Multi-shot Diffusion-Weighted PROPELLER MRI of the Abdomen

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Introduction:

Diffusion-weighted imaging (DWI) techniques use water mobility as an exogenous probe for non-invasive interrogation of microstructural tissue properties. Single-shot DW-EPI techniques are routinely used for neuroimaging applications due to relative insensitivity to bulk motion artifacts. However, these single-shot techniques can suffer significant image distortion, chemical shift artifacts, and reduced spatial resolution particularly when extending the imaging field-of-view (FOV) as necessary for abdominal imaging applications. These limitations have significantly complicated routine clinical DWI of the visceral organs. The recently introduced DW-PROPELLER strategy offers the potential to overcome these limitations [1,2]. The PROPELLER sequence uses a multi-shot acquisition strategy while permitting segmental phase correction to reduce bulk motion artifacts. In this study, we evaluated the feasibility of using the multi-shot DW-PROPELLER sequence for diffusion-weighted imaging of the abdomen. We tested the hypothesis that DW-PROPELLER provides accurate quantitative diffusion measurements while improving qualitative image sharpness, distortion, and artifact levels compared to single-shot DW-EPI.

Methods:

The PROPELLER technique uses a multi-shot turbo-spin echo (TSE) acquisition strategy with each segment of data acquired as a single rectilinear blade along a 'propeller-shaped' *k*-space trajectory. From each *k*-space blade, a low-resolution image is reconstructed permitting phase correction of motion artifacts. Following data correction, *k*-space blade segments are combined using *k*-space regridding for high resolution image reconstruction. Our implemented pulse sequence was based upon the BLADE pulse sequence (Siemens Medical Solutions implementation of PROPELLER TSE). Motion-probing gradients separated by a slice-selective 180° refocusing pulse provided the requisite diffusion-weighing. Phantom experiments were performed to test the accuracy of DW-PROPELLER quantitative diffusion measurements (three cylindrical vials consisting of distilled water, acetone and ethanol at room temperature). For abdominal imaging studies, DW-PROPELLER image series were compared to corresponding single-shot spin-echo EPI (SS-SE-EPI) diffusion-weighted image series.

All imaging experiments were performed using the Magnetom Sonata 1.5T clinical MR scanner (Siemens Medical Solutions, Erlangen, Germany) with high-performance gradient subsystem (40 mT/m maximum amplitude; 200 mT/m/ms maximum slew rate) and flexible six-channel phase-array abdominal imaging coil. Eight healthy volunteers were recruited for this study according to IRB protocol. Volunteer studies (N=8) were performed at a single axial slice position including both liver and pancreatic tissues with slice position chosen based upon T2-weighted TSE scout scans. Both DW-PROPELLER and SS-SE-EPI diffusion-weighted image series were acquired for each volunteer study with the following imaging parameters. DW-PROPELLER: TR/TE = 2000/105ms, 5mm slice-thickness, 400 Hz/pixel BW, 380x380 mm^2 FOV, 128x128 matrix (3.0x3.0x5.0 mm^3), ETL = 17, 44 segments, free-breathing with respiratory bellows triggering. SS-SE-EPI: TR/TE = 2000/82ms, 5mm slice thickness, 1.5 kHz/pixel BW, 380x260 mm^2 FOV, 70x128 matrix (3.7x3.0x5.0 mm^3), 6/8 partial Fourier, EPI factor = 70. Non-selective fat saturation and regional superior and inferior pre-saturation slabs were used for both sequences. At a fixed diffusion time, motion probing gradient amplitudes were varied to obtain diffusion weighting of b~0, 10,100 and 502 s/mm^2. For both sequences, separate image series were acquired with diffusion weighting applied along one of three orthogonal axis defined as (-0.5x, y, z), (x, -0.5y, z) and (x, y, -0.5z). Using DW images with b~10, 100 and 502 s/mm^2, apparent diffusion coefficient (ADC) maps were separately reconstructed for each direction of diffusion weighting and then averaged to obtain the isotropic diffusion coefficient D_{trace}. In each volunteer additional series of DW-PROPELLER images, 192x192 matrix (2.0x2.0x5.0 mm^3), were acquired to demonstrate the feasibility of improving spatial resolution.

Both qualitative and quantitative evaluations were performed to compare DW-SS-SE-EPI and DW-PROPELLER sequences. Isotropic diffusion-weighted images (b~0 and 502 s/mm^2) and reconstructed ADC images were randomized and qualitatively scored separately by a clinician blinded to the particular acquisition strategy. The ADC images were scored on a two-point scale: 1, organs appeared homogeneous; 2, organs partially or completely disappeared or appeared heterogeneous. Diffusion-weighted images were scored based on the artifacts level, image sharpness and image distortion with 1 as the best quality and 4 as the worst. For quantitative comparisons, mean ADC values of liver and pancreatic tissues in each volunteer were measured using corresponding ROI within DW-SS-SE-EPI and DW-PROPELLER ADC maps. A matched pair *t*-test was used (α=0.05) to test for statistical differences between both qualitative scores and quantitative measurements.

Results:

Representative diffusion-weighted images (b~0 and 502 s/mm^2) with reconstructed ADC maps acquired using DW-SS-SE-EPI and DW-PROPELLER sequences are shown in Fig. 1 along with an additional 192x192 matrix image series demonstrating the feasibility of improving spatial resolution with DW-PROPELLER. Overall, no image distortion or motion artifacts were observed in the DW-PROPELLER images which provided improved anatomic detail. DW-SS-SE-EPI images were commonly distorted and provided inferior spatial resolution.

Phantom Studies: Respective ADC values of water, acetone and ethanol as measured by the DW-PROPELLER sequence were $2.3x10^{-3}mm^2/s$, $4.9x10^{-3}$ mm^2/s and $1.3x10^{-3}mm^2/s$, consistent with those reported previously (2.25-$2.51x10^{-3}mm^2/s$, 4.5-$4.8\ x10^{-3}mm^2/s$ and 1.1-$1.2\ x10^{-3}mm^2/s$) [3-5].

Qualitative Comparison: Sharpness, distortion, and ADC organ homogeneity scores were significantly improved for DW-PROPELLER images in each category; artifact level scores were improved at b=0 s/mm^2 but not statistically different at b=502 s/mm^2.

Quantitative Comparison: The ADC map of each organ obtained using the DW-PROPELLER sequence was more homogeneous than the ADC map obtained using SS-SE-EPI. Mean D_{trace} of liver and pancreatic tissues measured using the DW-PROPELLER sequence were $(1.37\pm0.19)x10^{-3}$ mm^2/s and $(2.06\pm0.23)x10^{-3}mm^2/s$ respectively compared to $(1.17\pm0.14)x10^{-3}mm^2/s$ and $(1.82\pm0.23)x10^{-3}mm^2/s$ as measured using the DW-SS-SE-EPI sequence (mean±SD, no significant difference, $p>0.05$).

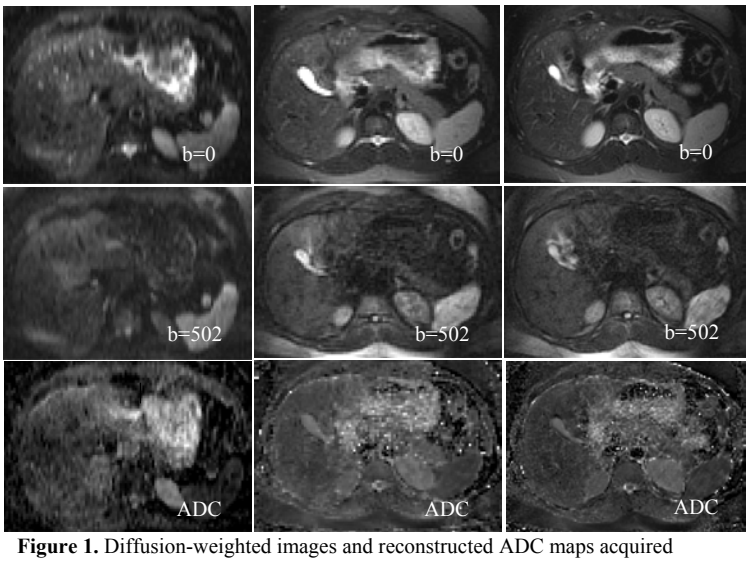

Figure 1. Diffusion-weighted images and reconstructed ADC maps acquired using DW-SS-SE-EPI (left), DW-PROPELLER (center) and increased spatial resolution DW-PROPELLER (right, 192x192 matrix).

Conclusions:

The DW-PROPELLER sequence is a promising technique for multi-shot diffusion-weighted imaging of abdominal organs. DW-PROPELLER improved image sharpness and reduced distortion while providing accurate isotropic water diffusion measurements. Future pre-clinical studies will evaluate the use of DW-PROPELLER techniques for abdominal oncologic imaging applications (lesion detection, characterization, and therapy assessment).

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