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A Pilot Study of Improved Lesion Characterization in Breast MRI Using a 3D Radial Balanced SSFP Technique With Isotropic Resolution and Efficient Fat-Water Separation

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Abstract

Purpose—To assess a 3D radial balanced steady state free precession technique that provides sub-millimeter isotropic resolution and inherently registered fat and water image volumes in comparison to conventional T2-weighted RARE imaging for lesion characterization in breast MRI.

Materials and Methods—3D PROjection SSFP (3DPR-SSFP) combines a dual half-echo radial k-space trajectory with a linear combination fat/water separation technique (Linear Combination SSFP). A pilot study was performed in 20 patients to assess fat suppression and depiction of lesion morphology using 3DPR-SSFP. For all patients fat suppression was measured for the 3DPR-SSFP image volumes and depiction of lesion morphology was compared against corresponding T2-weighted Fast Spin Echo (FSE) datasets for 15 lesions in 11 patients.

Results—The isotropic 0.63 mm resolution of the 3DPR-SSFP sequence demonstrated improved depiction of lesion morphology in comparison to FSE. The 3DPR-SSFP fat and water datasets were available in a 5 minute scan time while average fat suppression with 3DPR-SSFP was 71% across all twenty patients.

Conclusion—3DPR-SSFP has the potential to improve the lesion characterization information available in breast MRI, particularly in comparison to conventional FSE. A larger study is warranted to quantify the effect of 3DPR-SSFP on specificity.

Keywords

breast imaging; cancer imaging; radial acquisition; bSSFP; LC-SSFP

Introduction

Initial implementations of fully balanced steady state free precession (bSSFP) sequences were limited by long repetition times (TRs) which increased the possibility of banding artifacts due to magnetic field inhomogeneities (1,2). However, the continued development of high performance gradient systems, which allow for shorter TRs, has alleviated the

sensitivity of bSSFP to banding artifacts and thus improved the feasibility of using bSSFP for diagnostic tasks. In cardiac imaging, bSSFP provides high contrast in the myocardium without intravenous contrast injection while its inherent acceleration allows real-time wall motion studies without cardiac gating (3-5). In the musculoskeletal system, where the clinical standard has long been dominated by two dimensional RARE-based methods (6) (Fast Spin Echo (FSE), Turbo Spin Echo (TSE)), bSSFP better depicts contrast between cartilage and surrounding tissues and can accelerate T1 and T2 mapping (7,8). Further applications of bSSFP include recent studies which have demonstrated the possible diagnostic relevance of the T2/T1 contrast mechanism for lesion characterization; for example, in the liver, bSSFP can help to differentiate benign hemangiomas and malignant lesions (9).

Improved differential diagnosis in breast MRI may also be possible with bSSFP (10). By providing high SNR with T2-like contrast in rapid scan times, bSSFP provides an opportunity to improve the diagnostic information available with conventional T2-weighted sequences. In the T2-weighted breast MR image, both lesion signal intensity and lesion morphology can contain diagnostically relevant information (11-14). When lesion characterization remains equivocal based on Dynamic Contrast Enhanced (DCE) information in breast MRI, the T2-weighted acquisitions are typically analyzed. However, acquiring 3D T2-weighted high resolution images in clinically feasible scan times with FSE is unrealistic as extended TRs, and thus long scan times, are required to eliminate T1 signal contamination. Due to this limitation, conventional T2-weighted breast acquisitions are normally acquired in the sagittal plane as a set of 3-4 mm slices with gaps in between. While useful morphological detail is likely to exist in any plane, this acquisition requires that the detail be evident in the sagittal plane. In addition, partial voluming of the thick slices further limits visualization. The most recent developments in extended RARE echo trains now allow 3D T2-weighted acquisitions with 30-40 echoes per second (15); however, bSSFP methods offer the possibility to acquire 5-10 times as many echoes per second. Because of its superior acquisition efficiency, 3D bSSFP volumes with thin slices can be acquired in clinically feasible scan times, providing a more robust dataset in comparison to conventional T2-weighted techniques. While bSSFP contrast is T2/T1 dependent, more mechanisms contribute to T2 than T1. As Vasanawala (16) demonstrated tissues with T1s > 500 ms tend to produce T2-weighted contrast at moderate to high flip angles.

The aim of this work is to investigate a specific bSSFP technique, 3D PROjection SSFP (3DPR-SSFP) as described by Lu, et al. (17), in comparison to conventional FSE for the characterization of breast lesions. 3DPR-SSFP, which has applications in non-contrast angiography (17) and cartilage imaging (18) is potentially well tailored for breast MRI because it provides high isotropic resolution and efficient fat-water separation. In comparison to previous investigations of bSSFP in breast MRI (10), 3DPR-SSFP provides a reduction in voxel volume of more than 80%. To separate water and fat, 3DPR-SSFP utilizes Linear Combination SSFP (LC-SSFP) (16) while a dual half-echo radial trajectory is used to provide high isotropic resolution in the fat and water datasets. The radial trajectory is not highly undersampled but provides an increase in data acquisition efficiency in comparison to Cartesian LC-SSFP.

Fat suppression is imperative in bSSFP because the high T2/T1 ratio of fat relative to other tissues of interest leads to very strong fat signal (19). In conventional T2-weighted sequences preparation pulses are commonly used for fat suppression, but maintaining the steady state while using preparation pulses can be challenging (20). LC-SSFP, is one of a number of techniques including Fluctuating Equilibrium MRI (FEMR) (21) and Alternating Repetition Time MRI (ATR) (22), which use a combination of phase cycling and timing regimens to shift and extend the characteristic pass and stop bands in the bSSFP frequency

response spectrum in order to separate water and fat. In contrast to other techniques which produce only a fat-suppressed image volume, a favorable feature of using LC-SSFP is that it allows for the retrospective creation of both fat and water image volumes from a single scan. The width of the suppression bands of LC-SSFP are equal to $1/2TR$ and therefore generate more consistent suppression than would be possible by simply placing the notch in the bSSFP response spectrum at a frequency that one wants to suppress. As with other fat-water separation techniques, there is a possibility that B_0 inhomogeneity will push the desired signal into the other channel. Here the radial trajectory is used to provide significant time for encoding while generating pass bands and stopbands centered at the proper frequency offset. The ability to analyze both the fat and water regions of an image is particularly appealing in breast MR where distinct diagnostic information can be found in both of these image sets. Also, the separate fat and water images are diagnostically advantageous in comparison to a set of conventional fat and non-fat suppressed bSSFP acquisitions. The benefit of having water suppressed images is that lesions surrounded by fat are suppressed and as such their margins are emphasized; this information would not exist in a non fat-suppressed conventional bSSFP image.

In a single scan 3DPR-SSFP provides inherently registered high resolution fat and water images in which lesion morphology can be analyzed in any orientation. The goals of this work are to demonstrate the use of 3DPR-SSFP as an effective fat-water separation technique in the breast and to compare its ability to depict critical lesion morphology against FSE. In a twenty patient dataset, we measure the level of fat suppression in images acquired using 3DPR-SSFP and demonstrate the diagnostic utility, in terms of depiction of lesion morphology, of increased through plane resolution and the ability to reformat breast lesions with high resolution in any orientation.

Materials and Methods

3DPR-SSFP

The dual half-echo radial k-space trajectory of 3DPR-SSFP (Figure 1) facilitates the acquisition of a high resolution dataset within the timing constraints of LC-SSFP. For optimal fat-water separation, LC-SSFP requires a relative phase shift of π to accrue between fat and water spins across each TR leading to an optimal TR of only 2.4 ms at 1.5 T (16). Along with a specific TR time and a center frequency halfway between fat and water, LC-SSFP requires two passes of data to be collected with different phase cycling. In 3DPR-SSFP, the same set of radial lines is acquired during the first and second pass with each pass lasting 2.5 minutes. During the first pass, π phase cycling is used while constant phase cycling is performed in the second pass.

In Cartesian bSSFP scans, the data acquisition window is limited by the prewinder and rewinder gradients required to prepare and refocus the transverse magnetization. With a dual half echo radial trajectory, data can be acquired during the prewinder and rewinder intervals to increase the data acquisition efficiency despite the relatively short TR of LC-SSFP. Therefore, the dual half-echo radial trajectory used in 3DPR-SSFP improves data acquisition efficiency in comparison to a Cartesian trajectory which would leave minimal time for spatial encoding (Figure 2). For example, considering a TR of 2.9 ms, at which LC-SSFP still performs robustly, a slew rate of 150 mT/m/ms, gradient amplitude of 40 mT/m, and a 20 cm field of view, the minimum voxel dimension achievable using a Cartesian trajectory would be 1.1 mm leading to a voxel volume of 1.331 mm³. However, for the same imaging parameters using 3DPR-SSFP, the minimum voxel dimension is reduced to 0.63 mm and voxel volume is reduced by more than 80 percent to 0.25 mm³. Parallel imaging could be used to accelerate the Cartesian trajectory by reducing the number of phase encodes; however, parallel imaging does not alleviate the limited time available within each TR for

data acquisition. Thus, given the high resolution we desire, a Cartesian trajectory is still not a viable option even when accelerated with parallel imaging.

The use of a radial k-space trajectory also allows for undersampling which, in this implementation, facilitates a clinically feasible scan time. It is important to distinguish the advantage of the radial trajectory in 3DPR-SSFP in comparison to other implementations of radial imaging. The Nyquist sampling criteria for radial imaging requires about 50% more excitations than Cartesian scanning (23). Often, azimuthal undersampling is utilized for improved temporal resolution in sparse environments in which characteristic streak artifacts are less prevalent (24). However, with 3DPR-SSFP, undersampling the number of radial lines is feasible due to the limited sensitivity regions of the coils. For a given spatial resolution, the number of radial lines necessary in 3DPR to avoid aliasing grows as the square of the size of the sensitivity region of the receiver coil, not the size of the entire FOV (25). Because the coils that are commonly used in phased array breast imaging are sensitive to a region smaller than the entire FOV, undersampling is possible with the four channels used for a unilateral acquisition. Thus, since 3DPR-SSFP does not use a high degree of radial undersampling, Nyquist criteria is met for the regions of sensitivity of the coils in the array and characteristic aliasing artifacts are diminished. Specifically, in this implementation of 3DPR-SSFP, 2/3 of the number of radial lines needed to meet the Nyquist criteria for the full field of view are acquired. Gridding is performed using a triangular convolution kernel on each axis and immediate on-line reconstruction is available with the vendor provided reconstruction servers. Though 3DPR-SSFP has previously been referred to as Vastly undersampled Isotropic PROjection SSFP (VIPR-SSFP)(18,26) for applications in other parts of the body, we simply term the method 3DPR-SSFP in this application to reflect the limited amount of undersampling utilized.

Patient Scans

All patients were consented following IRB policies and procedures at our institution. Two recruitment methods were used to enroll patients in the study. In the first method, patients who had had a clinical MRI ordered were asked to sign an informed consent granting permission for an additional unilateral 3DPR-SSFP scan to be added to their clinical breast MRI exam. Recruitment was not based on the existence of specific pathology or clinical indication for ordering the MRI and according to IRB policy, the 3DPR-SSFP scan was not used to arrive at a clinical diagnosis. 3DPR-SSFP was only acquired on one breast per patient to limit the extension of the total exam session time by 5 minutes. Once a patient had consented, if pathology of interest was noted on the clinical MRI order, then the 3DPR-SSFP scan was run on that breast, otherwise the breast chosen for analysis was arbitrary as FSE is routinely acquired on both sides. Fourteen patients were recruited from this population.

Performing the 3DPR-SSFP scans as clinical add-ons provided a straightforward way to acquire the 3DPR-SSFP and corresponding FSE scans, however, many of the patients undergoing breast MRIs at our institution are found not to have pathology present. Thus while the first patient dataset allowed us to analyze the general performance and fat-water separation of 3DPR-SSFP, it did not provide sufficient data for the analysis of lesion morphology. Therefore, in the second recruitment method, to determine whether imaging performance on lesions warranted a larger study, patients with a known mass were recruited. These patients were recruited directly for a dedicated research MRI exam based on presence of a 1 cm or larger mass prescribed for biopsy that was found through ultrasound, mammography or clinical examination. Six patients were recruited from this population.

Imaging Parameters

Fourteen exams were performed on a GE Echospeed 1.5 T scanner (General Electric Health Care, Waukesha, WI) while six were performed on a GE Twinspeed 1.5 T scanner. A GE 8-channel HD Breast coil was used for 18 of the exams while a 4-channel breast coil (MRI Devices Corp., Waukesha, WI) was used for two of the exams. All 3DPR-SSFP and FSE acquisitions were performed unilaterally and for each patient, the shim volume used with 3DPR-SSFP was identical to the one used for the FSE acquisition. For the 3DPR-SSFP exams, a 20 cm diameter spherical field of view and matrix size of $320 \times 320 \times 320$ was chosen to match the $0.63 \text{ mm} \times 0.63 \text{ mm}$ in-plane resolution of the FSE datasets at our institution. The resultant isotropic resolution of 3DPR-SSFP was 0.63 mm in all directions. The resolution of the 3DPR-SSFP sequence was chosen to match the in-plane resolution of the FSE acquisition. Achieving this resolution with a 20 cm FOV resulted in TRs of 2.7-2.9 ms using moderately powered gradient systems (Echospeed: 33 mT/m, 77 mT/m/ms and Twinspeed: 40 mT/m, 150 mT/m/ms). Flip angle of 30° was chosen as it provided the best trade-off of maximizing signal and contrast for structures of interest in the breast (fat, fibroglandular tissue, malignant lesions, benign lesions) (27). In a total scan time of 5 minutes, approximately 106,000 TRs were acquired, each comprised of two radial lines.

The FSE datasets were acquired following the clinical protocol at our institution and the imaging parameters were as follows: 4 mm slice thickness, 256×256 in-plane matrix ($0.63 \times 0.63 \text{ mm}$ resolution), 16 cm – 22 cm FOV, TR/TE of 5000 ms/128 ms, and total scan time of 4 minutes. The average echo train length was 14 and average number of slices was 28. Fat suppression in the FSE acquisition used standard chemical presaturation (28).

Quantitative Measurement of Fat Suppression with 3DPR-SSFP

The ability of 3DPR-SSFP to separate fat and water using LC-SSFP has not been evaluated previously in breast imaging. Because 3DPR-SSFP allows for the reconstruction of both fat and water image volumes, the level of fat suppression can be calculated in a straightforward manner using images from these two volumes. To determine the fraction of fat signal suppressed with 3DPR-SSFP, signal was measured from an ROI placed in the fatty region on a central slice in the fat image volume. The signal was then measured for the same ROI on the corresponding water image. The level of fat suppression in the 3DPR-SSFP images was estimated as follows:

$$F_{\text{sup}} = (F_f - F_w) / F_f \quad [1]$$

where F_{sup} is the fraction of fat signal suppressed in the water image, F_f is the signal from the ROI in the fat image and F_w is the signal of the same ROI in the water image. The measure will tend to underestimate F_{sup} as we did not separate the mean of the rectified noise signal from the residual water signal in F_w . Each ROI was 40×40 pixels. As ROI placement was solely determined from the fat image volume, it was not biased by knowledge of the quality of fat suppression in the water image volume. To establish a baseline measurement for the level of fat suppression using 3DPR-SSFP that excluded physiological and anatomical factors, data was acquired in a phantom comprised of vegetable oil and water doped with gadolinium to mimic the T1 value of fibroglandular breast tissue ($\sim 800 \text{ ms}$) (Figure 3). The fraction of fat signal suppressed was measured in the phantom.

Previous work has shown that some residual fat signal is expected in the water image volumes with LC-SSFP because of differences in the fat and water signals in each of the two LC-SSFP passes (29). In light of this work all image volumes were reconstructed a second time using a modified LC-SSFP fat suppression technique termed Weighted Combination

(WC) SSFP (29) which compresses the difference in magnitude using a non-linear weighting of the magnitude of each pass. All twenty 3DPR-SSFP exams were reconstructed a second time using WC-SSFP and the fraction of fat signal suppressed was calculated for these image volumes. Comparable fat suppression measurements were not performed for the FSE images, as FSE is only acquired once with fat suppression at our institution.

Qualitative Assessment of Depiction of Lesion Morphology

A radiologist with over 15 years of clinical breast MRI experience assessed the depiction of lesion morphology in the 3DPR-SSFP images in comparison to the respective FSE images for each case. The 3DPR-SSFP exams were first reconstructed in the sagittal orientation and then analyzed side by side with the corresponding FSE images. For each case the radiologist was asked to identify lesions with high signal intensity and to note whether the lesion was seen on the FSE images, the 3DPR-SSFP images, or both. The radiologist assessed the depiction of lesion morphology in this set of lesions and noted any differences between the 3DPR-SSFP sagittal reformats and the FSE images. Following this side by side comparison, two additional features of the 3DPR-SSFP image volumes were evaluated to assess their potential to improve lesion characterization. First, a 3D representation of each 3DPR-SSFP image volume was analyzed to determine if the depiction of the lesion morphology was improved by being able to reformat the images at high resolution in any plane. Second, the radiologist was presented with the corresponding fat 3DPR-SSFP image volumes and was asked to note any additional lesion characterization information that was available through analysis of the fat image volumes in addition to the water image volumes. The respective DCE and pre-contrast T1-weighted data were available for reference during analysis of the fat image volumes to allow for assessment of structures with low signal intensity on the 3DPR-SSFP and FSE images. After qualitative assessment was complete, the entire exam was available to best characterize lesions that were not biopsy proven.

Results

Fat Suppression with 3DPR-SSFP

The clear delineation of scattered fibroglandular tissue in multiple planes, as well as the intrinsic registration of these high resolution features between the fat and water 3DPR-SSFP images are shown in Figure 4. The 3DPR-SSFP exam provided both fat and water datasets in a single 5 minute scan. The fraction of fat signal suppressed in the phantom was 92%. The fraction of fat signal suppressed (F_{sup}) in the 3DPR-SSFP images in all exams ranged from 64% to 80% with a mean value of 71% and standard deviation of $\pm 4\%$. Using the WC-SSFP reconstruction technique to improve fat suppression, F_{sup} ranged from 80% to 93% with a mean value of 88% and a standard deviation of $\pm 4\%$. An example of additional information of diagnostic relevance in the 3DPR-SSFP fat images is seen in the case of an invasive ductal carcinoma (IDC) surrounded by fatty tissue shown in Figure 5. The spiculated margin of the IDC in this case is more noticeable against the fatty background in the 3DPR-SSFP fat image and correlates well with its depiction in the DCE images.

Depiction of Lesion Morphology

A total of 18 lesions with high signal intensity were identified in 14 patients while six patients had no lesions present. Fifteen of the lesions were identified on both the 3DPR-SSFP images and the FSE images (Table 1). This group consisted of three complex cysts, one fibroadenoma, one mucinous carcinoma, and 10 lymph nodes. Three lesions demonstrated high signal on the 3DPR-SSFP dataset but not on the corresponding FSE images. These three structures were ductal and subareolar fluid, blood products, and a complex cyst. There were no lesions with high signal intensity that were identified on the FSE images but not in the 3DPR-SSFP images. The mucinous carcinoma was biopsy proven

while the other 17 lesions were characterized by the radiologist based on analysis of the entire breast MRI exam including pre-contrast T1-weighted images and the DCE information.

Specific morphologic features that help to differentiate benign and malignant lesions were more evident in the 3DPR-SSFP images in comparison to the conventional FSE images. The improved depiction of morphology due to the increased through plane resolution and the ability to analyze high resolution images in arbitrary orientations was demonstrated in a number of cases. In Figure 6 a small fibroadenoma is visible on both the conventional FSE and corresponding 3DPR-SSFP images. However, internal septations within the lesion, which can be indicative of benignity, are more evident on the 3DPR-SSFP sagittal image. The internal septations are much more evident in the reformatted axial and coronal 3DPR-SSFP images, demonstrating the diagnostic implications of analyzing high resolution depiction of the lesion morphology in arbitrary orientations. In Figure 7, fine structure within the breast is clearly depicted along with a biopsy proven mucinous carcinoma which has high T2-weighted signal. In this case, macrolobulation was thought to be present on standard FSE imaging while the 3DPR-SSFP images revealed a microlobulated border, more indicative of the true diagnosis of a malignant mucinous tumor. In this case, an oblique reformat of the 3DPR-SSFP data further clarified the depiction of microlobulated margins and internal structure. Figure 8 shows one of the cases in which a lesion with high signal intensity on a 3DPR-SSFP image did not demonstrate high signal intensity on the corresponding FSE image. The cyst with blood products is not clearly visible in the FSE images but has high signal on both the pre contrast T1-weighted image and on the 3DPR-SSFP image.

Discussion

The breast presents a particularly challenging environment for bSSFP acquisitions because of the high amount of fat and the often heterogenous distribution of fibroglandular tissue throughout the fat. Our research revealed that the level of fat suppression in the 3DPR-SSFP images was sufficient to perform clinical tasks, but an average of 29% fat signal remained in the fat voxels in the water image. Fraction of fat signal suppressed was therefore an average of 20% lower in vivo in comparison to the phantom experiment. Complete fat suppression is not expected as approximately 10% water signal is expected in fat and our measurement technique did not distinguish between the non-zero mean of noise and residual water component compensate present in the lipid regions. An example of non uniformity of fat suppression is seen Figure 3d and e in which the level of fat suppression varies slowly in the SI direction. A number of factors may contribute to the residual fat signal and the variability from patient to patient. Extension of the TR to either 2.7 or 2.9 ms was necessary in this study due to the moderate gradient system used and thus narrowing of the the pass and stop bands of the 3DPR-SSFP spectrum occurred (Figure 9). We expect this shift in the stopbands to have a greater effect in vivo where the spectral fat peak is wider than that of the phantom. The results of the 3DPR-SSFP patient scans indicate that though this shift may slightly reduce the fat suppression, the technique is still fairly robust at these TR times as the stopband still encompasses the central fat peak (+ 75 Hz/-40 Hz). The extension of the TR would be more problematic in applications of 3DPR-SSFP at 3T (30) where the number of bands occurring between the spectral peaks and the center frequency is increased and thus the effect of the shifted spectrum at higher TRs is greater.

Further consideration of the frequency response spectrum may also help explain the inter patient variation in fraction of fat suppression. The residual fat signal in the 3DPR-SSFP images may also be attributed to the differences in magnitude between the two passes of data in LC-SSFP and techniques have been developed to address this problem (29,31). In the

twenty cases in this study, WC-SSFP improved fat suppression so that only 12% fat signal remained in the water images. A second method, Phase Difference SSFP, which uses a phase difference map between the passes to identify fat voxels and reduce their residual signal (31), may also help to improve the fat suppression of 3DPR-SSFP. Further studies will help to identify the best techniques to optimize fat suppression in the breast with 3DPR-SSFP. While WC-SSFP and Phase Difference SSFP may improve the fat suppression available with 3DPR-SSFP, it is important that any technique that reduces the residual fat signal also maintains the fidelity of the fat-water interfaces. One of the strengths of the LC-SSFP fat-water separation technique is that it correctly represents voxels at fat-water interfaces where there exists a mix of fat and water spins (16). Representation of these voxels is particularly important in the breast where interfaces between fat and fibroglandular tissue are scattered throughout the breast and vary from patient to patient.

As 3DPR-SSFP does not account for phase shifts due to B_0 inhomogeneity, fat-water signal swapping was observed in areas of severe B_0 inhomogeneity in the 3DPR-SSFP images. Such fat suppression artifacts are common in breast MRI at the edges of the breast near to the chest wall as seen in the superior region of the breast in Figure 6. In all twenty cases in this study, areas with fat suppression failures of this nature in an area in the 3DPR-SSFP images corresponded to a failure in the same location in the FSE images. There has been some success extending multi-point fat-water separation techniques (32) to 3D radial trajectories in order to account for these areas of inhomogeneity (33). It may also be possible to incorporate other multi-point fat-water separation methods (34-36) with radial 3D bSSFP. Future incorporation of these techniques into a bSSFP radial sequence would likely significantly reduce the swapping while maintaining high isotropic resolution.

The significant improvement in the depiction of lesion morphology in comparison to conventional FSE is the prominent feature of the 3DPR-SSFP images in this study. In conventional FSE, lesion morphology can only be analyzed in the orientation in which the images are acquired due to the relatively thick slices (3-4 mm). However, with 3DPR-SSFP, the images can be reformatted in any orientation thus increasing the possibility of identifying morphology for differential diagnosis. In the 15 lesions with concordant signal intensity in FSE and 3DPR-SSFP, FSE never depicted distinguishing morphological characteristics that were not seen in the corresponding 3DPR-SSFP images. As has been previously noted (10), the high resolution of bSSFP would also allow for better correlation with DCE images in comparison to FSE. Ultimately, the improved depiction of morphology would be most beneficial to differential diagnosis in cases in which lesion characterization based on the DCE data is equivocal. A much larger observer study, which is now underway, will allow us to focus on this subset of patients and to quantify any effect that 3DPR-SSFP will have on the sensitivity and specificity of breast MRI. This larger study will also allow us to address the shortcoming in this study that only one unblinded radiologist provided opinions on the results.

It is important to note that the expanded amount of information available with 3DPR-SSFP is acquired in a total scan time (5 minutes) similar to that needed for a single FSE fat-suppressed dataset (3-4 minutes). Because of the timing limitations of conventional FSE sequences, common practice in breast MRI is to acquire either a fat-suppressed or a non-fat suppressed FSE acquisition but not both. 3DPR-SSFP increases the possibility of detecting critical lesion morphology while also obviating the need to choose between fat- and non-fat-suppressed acquisitions with a minimal increase in total scan time. The potential advantage, in terms of lesion characterization, of the availability of the fat images was anecdotally demonstrated in this study in the case in which lesion margin detail of an IDC was more evident in the fat images. Opportunities exist to further facilitate clinical implementation of 3DPR-SSFP by expanding the technique to encompass bilateral acquisitions. The increase in

scan time from the large field of view for a bilateral acquisition could be mitigated by further undersampling the radial k-space trajectory to exploit the smaller coil sensitivity regions available with phased array breast coils. Two options to better tailor the field of view to include both breasts include using Partially parallel Imaging with Localized Sensitivity (PILS) (25) with a dual slab excitation or using an elliptical field of view with a coronal excitation (37).

While a quantitative analysis of the contrast of critical breast structures in bSSFP versus conventional T2-weighted methods was not a goal of this study, the three cases in which structures demonstrated significantly different contrast between 3DPR-SSFP and FSE were important ancillary findings. These three structures, a complex cyst, ductal and subareolar fluid all have shortened T1 values and thus do not demonstrate T2-like contrast. This reemphasizes that while the T2-like nature of the contrast mechanism in bSSFP may make it an attractive alternative to conventional T2-weighted acquisitions, further understanding of the T2/T1 contrast in ancillary structures in the breast is essential to properly incorporate bSSFP acquisitions such as 3DPR-SSFP into the lexicon of breast MRI.

In conclusion, this study demonstrates the improved lesion characterization available with a 3D isotropic T2-like imaging sequence in comparison to conventional FSE in breast MRI. Radial sampling is used within a bSSFP acquisition to simultaneously meet the requirements of high signal, high resolution, and fat-water separation. The depiction of lesion morphology, including internal structure and lesion margins, is greatly improved in these preliminary results using 3DPR-SSFP. Fat and water image volumes are available in a reasonable total scan time of five minutes and thus, the diagnostic information in both types of images can be utilized. Based on these results, a larger observer study is warranted to determine if 3DPR-SSFP can improve the specificity of breast MRI.

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Figure 1.

In 3DPR-SSFP, two separate radial lines are acquired per TR (a - radial lines acquired for 4 TRs). Dual-half echo radial trajectory allows for signal to be acquired (DAQ) throughout entire application of the imaging gradients (b), increasing data acquisition efficiency in comparison to Cartesian trajectory (c) in which data is not acquired during prewinder or rewinder gradients.

Figure 2.

Conventional bSSFP (a), 3DPR-SSFP water (b) and 3DPR-SSFP fat (c) images in phantom comprised of gadolinium doped water ($T_1 \sim 800$ ms) and vegetable oil; Phantom used to acquire baseline 3DPR-SSFP fat suppression measurements for comparison to in vivo results. Images acquired using breast coil and imaging parameters identical to those used for patient scans.

Figure 3. Single 5 minute 3DPR-SSFP acquisition provides both fat (a-c) and water (d-f) images that can be reformatted in any orientation due to the isotropic k-space acquisition trajectory; sagittal (a,d), coronal (b,e), and axial (c,f) 3DPR-SSFP reformats.

Figure 4.

One way 3DPR-SSFP fat images can improve lesion characterization is through depiction of lesion margins. In this patient, an invasive ductal carcinoma with characteristic low signal on T2-weighted images is detected on the post contrast T1-weighted data (a, white arrow). Spiculated margins of the lesion are corroborated in the 3DPR-SSFP fat image volume (b, black arrow).

Figure 5. Small (4 mm) fibroadenoma (white arrows) identified on sagittal FSE (a) and 3DPR-SSFP (b) images. Magnified images of the lesion, FSE (c) and 3DPR-SSFP (d), demonstrate the better depiction of characteristic internal septations due to the increased through-plane resolution of 3DPR-SSFP. The diagnostic significance of being able to reconstruct the 3DPR-SSFP data in any orientation is also evident as the internal septations are much more clearly depicted in the magnified axial (e) coronal (f) 3DPR-SSFP reformats.

Figure 6.

FSE (a) and 3DPR-SSFP (b) sagittal images with lobular cancer (white arrows) confirmed through biopsy. Due to reduced partial voluming, microlobulated margins, indicative of malignancy, are more clearly depicted in the magnified 3DPR-SSFP image (d) in comparison to the magnified FSE image (c). The advantage of being able to reformat the data in any orientation is again evident as microlobulation and internal lesion structure are corroborated in a magnified oblique reformat of the 3DPR-SSFP image volume (e).

Figure 7. 3DPR-SSFP contrast does not always reflect T2-weighted contrast. For this protienaceous/bloody cyst (white arrows), the lesion demonstrates low signal intensity in the FSE image (a) but high signal intensity in the 3DPR-SSFP image (b). For this lesion, 3DPR-SSFP contrast is more representative of the precontrast T1-weighted image (c) likely owing to the shortened T1 and T2 of the blood products in the cyst.

Figure 8.

In LC-SSFP, center frequency is halfway between fat and water. LC-SSFP response spectrum for fat ($T_1 = 260$ ms, $T_2 = 80$ ms, 30° FA) at TRs of 24. ms (solid line), 2.7 ms (dashed line) and 3.0 ms (dash-dot line) at 1.5 T. Stop and passbands narrow with extension of TR from optimal TR of 2.4 ms, however, suppression band still encompasses central fat peak ($+75$ Hz/ -40 Hz).

Table 1

Lesions identified for qualitative comparison of depiction of morphology in 3DPR-SSFP versus FSE.

Lesions demonstrating concordant high Signal intensity on 3DPR-SSFP and FSE images (N = 15)	3 complex cysts 1 fibroadenoma 1 mucinous Carcinoma 10 lymph nodes
Lesions demonstrating discordant Signal intensity between 3DPR-SSFP and FSE images (N = 3)	1 ductal/subareolar fluid 1 blood products 1 complex cyst