A surface crusher coil for human cardiac phosphorus (^{31}P) MR spectroscopic imaging study at 7 tesla

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Introduction: ^{31}P-MRS provides direct insights into myocardial energy supply (ATP, ADP, phosphocreatine (PCr) and inorganic phosphate)[1]. An initial study demonstrated that 7T cardiac ^{31}P-MRS has 2.8x greater SNR and higher quantification precision than at 3T[2]. Additional RF pulses for outer volume suppression are often inserted into main MR spectroscopy pulse sequence to suppress potential contaminating signals (e.g. overlying skeletal muscle may contaminate myocardial ^{31}P-MR spectra). However, the translation of these approaches to suppressing contamination at 7T is particularly challenged by increased RF heating of tissue at 7T. This incurs extended repetition times (TR) for MRS(I) at 7T and in some sequences prevent to achieve complete saturation with the remaining SAR. Chen and Ackerman[3] introduced the surface spoiling coil in 1990: a concept that was recently further developed[4] for lipid suppression in human brain ^{1}H-CSI. In this work, we introduce the first crusher coil for cardiac ^{31}P-MRS at 7T. This allows us to saturate more efficiently skeletal muscle signal whilst removing the RF heating associated with RF saturation bands.

Methods: Data were acquired with a Siemens 7T scanner. Localization used a 10cm ^{1}H Tx/Rx RF coil (Rapid Biomedical) to acquire CINE FLASH images. ^{31}P-MR spectra were acquired with a custom 10cm ^{31}P Tx/Rx loop. The magnetic field generated by the crusher coil was simulated using Matlab (Mathworks) and crusher coil design was optimized. A capacitor continuously charged by a power supply unit was used to drive the current pulse in the crusher coil (100µs duration). Spoiling was timed to coincide with the existing phase encoding gradients. A 2D-CSI experiment (TR=1s, TE= 2.3 ms, slice thickness=20 mm, matrix size = 180×180mm^2, res = 12×12) was performed on a two-compartment phantom with the ^{31}P-RF coil and the crusher coil placed above it. *In vivo* 3D-CSI was then performed with the crusher coil (TR=1s, TE=2.3ms, matrix size = 240×240×200mm^3, resolution = 16×16×8, 10 averages, acquisition weighted, TA = 28 min). The mean PCr skeletal muscle was calculated over voxels placed above the interventricular septum (n = 5). The residual signal obtained with crusher coil was compared with BISTRO saturation[5] in phantom and *in vivo*. The spectral analysis was performed using a custom Matlab fitting program that includes the AMARES fitting[6]. The SAR level was reduced from 96±1% to 16±1% when using the crusher coil (without BSITRO pulses).

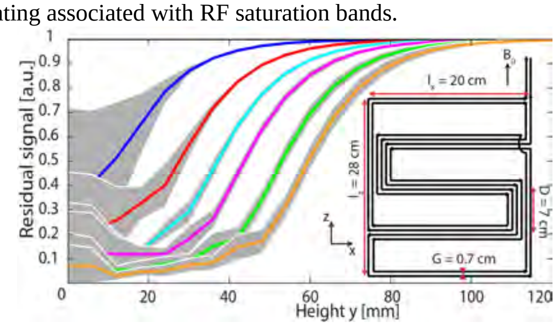

Figure 1: *(A) Simulated residual signal in function of the height above the crusher coil. The residual signal was calculated for different* $I_{spoil}\times T_{spoil}$ *: 0.75 (blue), 1.5 (red), 2.25 (cyan), 3 (purple), 4.5 (green) and 6 A·ms (orange).*

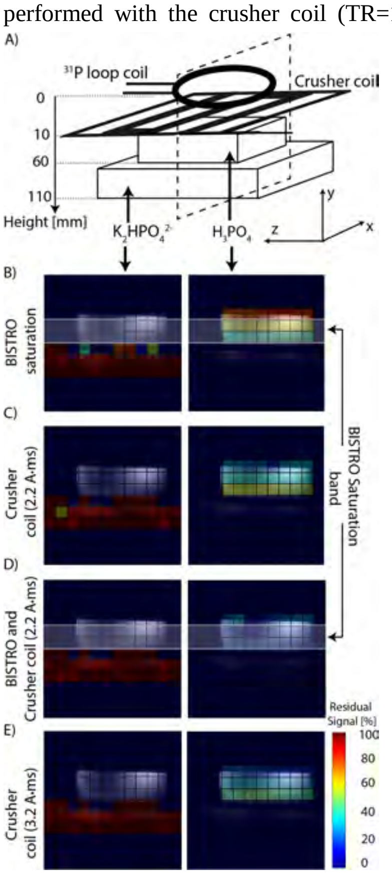

Figure 2: *2D CSI over a transverse slice with 5 saturation protocols: (i) BISTRO saturation bands (thickness = 30mm), (ii) crusher spoiling, (iii) BISTRO and crusher spoiling and (iv) crusher spoiling.*

Results: The coil geometry was optimized to saturate skeletal muscle signal (<40mm) with minimal disruption of cardiac signals (>70mm) (Fig. 1). Currents up to 35 A were driven through the crusher coil. SNR was measured *in vitro* (meas. area = 105×90×25mm^3) and decreased by 13±5% when the crusher coil was inserted. In the 2D-CSI *in vitro* experiment (Fig. 2), the bottom slice signal remained stable, while the top slice signal was spoiled differently depending on the acquisition protocol. The SAR-limited BISTRO saturation reduced the mean signal in the entire top slice to 50±10% of the original signal. A similar signal reduction (47±10%) occurred when using the crusher coil at $I_{spoil}\times T_{spoil}$ = 2.2 A·ms. When combining the BISTRO saturation and the crusher coil ($I_{spoil}\times T_{spoil}$ = 2.2 A·ms.), the mean signal was reduced to 15±5%. $I_{spoil}\times T_{spoil}$ was increased to 3.2 A·ms yielding to a 34±8% signal reduction. In 3D-CSI *in vivo* study, mean residual skeletal muscle PCr signal was reduced to 51±12% with BISTRO and to 35±12% with the crusher coil (Fig. 3). The crusher coil may also be used in addition to the BISTRO saturation yielding a mean residual skeletal muscle PCr signal of 29±5%. The PCr/ATP ratio in the septum (representative voxel 7 in Fig. 3) was 2.1±0.4 (BISTRO) and 1.9±0.3 (crusher) with a CRLB of ±20% and ±24%, respectively.

Discussion and Conclusion: A crusher coil is an efficient alternative to BISTRO saturation for suppressing skeletal muscle during cardiac ^{31}P-MRS at 7T without sacrificing MR signal quality in the myocardium. The flexibility offered by using the crusher coil allows us to employ sequence modules that would otherwise be SAR-prohibitive e.g. adiabatic excitation for absolute quantitation, ^{1}H-^{31}P NOE enhancement or saturation-transfer pulses for future clinical studies at 7T, without compromising the skeletal muscle suppression.

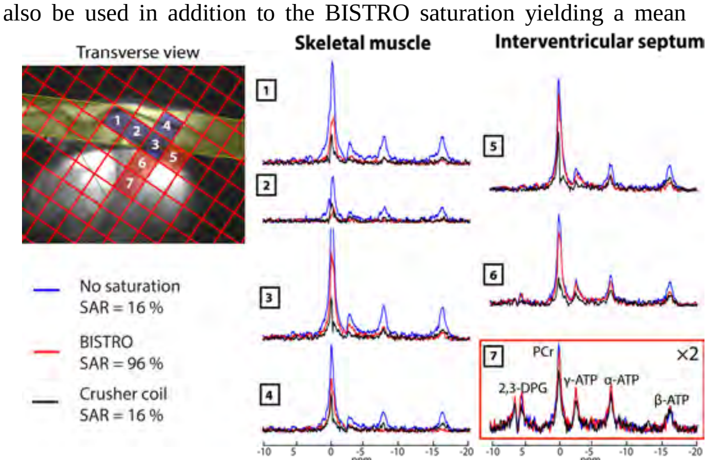

Figure 3: *^{31}P-MR spectra acquired in the skeletal muscle and in the interventricular septum with different saturation protocols: no saturation (blue spectra), BISTRO saturation band (red spectra) and crusher coil (black spectra,* $I_{spoil}\times T_{spoil}$*=0.9 A·ms). Inset: Overlap of CSI grid on CINE FLASH images showing voxel whose spectra are plotted. Yellow strip corresponds to BISTRO saturation band. Voxel 7 was used for AMARES fitting.*

References and Acknowledgements: [1] Bottomley PA, MRM, 1985 [2] Rodgers, CP, MRM, 2013 [3] Chen and Ackermann, NMR in BioMed, 1990 [4] Boer, MRM 2014 [5] Luo, MRM 2001 [6] Vanhamme JMR 1997.

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