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Removing silicone artifacts in diffusion-weighted breast MRI via shift-resolved spatiotemporally encoding

Eddy Solomon^{#1}, Noam Nissan^{#1}, Rita Schmidt¹, Edna Furman-Haran², Uriel Ben-Aharon³, and Lucio Frydman^{*,1}

¹Department of Chemical Physics, Weizmann Institute of Science, Rehovot, Israel

²Unit of Biological Services, Weizmann Institute of Science, Rehovot, Israel

³Breast Surgery Unit, Meuhedet Clinic, Ashdod, Israel

[#] These authors contributed equally to this work.

Abstract

Purpose—Evaluate the usefulness of diffusion-weighted spatiotemporally-encoded (SPEN) methods to obtain ADC maps of fibroglandular human breast tissue, in the presence of silicone implants.

Methods—Seven healthy volunteers with breast augmentation were scanned at 3T using customized SPEN sequences yielding separate silicone and water ¹H images in one scan, together with their corresponding diffusion-weightings.

Results—SPEN's ability to deliver multiple spectrally-resolved images in a single scan, coupled to the method's substantial robustness to magnetic field heterogeneities, served to acquire ADC maps that could be freed from contributions that did not belong to fibroglandular tissue.

Conclusion—SPEN-based sequences incorporating spectral discrimination and diffusion-weighting enable the acquisition of reliable ADC maps despite the presence of silicone implants, thereby opening new screening possibilities for the identification of malignancies in breast augmented patients.

Keywords

diffusion-weighted imaging - DWI; spatiotemporal encoding - SPEN; breast MRI; silicone implants

Introduction

There is a growing need for imaging breasts with silicone implants, driven by the extended use of augmentation procedures for cosmetic and cancer-related reconstruction purposes (1). A main radiological concern in these analyses resides in evaluating the implant's integrity (2–5), with magnetic resonance imaging (MRI) being the modality of choice to monitor the

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*Prof. Lucio Frydman, Department of Chemical Physics, Weizmann Institute of Science, Rehovot, Israel, 76100, Tel: 972-8-934-4903, Fax: 972-8-934-4123, lucio.frydman@weizmann.ac.il.

potential rupture of an implant (6). Most MRI protocols used for such evaluations rely on multi-shot T_1 and T_2 -weighted techniques (4,5,7), favored due to the detailed anatomical information that they provide about a silicone implant's integrity. Although silicone implants are not associated with an increased risk of breast cancer, augmented subjects may eventually develop the disease as they share similar lifetime risks as the general population. Even cancer patients that underwent surgery followed by silicone implant reconstruction, exhibit a risk –though greatly reduced– of cancer recurrence (8). Given the concerns that have been raised about the accuracy of mammography as a suitable approach to screen these cases (9,10), there is an increased interest in using MRI for detecting breast cancer in the presence of silicone implants (11). High-risk subjects will be candidates for dynamic contrast enhanced studies, a protocol involving the injection of contrast material that reveals the location of potential cancerous tissue by T_1 -weighted MRI scans (12–14). A promising alternative to diagnose breast cancer without injecting external contrasts, is diffusion-weighted MRI (DWI) (15). While still in a process of validation, the main goal of these tests is to monitor water's micro-diffusion via the calculation of apparent diffusion coefficient (ADC) maps. Cancerous tissues exhibit lower ADCs than normal fibroglandular tissue or benign lesions (16–18), reflecting the restricted diffusivity brought about by the high cellular density of proliferating cancer regions (14,19). Performing such cancer diagnoses based on diffusion measurements requires a fast technique, exhibiting reduced sensitivity to motional effects. ADC map measurements are thus based on techniques like spin-echo echo planar imaging (SE-EPI), which can provide the desired image with good quality in a single scan (20). Despite its speed and sensitivity SE-EPI is still prone to display artifacts, particularly when applied to the examination of challenging organs like silicone-implanted breasts. Indeed the presence of water-, silicone- and fat-rich regions in an off-axis organ results in chemical shift artifacts and field heterogeneities, leading to spurious replicas that may confound the radiological interpretation (21–23). Complex suppression schemes of the non-targeted resonances coupled to field-compensating navigator scans and image post-processing, are thus usually needed to enable a suitable EPI-based diagnosis of silicone-implanted breasts (24).

Over the last years single-shot imaging alternatives operating on the basis of *spatiotemporal encoding* (SPEN) methods, have succeeded to reduce the distortions incurred by field inhomogeneities and/or chemical shift artifacts (25–30). These advantages are a consequence of SPEN's non-Fourier nature, enabling its use of stronger acquisition gradients than those dictated by EPI's Nyquist criteria. Initial SPEN implementations exhibited SNR limitations, yet the use of super-resolved reconstruction techniques (31–35) have alleviated these. Furthermore, a suitable theoretical framework (36) enables the retrieval of ADC maps from a variety of SPEN implementations. These combined improvements have been recently brought to bear in a series of breast ADC map measurements in both healthy volunteers and cancer patients, that revealed systematically better *b*-zero images and cleaner ADC maps, than their SE-EPI counterparts (37).

A particular advantage of SPEN rests in its ability to resolve, without any changes in the basic imaging-oriented pulse sequence, the contributions of different chemical sites (38). This ability to deliver 1D spectral / 2D spatial correlations in a single scan has been demonstrated in both animal experiments on thermal and hyperpolarized substrates, as well

as in human water/fat separations (39,40). The present Note explores yet another possible application of SPEN's spectroscopic imaging abilities, with a SPEN-based study focusing on the acquisition of reliable ADC maps of fibroglandular tissue in silicone-implanted human breasts.

Methods

Phantoms and Patients

This study was approved by the Institutional Review Board of the Wolfson Medical Center (Holon, Israel), and informed consents were obtained from all participants. Seven healthy volunteers (mean age 34, range 24-54) were recruited for this comparative study, with different sizes of silicone implants and of fibroglandular tissue. Also examined was a round plastic phantom containing tap, oil and silicone.

MRI Protocols

Axial images of one or both breasts were acquired at 3T on a Siemens TrioTIM scanner (Erlangen, Germany) using a four-channel bilateral breast coil (Siemens). Phantom images were collected on the same scanner using a four-channel head coil. For all seven volunteers the MRI protocol included a T_2 -weighted turbo spin-echo (TSE) sequence covering the whole breast for anatomical reference. This was followed by DWI acquisitions of fat-suppressed twice-refocused SE-EPI (41) and by SPEN DWI of five central slices in the region of the nipple, with the diffusion-weighting gradients repeatedly applied along three orthogonal directions. Common overall parameters of these experiments included fat suppression, $\delta=17$ ms pulsed diffusion-weighting gradients, intergradient delays $\tau=35$ ms, and $n=7$ nominal b values of 0, 50, 150, 300, 450, 600 and 750 s/mm^2 . These b -values were subsequently corrected by imaging cross-term gradient effects for the SPEN experiments (36,42) before using them to calculate the actual ADC maps. The spatial resolutions of both SE-EPI and SPEN experiments were $2.0 \times 2.0 \times 2.5 \text{ mm}^3$; FOVs were set to $320 \times 320 \text{ mm}^2$ and $320 \times 160 \text{ mm}^2$ - respectively, exploiting in the latter case SPEN's ability to "zoom" without suffering from folding effects. In both SE-EPI and SPEN experiments the low bandwidth (phase- or SPEN-) directions were scanned in an anterior $\rightarrow$ posterior geometry. The total scan durations (per slice) were 180 ms and 277 ms for DWI SPEN and SE-EPI, respectively. Each scan was preceded by a scanner-provided, spectrally-selective fat saturation procedure: SPAIR for SE-EPI and FatSat for the SPEN experiments. In order to shorten the SE-EPI echo times, a partial Fourier k-scan was set to 6/8. The scanner-supplied "Assume Silicone" option was also assayed in the SE-EPI scans, but did not provide improved images. No parallel imaging was used for either method. Minimum echo times for the SE-EPI and SPEN acquisitions were 101 ms and 124 ms, respectively. The sequence bandwidth was 1736 Hz/pixel with an echo spacing of 0.72 ms and 2232 Hz/pixel with an echo spacing of 0.69 ms, for the SE-EPI and SPEN experiments respectively.

Single-scan DWI in the presence of multiple chemical shifts

Figure 1 illustrates the SPEN sequence used in this study. It includes a FatSat pulse; an initial slice-selective $\pi/2$ excitation; a diffusion weighting block where bipolar gradient pulses of duration δ are separated by a diffusion time τ ; a SPEN module including an

adiabatic π sweeping in the presence of a gradient G_e a FOV defined by the adiabatic frequency range $\gamma G_e \text{FOV}$ (and thereby introducing a quadratic evolution phase $\phi_e(r) \propto r^2$ along the encoding gradient's direction (29,43,44)); and an acquisition including an oscillating $\pm G_{ro}$ gradient providing a modulation that when subject to Fourier Transform (FT) gives the spatial profile along the readout axis, interspersed with blipped G_a gradients resolving the position of each SPEN-encoded spin packet. Focusing on the acquisition along the latter axis only, the ensuing signal is of the form

$$S(t) \propto \Delta r \cdot \sum_{\text{sites } \Omega_{cs}} \int_{\text{FOV}} \rho_{cs}(\Omega_{cs}, r) \cdot \exp[i(\phi_e(r) + k_a(t)r + \Omega_{cs}t)] dr \quad [1]$$

where $\Delta r = \sqrt{\frac{\text{FOV}}{\gamma G_e T_e}}$ is a nominal spatial resolution defined by the encoding characteristics, $\rho_{cs}(t)$ is the spin density for a particular chemical site of shift Ω_{cs} , and

$k_a(t) = \gamma \int_0^t G_a(t') dt'$. The linear spatial nature of k_a means that SPEN's highest-sensitivity point, contributing at an instant t to the signal $S(t)$, will be unraveled on a t -dependent fashion. This in turn implies that each image pixel will be modulated along the SPEN dimension by a phase evolution that is proportional to $\Omega_{cs} \cdot t$, reflecting the chemical shift(s) of the emitting species. While the SPEN image retrieval process does not necessitate Fourier processing, it follows that FT along the SPEN/time acquisition axis, will yield the sample's chemical shift spectrum (38). The SPEN-specific portion of the sequence in Figure 1 can therefore provide a spatial image discriminated according to chemically shifted resonances, if the following procedure is adopted: (i) A modified signal $S_O(t)$ is calculated, given by the acquired $S(t)$ in eq. (1) demodulated by the r^2 quadratic contribution associated to $\phi_e(r)$ (i.e., multiplied by $\exp[-i\phi_e(r^2)]$); this is carried out in a procedure that already includes a super-resolution image reconstruction along the SPEN axis (31,35). (ii) A FT is applied to the ensuing arrays in order to resolve the magnetic resonance spectrum of every chemical shifted peak along the SPEN-encoded axis. (iii) Individual contributions arising from each chemical-resolved site are isolated (or removed) by applying a suitable spectral filtering –in our particular case aiming at erasing the contributions of unwanted residual silicone peaks. (iv) An inverse FT is applied to reconstruct back a spatial image characterized by the selection/erasure of a particular chemically shifted peak. With this data acquisition and processing protocol at hand, further analyses of the images collected for different b -values yields the ADC maps being sought (36,37). These image reconstruction and ADC map calculations were here implemented using customized Matlab® (The Mathworks Inc., Natick, Massachusetts, USA) routines that are available upon request. Diffusion statistics are presented bellow based on results obtained for five out of the seven scanned volunteers, as one volunteer's fibroglandular tissue was too small and placed in the nipple region, while a second case failed to show sufficient intensity signal of the fibroglandular tissue altogether.

Results

Phantom imaging example

Figure 2 illustrates the main steps adopted for the SPEN-based acquisition of breast images free from silicone signal interferences, illustrated with a single-slice experiment collected on a 12 cm diameter round plastic phantom containing tap water, a tube with oil (mimicking fat) and a medical silicone breast implant (Fig. 2e). As a first step in the experiment a chemical shift resolved spectrum of the specimen was obtained by taking the raw 2D fat-suppressed data (Fig. 2a), and applying on it a FT along the readout axis and a super-

resolved reconstruction eliminating from the signal the parabolic $\frac{\gamma G_e T_e}{FOV} r^2$ phase contribution along the SPEN dimension. Applying then a FT along the latter axis reveals the frequencies of the silicone signal to be removed, as well as of the water signal to be targeted (Fig. 2b). With this separation, the silicone (and if need be the residual fat) contribution to the total image can be eliminated by suitably masking a region in the ensuing spectral/spatial 2D plane (Fig. 2c). Replacing in this manner the silicone peak by zeroes and suitably re-processing the data, leads to a clean 2D image of the targeted phantom containing solely water and collected in a single scan (Fig. 2d). This is devoid from the interferences that would otherwise arise from a regular processing of the SPEN-collected data (Fig. 2f).

Separated water and silicone images in a single scan

Figure 3 illustrates the silicone filtering procedure, with the single-shot acquisition of separate silicone- and water-based images from a single breast anatomical scan. Utilized in this evaluation was SPEN's capability to evaluate tissues using a reduced FOV, while avoiding folding. Figure 3a shows a high-definition TSE multi-shot scan showing the boundaries of the silicone implant, the fibroglandular tissue, and the fatty tissue. Applying an acquisition scheme similar as that described for the phantom in Fig. 2 yields solely the silicone and water contributions; a suitable post-processing then enables one to target either one of these peak, leading to a selective separation of the anatomical images arising from either fibroglandular tissue (Fig. 3b) or from the silicone implant (Fig. 3c) – both reconstructed from the same single-shot scan.

Breast ADC maps based on anatomical, silicone-free images

Seven healthy volunteers with a variety of silicone implant sizes were scanned using the sequence in Fig. 1, and their breast ADC maps were generated. Figure 4 shows representative results on a healthy volunteer, presenting a T₂-weighted multi-scan anatomical image (Fig. 4a), as well as anatomical *b*-zero images (Fig. 4b) and ADC maps (Fig. 4c) delivered by DWI SE-EPI and by multi-slice SPEN, respectively. To avoid folding artifacts the FOV used in the SE-EPI scans was chosen to cover the whole body length along the axial direction, whereas in the folding-free SPEN scans the FOV along the low bandwidth direction could be reduced to half this size. Even after masking low-intensity noises and ghosts, the *b*-zero images afforded by SE-EPI show a noticeable chemical shift displacement artifact of the silicone implant, which together with a sizable ghost of both the water and silicone signals (yellow arrows in Fig. 4b) appear below the fibroglandular tissue. For the same volunteer and under very similar conditions SPEN succeeds to deliver images

that are much less influenced by ghosts, showing the fibroglandular tissue in its right location and a considerably weaker silicone contribution. Still, a residue from the implant can be seen in the filtered anatomical SPEN image as a result of an imperfect zeroing of the silicone peak; the zeroing of the silicone points also brings about a partial nulling of the water contribution, which therefore leads to a slight decrease of resolution when the SPEN data are subject to super-resolution reconstruction. Despite this, ADC maps arising from the SPEN experiments were unaffected by these residuals, and gave diffusion values that mimicked the changes observed by the genuine fibroglandular signals in SE-EPI (Fig. 4c).

A final example of the advantages resulting from this silicone-filtering DWI methodology is illustrated in Figure 5, which compares the performance of SE-EPI and SPEN sequences for a multislice scenario. Anatomical multi-scan T_2 -weighted images (Fig. 5. upper row) outline the structural tissue organization of the breast, involving fatty and fibroglandular tissue together with the silicone implant. Upon evaluating the ADC maps arising from SE-EPI and from silicone-filtered SPEN experiments (Fig. 5, middle and bottom rows respectively), much cleaner images can clearly be retrieved from the latter. The original compartmentalization of the fibroglandular tissues, the silicone implant and the fatty tissues are preserved for the different SPEN slices, even if comparable diffusion ranges are delivered by both methods: for the fibroglandular tissues the mean SE-EPI ADC = 1.63 ± 0.13 mm²/s, whereas for the SPEN slices the mean = 1.59 ± 0.18 mm²/s.

Discussion and Conclusions

Breast imaging in the presence of silicone implants, and measurements of fibroglandular diffusion maps in augmented breasts in particular, can help to follow-up an implant's integrity and/or assess a malignancy. When using SE-EPI for doing so poor image quality and severe artifacts result, particularly when sizable fat and silicone resonance contributions are present in the targeted FOV. This study discussed an alternative that, based on SPEN principles, could assist in handling such multiple chemical contributions in this spatially heterogeneous organ. Supporting this improved performance is SPEN's ability to provide single-scan images that are less affected by field inhomogeneities than SE-EPI's counterparts, as well as SPEN's built-in capacity to separate multiple spectral contributions without demanding additions or modifications to the original single-scan 2D imaging sequence. When combined with multi-slice operation and a diffusion-sensitizing protocol, a new approach to retrieve ADC maps of fibroglandular tissue in augmented breasts emerges. These SPEN measurements evidenced comparable ADC maps as those afforded by SE-EPI experiments (tailed $p = 0.16$), yet substantially freer from a variety of artifacts. Both methods showed relatively low diffusion values (mean ADCs ≈ 1.6 mm²/s), yet this is also in agreement with previously reported studies (45–47). When considering further DWI analyses incorporating SPEN-based chemical shift discrimination for evaluating breasts with silicone implants, the limited number of slices that specific absorption rate (SAR) currently permits to collect at 3 T, needs to be taken into account. This limitation derives from the sequence's use of a swept 180° inversion pulse to impose the spatiotemporal encoding, and thereby enable multi-slice acquisitions. Approaches to alleviate this technical limitation will be presented in an upcoming study.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

ADC	Apparent Diffusion Coefficient
DWI	Diffusion Weighted Imaging
EPI	Echo Planar Imaging
FT	Fourier transform
FOV	Field of View
SE	Spin Echo
SPEN	SPatio-temporal ENcoding
TSE	Turbo Spin Echo

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Figure 1.

Multi-slice “hybrid” SPEN pulse sequence including a fat presaturation (FatSat) block, a slice-selective excitation, a diffusion block placed in a pre-encoding delay, an adiabatic π pulse imposing the spatiotemporal encoding, a 2D single-shot signal acquisition module, and a final π pulse restoring spins in the volume that was not addressed by the slice-selective pulse back to thermal equilibrium. To discriminate among multiple chemical sites, this sequence operates in the so-called “non fully-refocused” mode; *i.e.*, with T_e different (in our case $\ll$) than $T_a/2$. The RF/ADC line displays the radiofrequency irradiation and signal acquisition; definitions include: G_{ss} , slice-selective gradient; G_d , diffusion-weighting gradients; G_{pr} , purge gradients; G_e , encoding gradient; G_a , SPEN acquisition gradients; G_{ro} , readout acquisition gradients; T_e , encoding time; T_a , acquisition time; N_{PE} = number of phase-encode steps; diffusion timing parameters are δ and Δ .

Figure 2.

Describing the silicone elimination procedure with a 12 cm plastic phantom containing a medical silicone breast implant and an oil tube, inside a water-filled sphere. (a) Raw data arising from the experiment, which included a FatSat-based suppression of the oil signal. (b) Mixed spectral/spatial information arising upon subjecting the raw data to a suitable 2D FT processing, highlighting with the yellow arrow the position of the silicone contribution to be eliminated. (c) Data set resulting upon zeroing in the set (b), the unwanted silicone contribution. (d) Ensuing image of the phantom arising by subjecting the data in (c) to inverse FT along the spectral axes, leading to a SPEN hybrid magnitude image including a water signal but free from the silicone contribution. This is to be compared with (e), which is the image arising upon subjecting the SPEN data to super-resolution reconstruction without filtration. This shows a clear contribution of a silicone signal, whose chemical shift displacement overlaps its image with that of the water signal. Shown for completion in (f) is a picture of the examined phantom. SPEN acquisition parameters included a FOV = 24×19.2 cm², slice thickness 2.5 mm, $T_a = 77$ ms, $T_e = 5.9$ ms, $G_e = -0.15$ G/cm. The in-plane effective resolution was 1.7×1.7 mm².

Figure 3.

Axial single breast slice of a volunteer with an augmented breast. (a) Multi-shot T_2 -weighted TSE image and (b, c) single-shot SPEN images of fibroglandular tissue and silicone. Acquisition parameters: For the multi-shot: FOV = $18 \times 18 \text{ cm}^2$, slice thickness 2.5 mm, in-plane effective resolution = $0.28 \times 0.28 \text{ mm}^2$. For SPEN: FOV = $19.2 \times 19.2 \text{ cm}^2$, slice thickness 2.5 mm, in-plane effective resolution = $1.9 \times 1.9 \text{ mm}^2$, $T_a = 70 \text{ ms}$, $T_e = 5.9 \text{ ms}$, $G_e = -0.16 \text{ G/cm}$.

Figure 4.

Comparison between axial anatomical slices (left and middle panels) and ADC maps (right panel) arising from multislice SE-EPI and SPEN experiments on an augmented breast volunteer. (a) Multi-shot T₂-weighted TSE image. (b) Anatomical single-shot A→P images illustrating with yellow arrows residual silicone and ghosted fibroglandular signals. (c) ADC maps arising from twice-refocused SE-EPI (upper panel) and from multislice SPEN (lower panel) sequences. The corresponding ADC maps were weighted by *b*-values applied along three orthogonal axes as described in Methods. Acquisition parameters were as follows. Multi-shot scan: FOV = 36×36 cm², slice thickness 2.5 mm, in-plane resolution 0.8×0.6 mm². SE-EPI imaging: FOV = 32×32 cm², slice thickness 2.5 mm, in-plane resolution 2×2 mm². SPEN imaging: FOV = 32×16 cm², slice thickness 2.5 mm, in-plane resolution 2×2 mm², T_a = 55.2 ms, T_e = 5.1 ms, G_e = -0.3 G/cm.

Figure 5.

Five axial slices showing multi-shot anatomical images (top row) and ADC maps (central and lower rows) derived from SE-EPI and SPEN sequences applied on an augmented breast volunteer. Anatomical images were collected with a T_2 -weighted TSE sequence; ADC maps arose from b-values applied along three orthogonal axes as described in Methods.

Acquisition parameters for the multi-scan, the SE-EPI and the SPEN acquisitions are identical as described in Figure 4, except for the fact that in the SPEN experiments $T_a = 59$ ms, $T_e = 5.1$ ms, $G_e = -0.25$ G/cm.