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Distortion correction in diffusion weighted imaging of the breast: performance assessment of prospective, retrospective and combined (prospective+ retrospective) approaches

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Abstract

Purpose—To compare the effectiveness of prospective, retrospective and combined (prospective +retrospective) EPI distortion correction methods in bilateral breast diffusion weighted imaging (DWI) scans

Methods—Five healthy female subjects underwent an axial bilateral breast DWI exam with and without prospective B_0 inhomogeneity correction using slice-by-slice linear shimming. In each case an additional $b=0$ DWI scan was performed with the polarity of the phase encoding gradient reversed, to generate an estimated B_0 map; this map or a separately acquired B_0 map was used for retrospective correction, either alone or in combination with the prospective correction. The alignment between an undistorted, anatomical reference scan with similar contrast and the corrected $b=0$ DWI images with different correction schemes was assessed.

Results—The average cross correlation coefficient between the DWI images and the anatomical reference scan was increased from 0.82 to 0.92 over the five volunteers when combined prospective and retrospective distortion correction was applied. Furthermore, such correction substantially reduced patient-to-patient variation of the image alignment and the variability of the average apparent diffusion coefficient in normal glandular tissue.

Conclusion—Combined prospective and retrospective distortion correction can provide an efficient way to reduce susceptibility-induced image distortions and enhance the reliability of breast DWI exams.

Keywords

distortion; correction; EPI; breast; diffusion weighted imaging; shim (DWI); prospective; retrospective

Introduction

There is growing evidence on the utility of diffusion weighted imaging (DWI) and apparent diffusion coefficient (ADC) mapping for breast cancer detection, alone or in conjunction with dynamic contrast enhanced (DCE) MRI (1-6). Although diffusion weighted gradient-echo based readouts were also proposed (7,8), echo planar imaging (EPI) has been the preferred method for reading out diffusion weighted data, due to its tolerance to motion and short imaging time. However, time-efficient EPI readouts are plagued by geometric distortion due to susceptibility-induced static field (B_0) inhomogeneity, determined by the subject-specific anatomy. Assuming in-plane image resolution of 192×192 , a typical spacing between adjacent points in the EPI phase-encode direction of $750 \mu\text{s}$ results in a bandwidth of $\sim 7 \text{ Hz/pixel}$. For a $\sim 300 \text{ Hz}$ field non-uniformity typical of the well-shimmed breast anatomy (9), multi-pixel signal shifts are commonly seen in EPI/DWI images. These localized effects result in the inability to align functional DWI/ADC images with their structural counterparts, and the difficulty of segmenting and characterizing lesions in the ADC maps.

Proposed solutions to the problem of distortion in EPI-based breast DWI generally fall in three categories. First, a *post-processing* correction of the diffusion weighted images can be performed from a measured or estimated map of field inhomogeneity (10). Secondly, the susceptibility-induced magnetic field over the breast area can be measured prior to the DWI acquisition; its variability can be minimized *prospectively* by slice-by-slice center frequency and shim updates (11). As compared to a retrospective method, prospective correction limits signal dropouts due to severe distortions, which cannot be reversed by post-processing alone. An obvious limitation of the slice-by-slice shim, on the other hand, is that high-order in-plane B_0 variation cannot be compensated. Last, distortion reduction can be achieved by accelerating k-space traversal in the phase-encoding direction through readout segmented (rs) (12) or reduced field-of-view (rFOV) EPI (13). These approaches, however, increase scan time, through multiple (rs-EPI) or lengthened (rFOV-EPI) slice excitation events, partly reversing the advantage of the rapid, motion-tolerant EPI readouts.

In this work we demonstrate several different distortion correction methods and evaluate their effectiveness. Specifically, we compare the performance of the prospective slice-by-slice shim update and field map-based retrospective methods in correcting geometric distortion in bilateral breast DWI. Additionally, “hybrid” approaches, that combine prospective per-slice field inhomogeneity minimization with retrospective correction of remnant distortion, were also implemented; their performance was compared against single (prospective or retrospective) correction methods to identify the best overall strategy for minimizing distortion in breast DWI.

Methods

In vivo Imaging

All imaging experiments described in this work were performed on a 3T MR750 system (General Electric, Waukesha, WI), using an 8-channel breast coil (14). Following a protocol approved by our Institutional Review Board, five normal volunteers were recruited for this study. All volunteers underwent the dual breast, axial scans summarized in Table 1. All data were acquired using a field of view of 38 cm and a slice thickness of 3 mm. An adiabatic spectral inversion recovery pre-pulse was added to the T₂-weighted FSE sequence for fat suppression; spectro-spatial water excitation was used for fat suppression in the DWI sequence. Twice-refocused diffusion weighted EPI scans (15) were acquired with an acceleration factor of 2 in the (anterior-posterior) phase-encode direction; they were reconstructed using a SENSE approach (16). The DWI scans include:

- Standard DWI data of series 2 and 3, acquired with identical volumetric shim and center frequency values, obtained using the dual localized shim approach. For each breast, three orthogonal planes of B₀ maps were acquired in prescan; the average shims and center frequency values that placed the six B₀ maps on resonance and minimized their variability were chosen as the scan's shims and center frequency. Among shimming region definition approaches available clinically on the scanner, this method results in the best overall field homogeneity (strategy 13 in reference (17)).
- Per slice shim (PSS) DWI data of series 5 and 6, acquired with identical per-slice shim and frequency offset adjustments, determined by minimizing the inhomogeneity of the field maps (of series 4) for each slice.

Distortion correction methods

Five approaches for correction of distortion in bilateral breast DWI images were implemented and tested. Two were retrospective (based on either measured or estimated of field maps); one was prospective (based on adjustment of center frequency and shims on a per slice basis). The last two were hybrid, combining prospective optimization of center frequency/shims with either of the two retrospective correction methods. Details of the five approaches are explained below.

1. The first *retrospective* approach represents a post-processing correction based on field maps (18) acquired using double-echo 2D gradient echo acquisitions. Two scans with echo time difference $TE = 0.002304\text{ s}$ ($TE_1 = 4.608\text{ ms}$, ($TE_2 = 6.912\text{ ms}$), for which water and fat were in phase, were acquired; for each slice, the phase difference between the two scans ($\phi[\text{radians}]$) was used to compute the field offset B_0 [T] as

$$\Delta B_0(m, n) = (\gamma \cdot \Delta TE)^{-1} \Delta \phi(m, n). \quad [1]$$

Here, m and n are the indices for the two dimensions. The mean pixel shift of the DWI images in the phase encode (PE) direction, y (in cm), was then calculated as

$$\Delta y(m, n) = \frac{\gamma}{2\pi} \text{ESP} \times \text{FOV}_{PE} \times \Delta B_0(m, n). \quad [2]$$

Here, γ is the gyromagnetic ratio ($\gamma/2\pi = 42.575 \cdot 10^6 \text{ Hz/T}$), ESP represents the echo spacing (in seconds), FOV_{PE} the field of view in the phase encode direction (in cm), and B_0 in the field offset computed above. Prior to the pixel displacement calculation, smoothing of the B_0 maps was performed by low-pass filtering: the B_0 maps were fitted to discrete cosine basis functions, whereby basis sets with resolution coarser than 14 mm were retained. To exclude background noise, pixels with magnitude values smaller than 1% of the peak magnitude were excluded from the fit. These steps were undertaken to minimize the effect of noise and extend the B_0 maps to the distorted EPI space. The corrected DWI image was obtained from the distorted DWI image of series 2 (Table 1) and the B_0 maps of series 4 (Table 1). This method is referred to as POST(B_0) in the ensuing figures/tables.

2. The second *retrospective* approach is based on an estimation of the field map using a reverse polarity gradient (RPG) acquisition. Based on the observation that traversal of the k-space in the opposite direction in the phase encode direction will lead to reversal of distortions (i.e. a compression transforms into an expansion), a field map that causes the forward polarity gradient (FPG) and RPG images to overlap can be estimated. Using the algorithm described in (19), this B_0 estimation is done by setting up a least squares cost function that explicitly depends on all voxel displacements; the smoothness of the deformation field is controlled by the introduction of regularization parameters limiting the sum of the squares of the gradients of the displacements at each voxel (and possibly the amplitude of displacements). The numerical task of efficiently minimizing this cost function is achieved by starting with heavily blurred FPG and RPG images, then progressively decreasing the blurring Gaussian kernel width. For all the distortion correction performed by us in this work, this schedule of blurring started with a kernel width of 25 pixels, decreasing in steps of 2 to the native resolution of the input images, for a total of 13 iterations; the regularization parameters were $\lambda_1, \lambda_2 = 1100$ (Eq. 9. in reference (19)). To summarize, the estimated B_0 maps are first obtained using the $b=0$ acquisitions of series 2 and 3 (Table 1); the corrected DWI images are obtained by applying the shifts of Eq. [2] to the distorted DWI images of series 2 (Table 1). This method is referred to as POST(RPG) in the next figures/tables.
3. The third approach is *prospective* in nature, and will be referred in figures/tables as PRE(PSS). Following the acquisition of field maps (series 4 in Table 1), a cost function (defined as the standard deviation of the B_0 map) is minimized for each slice, resulting in four optimized parameters per slice (three shim gradients and

one center frequency). These parameters were saved as a “shim table” in a file, and read by the PSS-DWI pulse sequence of series 5 (Table 1) prior to data acquisition. The calculation of the shim table and corresponding adjustment of gradient shim current and the RF frequency per repetition time were fully automated (11).

4. The fourth approach is *hybrid* and will be referred to in figures/tables as PRE(PSS)+POST(B0); it takes as an input the DWI images with prospectively reduced distortion (series 5, Table 1). The remaining distortion is then corrected through post-processing according to Eq. [2], using the baseline B_0 maps of series 4 adjusted by the shim table obtained in the PSS-DWI scan of series 5 (Table 1).
5. The 5th approach is also *hybrid*, starting from the same prospectively corrected PSS-DWI of series 5, and will be referred to in figures/tables as PRE(PSS)+POST(RPG). The difference between this and the method above is that the field maps were not measured, but estimated using a RPG acquisition (series 6). This last series was acquired with the same shim table of series 5; the residual B_0 offset map per slice was estimated from the FPG and RPG images as described before (method 2). The PSS-DWI of series 5 was corrected by the estimated B_0 map according to Eq. [2].

Distortion correction performance metric

Our quantitative metric of success was the normalized cross-correlation coefficient (CCC) between the T_2 -weighted fast spin echo (FSE) images and the uncorrected/corrected DWI scans with $b=0$, over the breast area. This metric was computed for each slice:

$$CCC = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \bar{A})^2\right) \left(\sum_m \sum_n (B_{mn} - \bar{B})^2\right)}}. \quad [3]$$

In this equation the indices m and n span the x and y FOV of the scans, the matrix A represents the anatomical reference scan, and B the uncorrected/corrected DWI ($b=0$) image. In the absence of a gold standard for correction performance evaluation, and given the similar contrast of the anatomically accurate FSE (series 1) and the DWI images (series 2 and 5), the cross correlation coefficient is a commonly used metric for assessing distortion correction performance (20). This metric was computed over the entire imaging volume after intensity based masking (to remove noise-only regions), for all volunteers and all slices; the per-slice CCC was then averaged (using weights proportional to the number of voxels in each slice) to obtain the mean and standard deviation of the CCC for all slices.

Statistical data analysis

The Wilcoxon signed rank test was used to assess whether the mean cross correlation coefficient ranks differ between distortion correction approaches. As a non-parametric test, it

was preferred over the paired Student's t-test for our small number of samples, whose distribution was not assumed to be normal.

Apparent diffusion coefficient

To understand the impact that our correction methodology had on the apparent diffusion coefficients, ADC maps were computed on a pixel by pixel basis, using

$ADC = \ln \left(\frac{S(b_1)}{S(b_2)} \right) / (b_2 - b_1)$. Glandular tissue masks were created by thresholding the $b=0$ DWI images (corrected and uncorrected); the average ADC over the glandular tissue was then generated and compared between the different correction approaches.

Results

An example of the performance of all correction methods in three representative volunteers is presented in Figure 1. Here, an illustrative slice of the $b=0$ DWI data is presented as an overlay with the T_2 weighted FSE image of series 1. The diffusion/anatomical mismatch is visible in areas where green/purple occupy different regions in space. The top row displays DWI images as acquired with volumetric shim (series 2) in three volunteers; the second through the sixth rows present data obtained by the distortion correction methods 1 to 5 described in the previous section, respectively. An additional figure, highlighting the performance of all correction methods in one of the volunteers, with slices spanning the entire field of view, is presented as Supporting Figure S1.

For quantitative comparison, Table 2 presents the *CCC*'s between FSE and ($b=0$) DWI images before and after each correction. Data from all 5 volunteers are listed, together with the average, standard deviation (std) and percent standard deviation (std/average*100) computed over the subjects. Note a few important results from this table:

- All correction methods result in consistently less distorted images (higher *CCC*'s) than the ones with no correction ($p < 0.05$)
- The single approaches (prospective or retrospective) were statistically equivalent; the post-processing, RPG approach exhibited slightly better (but not statistically significant) performance than the other, POST(B_0) and PRE(PSS) approaches.
- The addition of the post-processing correction using the already measured B_0 maps to the prospectively corrected images further reduced distortion ($p = 0.05$). This hybrid combination, however, was not better than the single POST(RPG) method.
- The best and most consistent approach for reducing distortion was the combination of prospective and retrospective correction using the RPG acquisition. Not only did it result in the highest average *CCC*, it also resulted in the lowest % standard deviation among different subjects. This combination of prospective and retrospective correction was statistically better than PSS or B_0 alone, although it only exhibited a trend for being better than RPG alone ($p = 0.09$). In terms of the standard deviation, the combined approach resulted in

very substantial reduction of inter-subject variability, from 4.8% to 2.66% (45% reduction).

The impact of the distortion correction methods on the ADC maps is presented in Table 3; here, the average ADC coefficients are displayed for each subject; data was also then pooled across subjects. While no consistent trend of increasing/decreasing ADC's was seen as a consequence of performing the distortion correction, note that hybrid methods, in particular PRE(PSS)+POST(RPG), resulted in the most consistent ADC values across multiple healthy subjects. This can be particularly valuable for reducing the size of patient cohorts enrolled in clinical studies, e.g., evaluating treatment efficacy using DWI (21).

Discussion and Conclusions

In this work we have shown that by combining prospective B_0 inhomogeneity compensation and B_0 -map based retrospective pixel shift correction, more reliable breast DWI/anatomical image alignment can be achieved. In our data with a relatively low b value, distortion correction did not significantly affect average ADC values in the glandular tissue. However, scans with larger b -values or higher spatial resolution will have lower image SNR and higher image distortion, which can impact computed ADC's more significantly. The latter point can be confirmed by a simple Monte Carlo simulation, similar to the one described in (17). Assuming Rician noise distribution and an ADC value of $1.8 \times 10^{-3} \text{ mm}^2/\text{s}$, the ADC artificially decreases by 2.6 % as the SNR diminishes from 20 to 15 at $b=600 \text{ s/mm}^2$, and by 4.2 % at $b=1200 \text{ s/mm}^2$.

The additional acquisition time needed to enable distortion correction was different for the different methods considered here. For B_0 -measurement and RPG-type corrections, (additional) acquisition times were 80 and 38 seconds, respectively. Given the slow inferior/superior variation in field inhomogeneity over the breast area (9), through plane resolution in B_0 mapping can be easily reduced by a factor of 2. With the addition of image acceleration in the B_0 mapping sequence (which we did not use), the acquisition time could be reduced by an additional factor of 2, e.g., bringing it to around 20 seconds. The RPG acquisition time could also be reduced to ~20 seconds by decreasing the number of averages (currently 8). While the first four correction methods considered here only incur the additional scan penalty once (for either B_0 mapping or the RPG scan), the optimal, hybrid correction approach of PRE(PSS)+POST(RPG) will unfortunately incur both.

Among the two retrospective methods tried, RPG-based correction slightly outperformed the B_0 map based one (Table 2, $p=0.053$). This is possibly due to the errors obtained from extrapolating B_0 maps in the distorted EPI image space.

Average computation time for retrospective distortion correction using B_0 -mapping and RPG was 3 and 2 minutes, respectively, on a quad-core 3.2 GHz computer. The majority of the B_0 map-based distortion correction time was spent for discrete cosine fitting. By comparison, simple thresholding on the B_0 map without fitting to basis functions reduced the average processing time to 40 seconds, but decreased the average CCC slightly, by about 0.02. As the post-processing corrections are performed after scans are completed and take

similar times to complete, it is likely that post-processing time will not be a determining factor in deciding upon the correction procedure.

Among our five volunteers, one had extremely dense breasts, three had heterogeneously dense breasts, and one had scattered fibroglandular tissue. As it is evident from the last slices of the Supporting Figure S1, none of the correction methodologies appear to decrease their performance in areas of high fat content. To assess whether a correlation exists between breast density and distortion correction performance, or whether our top performer PRE(PSS)+POST(RPG) is statistically better than its closest competitor, POST(RPG), a larger number of subjects would be necessary. Breast densities spanning the entire range, including the fatty breast category (in which ~10% of the population lies), would need to be considered.

As implemented, using separate B_0 mapping and RPG acquisitions, our post-processing correction strategies are sensitive to motion. Additionally, pixel shifts computed based on the $b=0$ data are applied to the high b -value DWI. While twice-refocused DWI is not particularly sensitive to gradient induced eddy currents, their presence could result in a shift of the high b -value data with respect to the $b=0$ image. Both motion and the eddy current problems can be mitigated to a large extent by an integrated implementation of a RPG-FPG pulse sequence, coupled to an affine registration of the T_2 and high b -value FPG volumes. Acquiring the first, $b=0$, RPG data set immediately prior to the ($b=0$ and high b -value) FPG volumes ensures minimal motion between the two series needed for the POST(RPG) correction; affine registration between the high b -value and $b=0$ FPG volumes, in a manner similar to the one presented in (22), will minimize the effect of eddy currents on the resulting ADC maps, e.g.

Our results suggest that the best strategy for distortion correction in breast DWI scans depend on the available additional scan time. If a relatively short time (~20 seconds) can be spared, it is suggested for the DWI study to be performed with default volumetric shims; at the end, an additional RPG acquisition would enable post-processing correction using RPG. Provided more time is available (~40 seconds), prospective, dynamic shimming, followed by post-processing correction using an estimated B_0 map from the FPG and RPG $b=0$ acquisitions could produce the best and most consistent outcome, both in terms of match between the anatomical to DWI images and consistent ADC values.

In this work we have not considered high order shims; previous reports on the susceptibility-induced B_0 distribution in the breast (23) found that due to the characteristic anatomy of the breast and the chest area, small-volume or slice-by-slice linear shimming is likely better than whole-body second-order shimming. Tailored local breast shim coils (24), on the other hand, may provide an alternative hardware solution to the distortion problem.

In conclusion, we have demonstrated that combined prospective and retrospective distortion correction, which can be implemented with no changes in hardware or single-shot EPI scan trajectories, can be an effective way to enhance the DWI/anatomical image registration and improve the quantitative accuracy of bilateral breast DWI exams.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Example of the overlay between the $b=0$ DWI image and the anatomical, T_2 weighted FSE image in 3 volunteers (different columns). The results of different distortion correction approaches are illustrated in the different rows.

Table 1

Imaging protocol for the volunteers.

	Sequence	TE/TR [ms]	b values [s/mm ²]	# of averages	In plane matrix size	Shim type	Scan time	Purpose	Acceleration factor
1	2D FSE	68/6000		2	192 × 192	volumetric	2 min 36 sec	Anatomical standard for DWI data sets	R=2.5
2	DWI scan (FPG)	68/6000	0,600	8	192 × 192	volumetric	1 min 36 sec	Standard DWI	R=2
3	DWI scan (RPG)	68/6000	0	8	192 × 192	volumetric	48 sec	RPG based correction of series 2	R=2
4	B0 mapping	4.6/400; 6.9/400		1	96 × 96	volumetric	1 min 20 sec	B0-based retrospective correction and per slice shim	none
5	DWI scan (FPG)	68/6000	0,600	8	192 × 192	per slice	1 min 36 sec	Prospectively corrected DWI	R=2
6	DWI scan (RPG)	68/6000	0	8	192 × 192	per slice	48 sec	RPG based correction of series 5	R=2

Table 2

Cross correlation coefficients between FSE images and DWI images before and after all correction methods. The average, standard deviations (std) and percent standard deviations (std/average*100) are computed over the 5 subjects in each group.

	No correction	POST(B0)	POST(RPG)	PRE (PSS)	PRE(PSS)+POST(B0)	PRE(PSS)+POST(RPG)
vol1	0.79	0.86	0.85	0.87	0.88	0.93
vol2	0.82	0.83	0.89	0.83	0.89	0.9
vol3	0.78	0.85	0.89	0.84	0.85	0.89
vol4	0.86	0.89	0.91	0.89	0.9	0.93
vol5	0.87	0.93	0.95	0.92	0.92	0.95
average	0.82	0.87	0.90	0.87	0.89	0.92
std	0.040	0.039	0.035	0.037	0.026	0.024
std/average*100	4.80	4.47	3.93	4.22	2.91	2.66

Table 3

Average ADC values [$\times 10^{-3} \text{mm}^2/\text{s}$] over the glandular tissue for the volunteers studied, before and after application of each of the five correction approaches. The average, standard deviations (std) and percent standard deviations (std/average $\times 100$) are also computed over the 5 subjects in each group.

	No correction	POST(B0)	POST(RPG)	PRE (PSS)	PRE(PSS)+POST(B0)	PRE(PSS)+POST(RPG)
vol1	1.86	1.84	1.84	2.07	2.07	2.14
vol2	2.49	2.39	2.46	2.42	2.40	2.32
vol3	2.38	2.34	2.31	2.44	2.32	2.46
vol4	2.29	2.28	2.26	2.29	2.27	2.27
vol5	2.39	2.40	2.30	2.38	2.40	2.38
average	2.26	2.21	2.22	2.31	2.27	2.30
std	0.28	0.25	0.27	0.17	0.14	0.13
std/average$\times 100$	12.23	11.41	11.98	7.38	6.21	5.76