Clinical Note

High-Speed 3T MR Spectroscopic Imaging of Prostate With Flyback Echo-Planar Encoding

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Prostate MR spectroscopic imaging (MRSI) at 3T may provide two-fold higher spatial resolution over 1.5T, but this can result in longer acquisition times to cover the entire gland using conventional phase-encoding. In this study, flyback echo-planar readout trajectories were incorporated into a Malcolm Levitt's composite-pulse decoupling sequence (MLEV)–point-resolved spectroscopy sequence (PRESS) to accelerate the acquisition of large array ($16 \times 16 \times 8$), high spatial (0.154 cm^3) resolution MRSI data by eight-fold to just 8.5 minutes. Artifact free, high-quality MRSI data was obtained in nine prostate cancer patients. Easy data reconstruction and the robustness of the flyback echo-planar encoding make this technique particularly suitable for the clinical setting. The short acquisition time provided by this method reduces the 3T prostate MRI/MRSI exam time, allows longer repetition times, and/or allows the acquisition of additional MR acquisitions within the same exam.

Key Words: prostate; MRSI; 3T; flyback; echo-planar
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THREE-DIMENSIONAL (3D) MR spectroscopic imaging (MRSI) has been used clinically in prostate cancer patients for assessment of tumor extent, planning treatment, and therapeutic follow-up (1,2). One limitation of this technique is the time needed to acquire large-volume 3D MRSI datasets when using conventional phase encoding in three directions to traverse k-space. With higher-field MR systems such as 3T scanners becoming widely available and improved coil arrays providing increased signal-to-noise ratio (SNR), MRSI data can be acquired with higher spatial resolution. However, the scan time required for the acquisition of 3D high-resolution MRSI data with adequate spatial coverage may be prohibitively long for clinical exams. Also, with increased specific absorption rate (SAR) and longer T1 relaxation times at higher fields, scan time may be further increased by the necessity of using longer repetition time (TR). In addition, J-modulation of citrate resonances at 3T makes acquisition of upright citrate peaks at reasonable echo times difficult (3–5). New methods are required to overcome these challenges and to reduce the scan time to the order of 10 minutes or less, which would further improve the clinical utility of this technique. Also, the scan time saved may be used to incorporate other MRI techniques into the prostate MR exam such as T2-mapping, diffusion tensor imaging (DTI), and dynamic contrast-enhanced (DCE) imaging.

Approaches such as echo-planar spectroscopic imaging (EPSI) and spiral spectroscopic imaging (SI) have been applied to provide higher-speed MRSI data acquisition (6,7). However, limitations such as timing error, eddy currents, susceptibility artifacts, low spectral bandwidth (SBW), and difficult data reconstruction reduce the applicability of these techniques in the clinical setting. The flyback k-space trajectory has been shown to provide robust data acquisition with reduced flow and off-resonance artifacts in cardiac imaging and insensitivities to timing errors and eddy currents in spectroscopic imaging (8,9). In this study, we utilized Malcolm Levitt's composite-pulse decoupling sequence (MLEV)–point resolved spectroscopic imaging sequence (PRESS), which incorporates dual-band spectral spatial refocusing pulses for water and lipid suppression and a nonselective refocusing pulse train to allow acquisition of upright citrate resonance at echo time of 85 msec (3). Flyback echo-planar readout trajectories were incorporated into the prostate MLEV-PRESS and applied in nine prostate cancer patient 3T research exams to provide large array, high spatial and spectral resolution MRSI data in 8.5 minutes.

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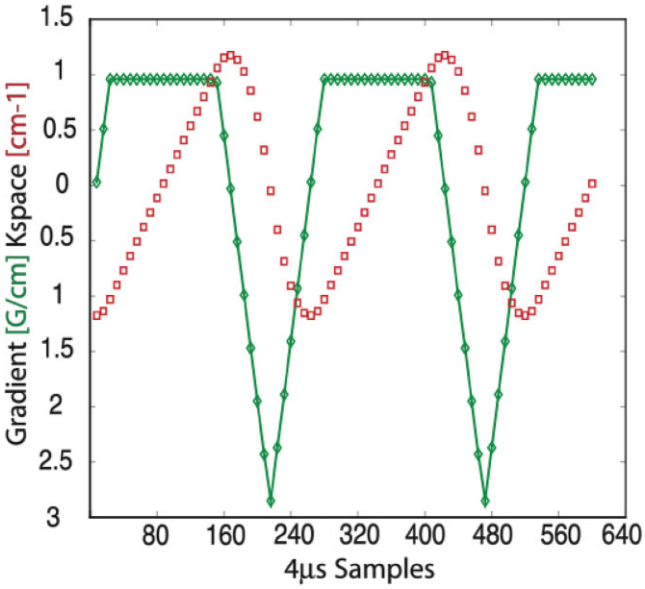

Figure 1. Flyback echo-planar readout trajectory designed for high-speed prostate MRSI with high spatial and spectral resolution. The trajectory is designed for SBW = 976 Hz, minimum spatial resolution = 4.9 mm, and SNR efficiency = 71%. With 16,384 samples and 31,250 Hz sampling rate per readout, 16 spatial encoding steps are achieved.

MATERIALS AND METHODS

Flyback Trajectories

Two flyback echo-planar trajectories were designed specifically for 3T prostate MRSI and implemented on a 3T GE MR scanner. They were developed to provide up to 16-fold acceleration in k-space sampling. The first trajectory was designed for 976 Hz SBW (time between k-space point traversals = 1.0246 msec) and 4.9 mm minimum spatial resolution (Fig. 1). A total of 512 readout/rewind lobes was included during each readout for a spectral resolution of 1.9 Hz. The gradient waveform used the maximum slew rate allowable by the system (150 mT/m/msec) at the designed spatial resolution. In this design, the readout lobe and the rewind lobe have the same duration. Since data is not acquired during the rewind lobe, this trajectory has a theoretical signal to noise efficiency of 71% (SNR efficiency = [time of readout lobe]/[time of readout lobe + time of rewind lobe]). With 16,384 data samples at a 31,250 Hz sampling rate, 16 k-space points are covered during each readout lobe.

The second trajectory is designed for interleaved acquisition with 506 Hz SBW (time between k-space points traversals = 1.976 msec) and 5-mm minimum spatial resolution (Fig. 2). A total of 432 readout/rewind lobes were included during each readout for a spectral resolution of 1.2 Hz. The gradient waveform used the maximum slew rate allowable by the system (150 mT/m/msec) at minimum spatial resolution. In this design, the theoretical SNR efficiency is 92%. A two-acquisition scheme is employed for this trajectory, with the second acquisition shifted temporally by 1/(2× SBW). Thus, when the two acquisitions are combined, the reconstructed data would have twice the SBW (1012 Hz). With 8208 data samples at 9615 Hz sampling rate, 16 k-space points are covered during each readout lobe.

MRI/MRSI Protocol

All studies were performed on a 3T GE Signa scanner (GE Healthcare Technologies, Waukesha, WI, USA) using the body coil for excitation and a 3T Medrad prototype inflatable endorectal coil (Medrad, Pittsburgh, PA, USA) filled with Flutech-T14™ (F2 Chemicals, UK) or a custom-designed rigid coil in conjunction with a pelvic phase-array coil for signal reception. Flutech-T14 is a fully fluorinated, colorless, odorless, nontoxic fluid with a magnetic susceptibility similar to tissue and thus is an ideal substitute for air to inflate the endorectal coil.

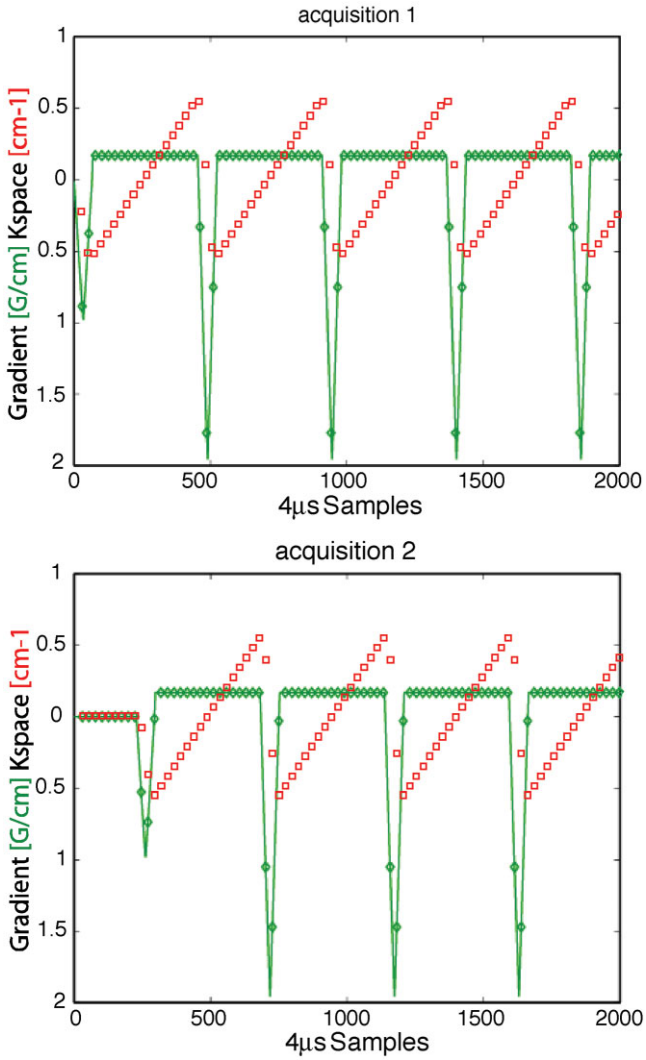

Figure 2. Flyback echo-planar gradient waveform designed for high speed MRSI acquisition with 5 mm minimum spatial resolution and high efficiency (92%). SBW of the waveform is 506 Hz. With a two-acquisition scheme that involves a temporal interleave that shifts the gradient by 1/(2× SBW) in the second acquisition as shown above, the two acquisitions can be combined to regain SBW = 1012 Hz. With 8208 samples and 9615 Hz sampling rate per readout, 16 spatial encodes are achieved during readout.

All MRI/MRSI exams included the following imaging sequences. Sagittal fast spin echo (FSE) localizer images were acquired to check coil placement and to prescribe the subsequent imaging series. Oblique axial T2-weighted FSE images (TR/TE = 6000 msec/102 msec, slice thickness = 3 mm, no interslice skip, field of view (FOV) = 12 cm, matrix size = 256 × 192, and no phase wrap) were obtained next. Oblique coronal T2-weighted FSE images (TR/TE = 6000 msec/102 msec, slice thickness = 3 mm, no interslice skip, FOV = 14 cm, matrix size = 256 × 192, and no phase wrap) were acquired following the oblique axial FSE images. Axial T1-weighted spin-echo (SE) images (TR/TE = 950 msec/9 msec, slice thickness = 5 mm, interslice skip =1 mm, FOV = 24 cm, and matrix size = 256 × 192) were also obtained.

A modified MLEV-PRESS incorporating the first trajectory was applied in four prostate cancer patient exams. MRSI data was acquired with a 16 × 1 × 8 phase encoding matrix using flyback echo planar readout in the Y-gradient direction (effective matrix = 16 ×16 × 8) and a FOV = 86.4 mm × 86.4 mm × 43.2 mm (nominal spatial resolution of 0.157 cm^3). TE = 85 msec and TR = 2 seconds. Data acquisition time was 8.5 minutes with number of excitations (NEX) = 2 (eight-fold acceleration). The MLEV-PRESS incorporating the second trajectory was applied in five prostate cancer patient exams. MRSI data was acquired with the same encoding matrix, FOV (thus the same spatial resolution), TE, and TR as above. Data acquisition time was also 8.5 minutes with the two acquisition scheme and a temporal interleave in the second acquisition. MRSI data was also acquired using the MLEV-PRESS with conventional phase-encoding in all three gradient directions in all exams. A 12 × 8 × 8 phase encoding matrix and a FOV = 64.8 mm × 64.8 mm × 43.2 mm (nominal spatial resolution of 0.157 cm^3) was used with the same TE as described above except for a shorter TR of 1.3 seconds. Total acquisition time was 17 minutes.

Data Analysis

All MRSI data were processed using custom processing software. The raw data acquired with the modified PRESS incorporating the flyback echo-planar readout trajectory were ordered as a 4D array with the first dimension being k-space values in the flyback direction, the second being time decay, the third being one phase-encoding direction, and the fourth being the other phase-encoding direction. The k-space points in the flyback dimension corresponding to the constant gradient portion of the trajectory were selected out and the data set was reordered so that the time decay was the first dimension. The reordered dataset was then processed in the same manner as the conventional 4D MRSI dataset with the exception that the k-space points in the flyback dimension were each acquired at a slightly different time point (10). This can be corrected during the standard 4D Fourier reconstruction using the fact that an origin shift in k-space is equivalent to a phase-shift in the transformed domain. The total reconstruction time on a standard UNIX workstation (Sun Microsystems, Inc., Santa Clara, CA, USA) was ~25 seconds for 3D MRSI data sets acquired with flyback echo-planar trajectory.

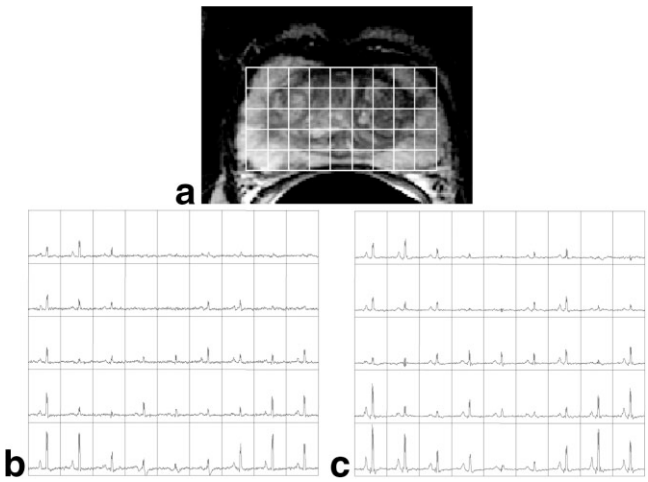

Figure 3. A 73-year-old prostate cancer patient with biopsy-confirmed cancer at unspecified location (G3+3). A T2-weighted axial FSE image of the prostate is shown (**a**) 3D-MRSI data were acquired with MLEV-PRESS with both flyback echo-planar readout trajectory (**b**) and conventional phase encode (**c**). The flyback trajectory shown in Fig. 1 was used with an effective matrix of 16 × 16 × 8 (with flyback encoding on the second axis), TR = two seconds, NEX = 2, and acquisition time = 8.5 minutes. A 12 × 8 × 8 matrix was used for the conventional phase encode method with TR = 1.3 seconds, and acquisition time = 17.5 minutes. High-quality, artifact free MRSI data were acquired with flyback echo-planar readout trajectory with identical spectral pattern as compared to data acquired with conventional phase-encoding.

The SNR was calculated using peak height of citrate resonance and noise from the right of the spectrum that does not contain any metabolites for each patients from voxels within the prostate. Apparent SNR efficiency was calculated for each study. It is given by: SNR efficiency = $(SNR_{flyback}/\ SNR_{phase\text{-}encode})$ * $(\text{acquisition time}_{phase\text{-}encode}/\text{acqusition time}_{flyback})^{1/2}$. The difference in TRs used in the flyback acquisition and the conventional phase encode acquisition was not included in the SNR comparison.

RESULTS

High-quality, artifact-free MRSI data were obtained from the prostate using modified MLEV-PRESS incorporating the flyback echo-planar readout trajectories as shown by the representative data in Figs. 3 and 4. Identical spectral patterns were observed for data acquired with the sequence that incorporated the flyback readout trajectory as compared to data acquired using conventional phase encoding (Fig. 3). The SNR lost due to data not being acquired during the rewind portion of the flyback trajectory and the shortened acquisition time did not affect the interpretability of the spectra. High levels of citrate and polyamines were observed in regions of normal prostate peripheral zone and reduced citrate and polyamine and elevated choline were found in regions of prostate cancer (Fig. 4).

Table 1a summarizes the SNR comparison between MRSI data acquired with the flyback echo planar read-

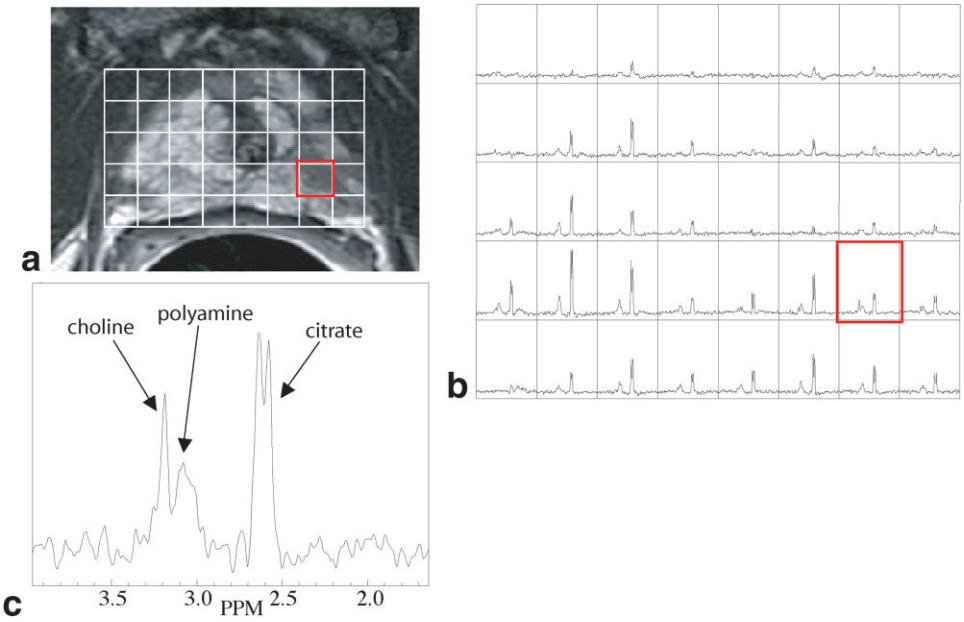

Figure 4. A 61-year-old prostate cancer patient with biopsy-confirmed cancer in the left gland (G2+3, 2 mm). 3D MRSI data were acquired with MLEV-PRESS with the flyback echo-planar trajectory shown in Fig. 2. A two-acquisition scheme with a time interleave in the second acquisition was used to obtain SBW = 1012 Hz to cover all metabolites of interest and residual water (not shown in spectra). Effective encoding matrix was 16 × 16 × 8 with flyback encoding on the second axis, TR = two seconds, and total acquisition time = 8.5 minutes. Axial T2-weighted FSE image is shown (**a**). Elevated choline and reduced citrate was observed in the voxel containing prostate cancer (**b**), while a high level of citrate was observed in the healthy regions of the prostate peripheral zone (**c**).

out trajectory shown in Fig. 1 and conventional phase encoding. The average SNR efficiency was 11% lower than that predicted in theory, based on the design of the trajectory (59% vs. 71%). Table 1b summarizes the SNR comparison between MRSI data acquired with the flyback echo-planar readout trajectory shown in Fig. 2 and conventional phase-encoding. The average SNR efficiency was 11% lower than the theoretical SNR efficiency for this trajectory (80% vs. 91%).

DISCUSSION

One of the major obstacles of incorporating MRSI in a clinical prostate MRI exam is the acquisition time required to acquire large-volume 3D spectral data sets using conventional phase-encoding in all three dimensions, especially at the high spatial resolutions offered by 3T. With a 12 × 8 × 8 phase encoding matrix and a repetition time of 1.3 seconds, the acquisition of a prostate 3D MRSI data set requires 17.5 minutes (5). At a nominal spatial resolution of 1.57 cm^3 (5.4-mm isotropic voxels), the FOV for this acquisition is only 64.8 mm × 43.2 mm × 43.2 mm. For larger prostates, either a larger voxel size or larger phase-encoding matrix needs to be used. Increased voxel size is not desirable since it would increase partial volume effects and decrease the sensitivity of this technique for detecting small cancers. Increased phase encoding matrix sizes

Table 1
SNR Comparison Between Flyback Echo-planar Readout and Conventional Phase Encoding

Patient	Phase encoding SNR	Flyback echo-planar SNR	Apparent SNR efficiency[a]
1a. First flyback trajectory (Fig. 1)			
1	17.07	5.52	0.56
2	33.55	10.63	0.55
3	22.29	8.54	0.66
4	9.79	3.50	0.62
1b. Second flyback trajectory with interleaved acquisition (Fig. 2)			
1	11.08	5.18	0.81
2	34.41	16.53	0.83
3	16.55	6.96	0.73
4	18.19	7.37	0.70
5	35.76	16.71	0.81

[a]Scan time differences were corrected for the phase encoding SNR and flyback echo-planar SNR before they were used to calculate apparent SNR efficiency.

may cause the scan time for the exam to be undesirably long. In addition, as shown by prior studies, the T1 relaxation time of prostatic choline is approximately 1 second at 3T (4,5). Repetition times of 0.65 to 1.3 seconds typically employed at 3T are not sufficiently long to avoid saturation of the choline signal and thus may reduce the ability of MRSI to detect increased choline levels in regions of cancer (4–5,11). Since the (choline + creatine)/citrate ratio has been shown to be a useful tool for characterization of prostate cancer (1,2), saturation of choline signal would decrease the sensitivity of this important parameter for prostate cancer. Therefore, faster k-space sampling is clearly needed to further improve the robustness and usefulness of 3T prostate MRSI without making compromises in spatial resolution, sensitivity, or patient tolerance.

Although the utilization of time-varying gradients during readout to encode spatial information for high-speed MRSI acquisition has been demonstrated previously, routine use of this technique has not been realized in clinical settings due to limitations such as timing error, eddy currents, low SBW, and difficult data reconstruction. One of the advantages of flyback echo-planar trajectory is the insensitivity to timing error and eddy current effects (8,9). With the improvement of the gradient hardware, high SBW flyback readouts are now achievable on clinical scanners. The simple reconstruction process also makes it suitable as a routine clinical tool.

High-quality prostate MRSI data was demonstrated in this study with the implementation of both readout trajectories. However, the SNR penalty observed was 10% more than theoretically expected but was consistent with previous publications using flyback echo-planar acquisition (9). Since the same 10% additional SNR penalty was observed for both interleaved and noninterleaved acquisitions, this indicates that two acquisition scheme with time interleave does not contribute additional SNR-loss and in fact offers much higher theoretical and observed SNR than the noninterleaved scheme. The small additional 10% loss is not fully understood but may be due to imperfect gradient coils and/or gradient instabilities near the maximum slew rates used.

Although the loss in sensitivity may seen large (17–41%), the utilization of the flyback echo-planar readout allowed the flexibility of acquiring clinically useable data in much shorter scan time (approximately one-half in this case). In particular, for the waveform designed for the two-acquisition scheme with time interleave, the loss in SNR was modest (17%), and this would be further improved with better gradient performance. Although different TRs were used for the acquisition utilizing flyback echo-planar readout trajectories and the conventional phase encoding method, this study was designed to investigate the feasibility of obtaining high-quality and clinically-useable data in approximately one-half the scan time compared to the current clinical acquisition. Further studies are required to elucidate the full effect of the flyback echo-planar trajectories when used for spectroscopic imaging acquisition.

In conclusion, high-efficiency flyback echo-planar readout trajectories were implemented in a new 3T MLEV-PRESS. High-quality, artifact-free, prostate 3D MRSI data with large spatial coverage acquired in 8.5 minutes were demonstrated. The robustness of this technique with respect to common fast-imaging artifacts and simple data reconstruction could greatly benefit the utilization of 3T MRSI in routine exams for prostate cancer and other pathologies.

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