# 2D and 3D Spectrally Selective $^{31}$P Imaging at 3 Tesla

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## INTRODUCTION

Phosphocreatine (or PCr) serves as a rapidly mobilizable reserve of high-energy phosphates in skeletal muscle and brain. It can anaerobically donate a phosphate group to ADP, leading to formation of ATP following muscular activity or neuronal activation [1, 2]. Characterization of PCr in biological tissues can thus provide valuable information on tissue physiology and metabolism, and may result in new disease markers. Changes in PCr have been typically observed using localized spectroscopy [1] or spectroscopic imaging (e.g., chemical shift imaging) [2]. The former offers limited spatial information, while the latter requires a long acquisition time. In this work, we have developed two spectrally selective phosphorus imaging techniques at 3T to form 3D or 2D images based solely on PCr signals. In both techniques, time-efficient frequency encoding is used to encode spatial information, instead of chemical shifts, leading to substantially reduced acquisition time as compared to spectroscopic imaging.

## METHODS

To perform 3D selective PCr imaging, a spectrally selective RF pulse was designed using a Shinnar-Le Roux (SLR) algorithm with minimum phase [3]. The parameters for the spectrally selective RF pulse were: time-bandwidth product = 2.1, pulse width = 14ms, and ripples in pass-band or stop-band = 2%. After confirming the frequency response through computer simulations, the RF pulse was implemented in a 3D gradient echo pulse sequence on a GE 3T Signa HDx scanner (General Electric Healthcare, Waukesha, WI) equipped with multi-nuclear imaging capability. To perform 2D selective PCr imaging in multi-slice mode, a 2D spatial-spectral (SPSP) RF pulse was designed to achieve spatial selection in one dimension and phosphorus spectral selection in the other dimension [4]. The pulse consisted of 24 sub-pulses, each designed and optimized using an SLR algorithm with a pulse width of 0.584 ms and a bandwidth of 3.4 kHz. All sub-pulses were placed under an envelope of a spectrally-selective RF pulse designed with the same parameters as in the 3D case. On the ramps of the accompanying slice-selection gradient, a VERSE technique was used to reduce the minimal TE. After extensive computer simulation to optimize the spatial and spectral responses, the SPSP pulse was implemented in a 2D gradient-echo pulse sequence on the 3T scanner. Given that the T1 relaxation time of PCr is exceedingly long (~6.7 sec), a "fast recovery" module consisting of a 180°-90° pulse pair was appended to the sequence to help restoring the longitudinal magnetization from the transverse plane. A pulse sequence diagram is shown in Fig. 1.

Experiments were conducted on a 6 cm spherical phantom containing phosphorus compounds ($Na_2HPO_4$, 100 mM), a fresh pork specimen (7x10x15 $cm^3$ in size) and the lower extremity of a human volunteer. All imaging studies were performed using a 7 inch surface coil tuned to 51.7MHz. For the 3D experiments, the key scan parameters were: TR/TE = 2500/17 ms, voxel size = 1.5$cm^3$, bandwidth = ±2.3 kHz, and NEX = 4, For the 2D multi-slice experiments with the SPSP pulse, similar scan parameters were used with a slice thickness of 40 mm. Both 3D and 2D images were reconstructed from 32x32 k-space matrices using a Fourier transform method after zero padding to a matrix size of 256x256.

## RESULTS

Figure 2 displays a set of representative PCr images from the phantom (a and b for 3D and 2D, respectively), the pork specimen (c), and a human leg (d). In Figs. 2c and 2d, the color PCr images with Gaussian smoothing are superimposed onto the corresponding proton images for better visualization. The non-overlapping regions in the top of each image were the locations where the sensitivity of the surface coil was diminishing (or the fatty tissue with negligible PCr concentration in Fig. 2c). The SNR for these images was measured to be 12, 8, 4, and 4, respectively. The scan times were between 5.4 and 10.8 minutes. Images and spectra without the spectrally selective pulses were also acquired, which demonstrated the PCr spectral selectivity (data not shown).

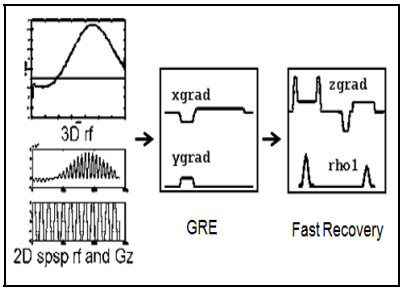


**Fig. 1** The pulse sequences used for PCr selective imaging at 3T.

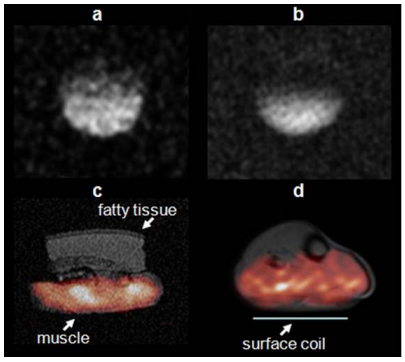


**Fig. 2** A set of PCr images acquired using the proposed techniques. (a) 3D phantom image, (b) 2D phantom image, (c) 2D image of the pork specimen, and (d) *in vivo* human image of the leg.

## DISCUSSION AND CONCLUSIONS

Our results have demonstrated that selective PCr imaging is possible at 3T. Even with a very low physiologic concentration (~20 mM for muscle), low-resolution PCr images can be obtained both *in vitro* and *in vivo*. Although similar information can also be obtained using spectroscopic imaging techniques, the proposed spectrally selective imaging method offers significantly shorter scan times. The scan time relies heavily on the number of signal averages to increase the SNR and the choice of TR to avoid signal saturation. The inclusion of the "fast recovery" module allows a shorter TR time to be used with minimal influence on signal saturation. Even with these techniques, the SNR remains low largely due to the low physiologic concentration. Considering the long T2 relaxation time, RARE sequence can be used in the future to improve the data acquisition efficiency so that the time saved can be used for more signal averages. In addition, ultra-high magnetic field (such as 7T or 9.4T) can further boost the SNR. In conclusion, we have shown that spectrally selective phosphorus imaging is a promising technique at 3T. With further improvements in data acquisition efficiency and SNR, the proposed technique will likely find applications in studying tissue metabolic changes in healthy human subjects and patients.

**REFERENCES** [1] Bottomley PA, et al, Magn Reson Med 1984, 1:113-114. [2] Arias-Mendoza F, Brown TR. Dis Markers 2003,19(2-3):49-68. [3] Pauly JM, et al., IEEE Trans Med Imaging 1999,10:53-66, [4] Meyer CH, et al, Magn Reson Med 1990, 15:287-304.

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