Spectrally Selective Phosphocreatine Imaging on a 9.4T Whole-Body Scanner Using a Spatial-Spectral RF Pulse

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Introduction: Phosphorus (^{31}P) NMR signals from biological tissues carry valuable metabolic information that can serve as sensitive disease markers [1]. *In vivo* ^{31}P MRI on human subjects has been challenging because of low sensitivity arising from the small gyromagnetic ratio and low metabolic concentrations (3~30 mM) [2]. The advent of 9.4T human MRI scanners opens a new opportunity of increased sensitivity. However, conventional spectroscopic imaging techniques, such as chemical shift imaging (CSI), are time-consuming, especially considering the long T1 relaxation times for most phosphorus metabolites. In many situations, only a specific metabolite such as phosphocreatine (PCr) is of interest [1] without the need of acquiring a full spectrum. This can be accomplished using spectrally selective imaging. This approach typically relies on spectrally selective pulses that do not provide spatial selection, which necessitates 3D imaging or is limited to 2D single-slice imaging, leading to long data acquisition times or insufficient spatial coverage, respectively. In this study, we report a spatial-spectral (SPSP) pulse [3, 4] that is tailored for selectively exciting the PCr resonance at 9.4T while suppressing all other major phosphorus metabolites including inorganic phosphate (Pi) and adenosine triphosphate (ATP). We demonstrate the performance of this pulse on phantoms and human volunteers for spectrally selective PCr imaging on a 9.4T whole-body scanner.

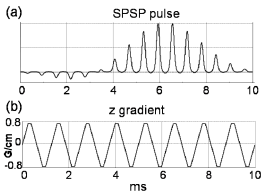

Fig. 1: The SPSP pulse optimized with VERSE. (a): RF waveforms (b): gradient wave-forms.

Methods: Our design strategy was to place the PCr (0 Hz) peak at the main pass-band of the frequency response of the SPSP pulse (Fig. 1) to achieve selective excitation of PCr, while positioning Pi (813Hz at 9.4T) and γ-,α-,β-ATPs (-402Hz, -1218Hz, and -2634Hz at 9.4T, respectively) at true nulls or opposed nulls to achieve signal suppression (Fig. 2). The sub-pulses for spatial selection were designed using a Shinnar-Le Roux (SLR) algorithm with the following parameters: pulse width=0.625ms, bandwidth=4kHz, and effective passband/stopband ripples (FIR filter)=0.01/0.01. A set of 16 identical sub-pulses was grouped together and placed under an envelope of a spectrally-selective minimum phase RF pulse which was designed using an SLR algorithm with pulse width=10ms and bandwidth=300Hz. In order to improve the spatial profile and reduce off-resonance effects, a VERSE technique [5, 6] was used to reshape the RF pulse (Fig. 1a) with an oscillatory z gradient by utilizing the gradient ramps (Fig 1b). After computer simulations to evaluate the performance of the pulse, the SPSP pulse was implemented in a RARE sequence tailored for ^{31}P imaging.

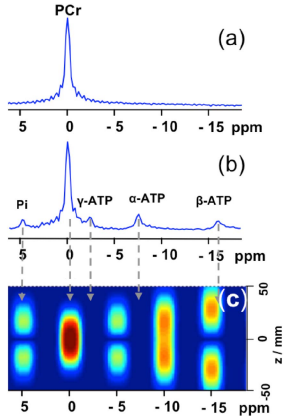

Fig. 2: The ^{31}P spectra of the human calf acquired using the SPSP pulse (a) and the SINC pulse (b). (c) Computer simulation results showing the spatiospectral response of the SPSP pulse.

Both phantom and *in vivo* experiments were conducted using a 9.4T whole-body scanner with an 80cm bore-size and a custom-made ^{31}P RF volume coil (inner diameter=24cm). The spatiospectral response of the SPSP pulse was experimentally obtained from a cylindrical phantom containing ^{31}P Na_2HPO_4 (50 mM) using the method in [4] with 16 averages. For the *in vivo* experiments, healthy human volunteers with informed consent were scanned by positioning the calf in the RF coil with the gastrocnemius at the center. ^{31}P spectra were acquired using an FID sequence with a frequency-non-selective SINC pulse and the SPSP pulse (TR=10s, TE=3ms, spectral width=4000Hz, points=64, NEX=16), respectively, to demonstrate the spectral selectivity. Axial PCr images were subsequently produced by a RARE sequence using the SPSP pulse with the following parameters: TR/TE=10000/20.5ms, matrix=32x16, FOV=240x120mm, voxel=7.5x7.5x60mm^3, echo train length=8, NEX=32, and scan time=10min20sec. The images were reconstructed and displayed with a matrix size of 512x512 with Gaussian smoothing. A T1-weighted ^{1}H image was acquired from the same volunteer on a 3T scanner, as an anatomic reference.

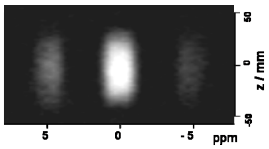

Fig. 3: The spatiospectral response of the SPSP pulse obtained experimentally.

Results: Both simulation (Fig. 2c) and experimental (Fig. 3) results confirmed that the SPSP pulse was able to produce a desirable slice thickness and a 300Hz spectral bandwidth for selective PCr imaging, as designed. The ^{31}P spectra from the calf of a human volunteer are shown in Figs. 2a (using the SPSP pulse) and 2b (using the spectrally non-selective SINC pulse). Comparison of the spectra from the two pulses demonstrated the excellent PCr selectivity with effective suppression of the other metabolites. The relationship between the unwanted metabolites and the true/opposed nulls in the frequency response (Fig. 2c) are indicated by the vertical dashed lines in Fig. 2. Figure 4 shows a representative PCr image (Fig. 4a) of the human calf where the location of the muscle and the bones (tibia and fibula) are clearly visible and spatially consistent with the ^{1}H image (Fig. 4b). The signal-to-noise ratio (SNR) of the PCr image in the muscle was approximately 14.

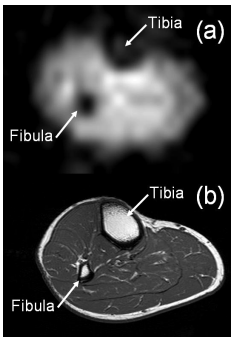

Fig. 4: A representative axial PCr image of the human calf acquired with the SPSP pulse (a), and a T1-weighted proton image as an anatomic reference (b) .

Discussion and Conclusions: Using a custom-designed SPSP pulse, we have demonstrated a method to perform spectrally selective multi-slice 2D imaging of phosphorus metabolites at 9.4T. At physiologic concentration of ~25 mM in the muscle, PCr images with an in-plane resolution of 7.5x7.5 mm^2 and an adequate SNR can be obtained in ~10 minutes. The SAR was well within the FDA guidelines. Although no direct comparison has been made, the proposed technique represents a significant reduction in imaging time as compared to 3D spectrally selective imaging or CSI methods. With further refinements in pulse sequences (e.g., shortening the TR time by employing driven equilibrium techniques), the acquisition efficiency can be further improved. The ability to form images based on a specific metabolite, which is enabled by ultra-high field at 9.4T, is expected to have applications to study the physiologic and metabolic processes in biological systems.

References:

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