for B_0 correction (Eq. 2). In ORACLE, a relatively small k-space convolution kernel (8×8) is used to approximate the Fourier transform of $e^{i\gamma B_0 t}$, which is equivalent to using a low-spatial frequency approximation of B_0 . Here, a B_0 estimate with high spatial frequencies is used to improve accuracy (i.e., equivalent kernel is large), and using Cartesian object-space data after gridding decreases computation time because of the use of fast Fourier transforms instead of convolution, which is particularly advantageous for large 3D data sets. Notably, there is no benefit to applying the correction to the pre-gridded raw data, because BMART corrects bins of k-space. That is, most adjacent raw data samples will be corrected using the B_0 map corresponding to the same bin. Also, B_0 mapping with varying sampling time differences has been described as a pre-processing step in the context of water-fat separation [15]; however, in that work only the sampling time when $k = 0$ was used (similar to a BMART reconstruction with one bin).

The off-resonance correction is built into the B_0 computation algorithm, which improves the reconstruction efficiency. On a Linux system with dual 2.6 GHz Xeon x5650 CPUs and 72 GB RAM, the total reconstruction time with BMART was 21 min compared to 7 min without. However, reconstruction times could likely be reduced with the implementation of GPU processing. The number of bins will also impact the processing time. In principle, exact time delays at every sampling point could be used to obtain the most accurate B_0 map estimation possible; however, with only 50 bins the processing time is 14x shorter while achieving good agreement with the multiple-TE method.

The determination of B_0^{error} needs to be evaluated for every specific trajectory. It may also require periodic updating to account for long-term variations such as B_0 drift. While this may limit free choice of parameters like FOV and resolution at run-time, multi-subject studies typically use consistent parameters for all scans. Also, it may be possible to omit B_0^{error} altogether if it is very small. On the system used in this work $B_0^{\text{error}} = -0.005\text{ x}$

$-0.007y + 0.056z$ ppm/cm, and deblurring was generally observed even with setting $B_0^{\text{error}} = 0$.

The non-uniform acquisition delays cause the variance of the B_0 map estimate to depend on k . For our 3D cones trajectory, the time delays are shorter for large k , which makes the higher spatial frequencies of the B_0 map estimate more sensitive to noise. This issue is partially mitigated by the low-pass-filter in Eq. 1, at the expense of a lower resolution B_0 map.

BMART can, in principle, correct for off-resonance from chemical shift. However, the current implementation of BMART does not correct for phase wrapping, and some phase-wrap errors were observed in fat. Phase-wrapping occurs in regions where the phase-difference between the normal and rewind images is larger than $\pm\pi$, which is aliased by Eq. 1 (Sup. Fig. S2). In our experience, phase-wrapping is not an issue in brain tissue at 1.5 T for typical readout durations, but it could be an issue at higher field strengths, in the body, or for longer readout durations. For our 2.8 ms long readout using 3D cones, off-resonance up to ± 180 Hz can be tolerated. Unwrapping the phase likely requires new innovation, because typical 3D phase unwrapping techniques could be prohibitively time consuming since they would need to be re-implemented for every bin. In addition, the performance of unwrapping near chemical shift (i.e., near fat) or rapid variation of B_0 would need to be evaluated. The phase wrapping could be reduced or eliminated by using a shorter total readout duration at the expense of increased scan time, because it would decrease the maximum acquisition delay between the normal and rewind portions of the trajectory.

The lower resolution of the BMART B_0 map compared to the normal imaging data could impair off-resonance estimation in regions with very rapid spatial variations of B_0 . While this was not necessary for the cases investigated here, parallel imaging reconstruction could be applied to the rewind data to improve the B_0 map resolution, at the expense of longer reconstruction times. However, it should be noted that the effective resolution of the BMART B_0 map is much higher compared to many other self-calibrated approaches [4-9]. Also, for some trajectories, using the shortest possible rewinds may not fill k -space sufficiently. This could potentially be remedied by designing more sophisticated rewind trajectories that fill k -space more fully. Furthermore, gridding before applying the BMART reconstruction algorithm is only applicable for trajectories that smoothly vary without crossing over themselves, because the algorithm uses the mean acquisition times in each gridded k -space sample.

In conclusion, BMART allows the efficient measurement and correction of off-resonance without an additional scan. It could be useful for reducing artifacts/blurring from B_0 inhomogeneity, or for improving accuracy of quantitative imaging that is sensitive to off-resonance, such as quantitative susceptibility imaging.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(a) An interleaved spiral trajectory with rewinds that bring the zeroth gradient moment back to zero is naturally suited to BMART. (b) If each interleave is formed by simple rotation of the trajectory, then all the rewinds will evenly fill k-space with a central region being fully sampled (depicted by the blue disk).

Figure 2.

(a) BMART algorithm for simultaneous B_0 map estimation and correction using normally acquired and rewind data. For each bin, i , a B_0 map estimate B_{0i} is computed using the time delay between normal (k_{NORM}) and rewind (k_{REW}) portions of the acquisition (after gridding) for the given bin (Eq. 1). B_{0i} is used to advance/decrement the phase of the images to match the phase of bin $i+1$ (Eq. 2), and the data from bins 1 to i are inserted back into the starting k-space data before starting computations on bin $i+1$. FT = fast Fourier transform, IFT = inverse fast Fourier transform. (b) Depiction of the k-space magnitude for a typical

excitation in the 3D cones trajectory, where two bins of sample points are shown. The acquisition delay between the normal and rewind portions of the trajectory are $t_{i,i+1}$, and the acquisition delay between the two bins for the normal and rewind trajectories are τ_{NORM} and τ_{REW} , respectively.

Figure 3.

Simulation results for a 1D object with random fine features and rapidly varying B_0 . With a sufficient number of bins, BMART produces excellent agreement with ground truth, except for in regions with phase wrapping. (b) At least 10 bins are required for accurate results in this 1D example. RMSE = root mean squared error of the B_0 map estimated using BMART.

Figure 4.

(a) B_0 maps generated using separate scans varying TE and a single scan using BMART with 50 bins. For the range of -3 to 3 ppm, the phase difference for the longest acquisition time delay of 2.8 ms (for BMART) was -1.1π to 1.1π radians. Agreement between the two methods is observed throughout the 3D volumes in both the phantom and human brain. The BMART maps appear smoother than the Multiple-TE maps because of the Hanning low-pass filtering, which was not performed for the Multiple-TE method. (b) Root-mean-squared-difference (RMSD) of BMART B_0 maps in the brain with a varying number of bins compared to the case with 100 bins.

Figure 5.

Images reconstructed using BMART exhibit less blurring in areas of off-resonance compared to images reconstructed with no off-resonance correction. A larger than typical B_0 off-resonance was artificially created by applying a deshim.