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Dynamic slice-dependent shim and center frequency update in 3 T breast diffusion weighted imaging

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Abstract

Purpose—To demonstrate dynamic slice-dependent shim update as a simple method to reduce susceptibility-induced B_0 inhomogeneity and associated pixel shift artifacts in diffusion-weighted echo planar imaging (DW-EPI) in 3 T breast imaging.

Methods—Dynamic slice-dependent update of linear shim and center frequency was implemented in a dual-echo B_0 mapping sequence and a DW-EPI sequence. Multi-slice axial B_0 maps and diffusion-weighted images were obtained from four volunteers with both conventional and dynamic shim methods. The two shim methods were compared in terms of B_0 homogeneity and EPI pixel shift artifacts.

Results—In all volunteers the B_0 maps showed significantly improved homogeneity; the left-right asymmetry was reduced by 79 % and within-slice B_0 standard deviation was reduced by 20 % on the average. The improvements were better than what was previously reported for conventional (static) third-order shim in bilateral breast. Anatomy-referenced apparent diffusion coefficient (ADC) maps showed reduced overall image registration error obtainable with dynamic shim.

Conclusion—Dynamic shim is an effective method to improve B_0 shimming and DW-EPI image quality in 3 T bilateral breast imaging.

Keywords

breast; DWI; EPI; dynamic shim; susceptibility

Introduction

Diffusion weighted imaging (DWI) is increasingly used in conjunction with dynamic contrast-enhanced (DCE) imaging in breast cancer screening due to its potential to improve the specificity of cancer detection (1). The readout portion of DWI typically consists of echo planar imaging (EPI), whose high speed of acquisition allows probing multiple diffusion directions in a clinically feasible time. Such DW-EPI can however suffer significant image

distortion in the presence of static field (B_0) inhomogeneity due to the low effective bandwidth of EPI sampling in the phase encoding direction (2). The distortion can hinder co-registration of DWI-DCE images and introduce errors in their interpretation. Distortion in DWI can also lead to spurious image intensity variation through pixel compression and expansion, which can affect calculation of diffusion parameters such as the apparent diffusion coefficient (ADC). These effects can potentially undermine and limit the benefit of DWI as a diagnostic tool in breast MRI.

Geometric distortion caused by B_0 inhomogeneity in EPI can be partially corrected for based on measured B_0 maps (3). However, post-processing-based correction has limitations such as inability to correct slice selection and fat suppression errors, and inability to recover lost SNR due to intravoxel dephasing. It is desirable, therefore, to reduce physical B_0 variation as much as possible through improved shimming during imaging, which is the focus of the present work.

While B_0 inhomogeneity can have many sources, susceptibility-induced B_0 field variation is the main contributor to the overall field inhomogeneity in the field-of-view (FOV) used in breast imaging. As previously reported, the air-breast susceptibility boundary is responsible for a dominant anterior-posterior B_0 gradient (4) observed in many patients, whereas susceptibility of the heart, lungs, and liver contributes varying degrees of left-right B_0 gradient (5). Susceptibility-induced B_0 disturbance in breast can also have strongly nonlinear and localized components (4), which cannot be shimmed away in many commercial scanners equipped with only low-order whole body shim coils. At 3 T, these spatially dependent residual off-resonance fields are on the order of 10 to 100 Hz, which for a typical breast-imaging FOV of 36–48 cm and phase-encoding bandwidth of 1–2 kHz, can cause significant, nonlinear pixel shift artifacts in high-resolution, single-shot EPI images.

In the past it was demonstrated that both strategic placement of shim regions of interest (ROIs) (6) and use of a local shim coil (7) could improve B_0 homogeneity in volumetric breast imaging. Whereas localized array of shim coils (8) and susceptibility padding (9) could further reduce localized B_0 disturbances from susceptibility boundaries, for practical purposes it would be desirable to improve shimming without additional hardware or major workflow changes.

One such method, dynamic slice-dependent shim update, has been previously demonstrated in head and abdomen (10,11). In axial multi-slice imaging, dynamic shimming can effectively compensate B_0 variations of type xz^n and yz^n . In bilateral breast imaging, such components exist due to the characteristic shape of the breast and asymmetric location of nearby organs. In particular, an earlier multi-volunteer B_0 map analysis (12) showed that the xz and yz terms were the strongest of all the second and third order harmonic shim terms in breast. This suggests that dynamic shim update could be particularly beneficial in breast imaging. Here we demonstrate implementation of slice-dependent linear shim and center frequency update in gradient-echo (GRE) and echo-planar imaging (EPI) in axial breast scans. Following initial demonstration of the proof of the principle (13), we show here significant reduction of B_0 inhomogeneity and mitigation of EPI pixel shift artifacts observed in scans of four volunteers.

Methods

Sequence modification and workflow

A standard DW-EPI workflow was modified as follows:

1. (Shim ROI) During the scan prescription of the DWI sequence, a rectangular shim ROI was specified by the user on an axial plane using a graphical interface. The ROI was chosen to encompass both breasts, and its location was saved upon sequence download. This information was used as an input to the shim calculation algorithm.
2. (Prescan) The standard pre-scan acquisition for DWI was appended with a multi-slice B_0 mapping sequence based on dual-echo GRE. In order to better account for multiple lipid chemical shift frequencies (14), the echo time difference ΔTE was chosen experimentally to visually minimize spurious water-fat B_0 boundaries in a volunteer's breast. The echo times chosen, 4.608 ms and 6.912 ms, were found to work reasonably well for all volunteers studied. The modified pre-scan added about 2 minutes to the total DWI scan time.
3. (Calculation) Following the B_0 acquisition, slice-dependent center frequency (CF) and in-plane linear shim values were calculated on the fly with B_0 maps, slice locations, and shim ROI as inputs. The linear shim values were determined using the "fminsearch" function from Matlab (Mathworks, Natick, MA, USA), whereby the cost function for minimization was defined as the standard deviation of the shimmed B_0 map for each slice. The intersection of the shim ROI and an image intensity mask defined a region in which the cost function was calculated. Since the shim ROI is in general not centered at the gradient isocenter, application of shim gradients tends to offset the mean resonance frequency in the ROI. This was corrected by CF adjustment. The CF for each slice was calculated as the average of the predicted, shimmed B_0 distribution in the ROI. The computation of the slice-dependent center frequency and shims was done by a compiled Matlab code on the scanner host computer and took less than 5 seconds.
4. (Scan) The CF and shim values were dynamically applied to the DW-EPI scan in a slice-by-slice manner (Fig. 1a).

The entire workflow was automated, requiring no user intervention beyond the initial prescription of the DWI scan. Although this method is generic with respect to the scan plane orientation, this work only considered axial imaging of bilateral breast. In what follows, we assume that "dynamic shimming" means dynamic slice dependent update of both the CF and the linear shim gradients.

Slice-dependent shim update was also implemented in the B_0 mapping sequence in order to verify the desired B_0 homogenization effect from dynamic shimming. At the conclusion of the dynamically shimmed DW-EPI scan, B_0 mapping was repeated with the calculated slice-dependent shim update.

Volunteer scan

Four healthy volunteers were recruited and scanned after informed consent was obtained in accordance with the guidelines of the Institutional Review Board of the authors' institution.

The volunteers were scanned in a GE Discovery MR750 3T scanner (Waukesha, WI, USA) with a modified 8-channel breast receiver array (15). An acceleration factor R of two (right/left) was used for DWI. All scans were performed under a free breathing condition. Each subject was first scanned with a high-resolution 3D gradient echo sequence with scan parameters typical in DCE imaging (Table 1). This provided reference for DWI pixel shift assessment. Next, the subject was scanned with a standard, multi-slice breast DWI protocol with shim values determined in a dual ROI placed on both breasts (6). Subsequently, keeping the same, conventionally determined CF and shim parameters, the B_0 maps on all the imaged slices were obtained. These two scans provided “baseline” data for DWI and B_0 maps achievable with conventional shimming. The volunteer was then scanned with the modified, dynamically-shimmed DWI and B_0 mapping sequences with the same scan parameters. Figure 1(b) shows actual slice-dependent CF and in-plane shim gradients applied during a volunteer scan. The scan parameters for DWI and B_0 mapping scans are shown in Table 1.

Data analysis

Shim improvement due to dynamic shim was measured in terms of reductions in the average off-resonance frequency, B_0 standard deviation, and the average left-right B_0 difference in each volunteer. All B_0 statistics were calculated in the same region over which slice-dependent shim values were calculated in the scan workflow—namely, the overlap of the shim ROI and an image intensity mask. The left vs right breast was defined with respect to the vertical middle line in the image matrix. No attempt was made to segment out breast from the rest of the tissue types, such as liver and heart, when such were included in the shim ROI. The ADC maps were computed and overlaid with anatomical images within the scanner's image processing and viewing module, with the noise threshold being the only user-adjusted parameter.

Results

In all volunteers, dynamic shim consistently reduced the mean off-resonance frequency of a slice to within about ± 10 Hz. The B_0 standard deviation in most slices was also reduced significantly. Figures 2a and 2c show measured improvements in the average off-resonance frequencies and B_0 homogeneity in all slices from two of the volunteers, with a relatively small (volunteer 1) and large (volunteer 3) fat fraction and physical size of the breasts. It was observed that conventional shim and dynamic shim produce similar B_0 homogeneity in a small number of slices in which the optimal linear shim values happen to coincide. Away from those slices, dynamic shim, with flexibility to adjust CF and shims per slice, gives consistently improved B_0 homogeneity and center frequency match.

B_0 maps of three representative slices for the two volunteers are shown in Figures 2b and 2d. A noticeable benefit of dynamic shim for bilateral breast imaging was reduction of left-right

B_0 asymmetry across the slices. Such reduction could lead to better diagnostic accuracy in bilateral breast exams, in which artificial left-right asymmetry can confound lesion identification. Table 2 summarizes B_0 improvements in all volunteers. Here the left-right asymmetry, denoted Δ_{LR} , is defined as the mean (across the slices) absolute difference between the within-slice average B_0 values in the left and the right breasts. Table 2 shows that dynamic shim was particularly effective in reducing mean off-resonance field and left-right asymmetry, providing about 80% reduction for each. Improvement in B_0 standard deviation (average 20%, varying between 9% and 30% for the 4 volunteers studied) was also greater than what was reported possible ($< 10\%$) for second and third order static shim (5).

The impact of improved shimming to diagnostic imaging is illustrated in Fig. 3, which shows anatomy-referenced ADC maps in three axial slices of volunteers 1 and 3. In Fig. 3, most significant pixel shift artifacts in conventionally shimmed images are observed near the left axilla in slice 25, and near the right nipple in slice 17, for volunteers 1 and 3, respectively (arrows). These slices were also the ones with strong left-right B_0 asymmetry as shown in Fig. 2. The observed pixel shift was consistent with predictions from the measured B_0 shift (3), $\delta y = y_{FOV} \cdot \delta B_0 \cdot esp/R$. For instance, around the right nipple in slice 17 of volunteer 3, the B_0 offset was $\delta B_0 \approx 50$ [Hz]. With $y_{FOV} = 36$ [cm], $esp = 844$ [μ s], $R = 2$, we calculate a pixel shift of $\delta y \approx 0.76$ [cm], which is roughly the amount observed in Fig. 3b. Comparison between the left and the right columns in Fig. 3 shows that dynamic shim substantially improved the quality of DWI-GRE image co-registration, and was particularly effective in reducing asymmetric pixel shifts between the left and the right breasts in the ADC maps.

Discussion and conclusions

In our study, dynamic shim reduced the B_0 standard deviation by 20% on average in four volunteers. The level of reduction was higher than that reported for static third order shim (5) in bilateral breast, and was comparable to the reduction by static shim methods in unilateral breast (16). Relative effectiveness of dynamic shim compared to static shim in bilateral breast can be understood in the following way. As was shown in Ref. (4), a dominant anterior/posterior gradient in breast comes from the half-spherical shape of the breast. A straightforward model calculation shows that such gradient depends on whether the imaged slice is near or away from the breast's (axial) mid-plane. This difference contributes to B_0 variation of type yz^n where y is in the anterior/posterior direction. On the other hand, the left-right B_0 difference caused by susceptibility of nearby organs (5) depends on the relative superior/inferior position of such organs with respect to a given breast slice. Such dependence creates B_0 variation of type xz^n . Both of these variations can be effectively compensated by slice-dependent shim update in axial imaging. This consideration is consistent with our earlier simulation study (12) which showed significance of xz and yz terms in bilateral breast B_0 maps.

Table 2 shows that the residual off-resonance frequency after dynamic CF/shim update is on the order of 3–6 Hz. For a static object, slice-dependent CF/shim update should in principle zero the mean frequency offset for any given slice. In reality, under a free breathing condition B_0 compensation is limited by respiratory motion, which contributes about 0.1

ppm (12.8 Hz at 3 T) shift near the chest wall (17). Note also that in our experimental protocol, dynamically shimmed DWI was acquired after conventional DWI for all volunteers. This could introduce order effects in the results and would better be avoided using pseudo-randomized order in a larger population study. However, the size of the effect and the systematic difference observed between the shimming methods could not rely on order effects only. Most of the improvement observed with dynamic shimming is therefore believed to be related to the shimming technique itself.

Table 2 also shows that over the volume of the bilateral breast, B_0 standard deviation of about 20–40 Hz still remained after dynamic shimming. The residual inhomogeneity comes primarily from higher order B_0 gradients that cannot be addressed by linear shim update alone (Fig. 2d, arrow). As reported in Ref. (4), subjects with relatively large breasts tend to have more localized B_0 “hot spots” that pose a challenge to any low order shim coil-based method including the present one. This suggests that dynamic shim may be more effective on smaller breasts. Our data on a limited number of volunteers appear to support this; volunteers 1 and 4 were the two subjects with smaller breasts, and they showed lower dynamically-shimmed B_0 standard deviation and Δ_{LR} than the other two volunteers (Table 2).

Proper choice of shim ROI is important to maximize the benefit of the proposed method. In the present work, a single rectangular ROI was applied to all slices. Such a method, while being simple, has a disadvantage that inclusion of axilla can force partial inclusion of heart and liver in some slices. A recent study (6) on the effect of ROI choice on breast shim outcome suggests that shimming over an ROI that includes heart can be problematic. Our experience shows, however, that for a *given* ROI, dynamic shim produces consistently better results than conventional shim. In the future, slice-dependent and tissue-segmented ROI definition could further increase the effectiveness of dynamic shimming.

Whereas the added time (2 min) for B_0 mapping was adequate for our initial investigation, for clinical applications it would be desirable to decrease the pre-scan time needed for shim calculation. One straightforward method is to reduce the B_0 map resolution both in plane and in terms of number of slices. A faster readout with EPI or spiral trajectories can further reduce the scan time. However, such a scheme will be more sensitive to initial B_0 inhomogeneity (10).

A short comparison between the proposed method and a B_0 map-based post-processing method (3) is in order. While both methods require an additional B_0 map acquisition in the scan protocol, post-processing correction has an advantage that no sequence modification is needed, since B_0 mapping is already available in most clinical scanners. Moreover, higher order distortions can be addressed as easily as lower order ones in post-processing. The advantage of dynamic shimming is that without hardware changes, better physical shimming is possible which addresses both excitation errors and image distortion. Note that the two methods are not mutually exclusive; they can be combined to improve, for example, both fat suppression (through dynamic shimming) and higher-order distortion correction (through subsequent B_0 -based post-processing).

In conclusion, we demonstrated improvements in B_0 homogeneity and reduction in DWI pixel shift artifacts in bilateral breast imaging by implementing slice-dependent dynamic shim and CF update. With only linear gradient coils, the method effectively compensated a significant portion of susceptibility-induced B_0 gradients that varied from slice to slice. Compared to a conventional, static shim method, the proposed method greatly reduced the mean off-resonance frequency and left-right B_0 asymmetry in bilateral breast imaging. Dynamic shim update as demonstrated here can be readily implemented in existing scanners with no hardware changes, and is more effective than static low-order shimming currently available in many scanners. The proposed method can thus provide an efficient way to enhance diagnostic confidence in DWI-assisted cancer detection in 3 T breast imaging. More quantitative assessment of clinical benefit remains as a future study.

Acknowledgments

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Figure 1.

(a) Schematic of a DWI-EPI sequence with dynamic shim and CF update. (b) Slice-dependent CF, Gx, Gy values applied during a volunteer scan (volunteer 3).

Figure 2.

(a) Slice-dependent average off-resonance frequency (left) and B₀ standard deviation (right) for volunteer 1. (b) Measured B₀ maps on three representative slices obtained with conventional and dynamic shim. (c–d) Same as (a–b) for a subject with a larger breast and larger fat fraction (volunteer 3). Dynamic shim does not help higher order in-plane B₀ variation (arrow).

Figure 3.

(a) Breast ADC maps (color) for volunteer 1 overlaid with anatomical images (grey scale). Arrows indicate pixel shift artifacts in conventionally shimmed DWI, that are significantly reduced by dynamic shim update (right column). (b) Same as (a) for volunteer 3.

Table 1

Scan parameters used in the volunteer study. Anatomical scan was with a 3D fast gradient echo sequence. Note that the FOV and slice number varied per volunteer.

Parameter	Unit	Scan		
		Anatomical	DWI	B ₀ map
TR	ms	3.9	6000	250
TE	ms	1.7	87	4.608, 6.912
bandwidth	kHz	±200	±250	±31
matrix size		320×320	256×256	128×128
FOV	cm	34–36		
slice number		60–64	30–32	30–32
slice thickness	mm	2	4	4
slice gap	mm	0	0	0
acceleration (R)		2	2	1
echo spacing (esp)	μs	N/A	844	N/A
shots		N/A	1	N/A

Mean, standard deviation, and left-right difference (ΔB_0) of B_0 in all volunteers obtained with conventional and dynamic shimming. Each number in the first four data rows is an average over all slices imaged in a given volunteer. The fifth data row shows numerical average of the four preceding rows.

Table 2

volunteer	B ₀ map, conventional shim		B ₀ map, dynamic shim	
	mean(Hz)	s.d. (Hz)	mean(Hz)	s.d. (Hz)
1	7.4	28.2	27.0	19.7
2	51.2	36.9	33.8	33.7
3	29.8	46.4	41.2	35.5
4	8.4	35.1	35.3	28.5
average	24.2	36.7	34.3	29.4
% reduction	-	-	-	20%