Optimal reconstruction using receive arrays for hyperpolarized ^{13}C cardiac imaging at 3T

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Target audience: hyperpolarized media and image reconstruction.

Purpose: Hyperpolarized ^{13}C substrates have become a promising tool to study real-time metabolic processes *in vivo*, particularly in the heart. This was first shown using hyperpolarized ^{13}C pyruvate to characterize cardiac metabolism noninvasively in the pig using a single slice chemical shift imaging (CSI) technique[1]. Recently, rapid multislice imaging of hyperpolarized ^{13}C pyruvate and bicarbonate was demonstrated by Lau et al.[2], using a single shot spiral pulse sequence and with up to 5-channel receiver coils[3]. Even though the SNR and coverage were increased by using multi-channel reception, the final images were biased by the coil sensitivity when a simple sum-of-squares channel combination was used. A better approach is to use the coil sensitivity coefficients as shown by Roemer et.al.[4] Measurement of the coil sensitivity with hyperpolarized ^{13}C in-vivo would require the partial use of the limited polarization available for the measurement, which is undesirable. Also in cardiac applications the ^{13}C signal varies in time throughout the chambers of the heart (Fig. 2 columns 1-3) making it more difficult to estimate the coil sensitivity maps. The objective of this work was to use fiducial markers to numerically estimate the coil sensitivity maps for a 4-channel receiver array for hyperpolarized ^{13}C imaging, and to use these derived maps to improve the reconstruction. Pyruvate images of a pig heart were obtained *in vivo* and reconstructed using Roemer-optimal coil combination and simple sum-of-squares for comparison.

Methods: A commercially available 1.5T ^{1}H four-channel cardiac array (GE Healthcare, Waukesha, WI) was tuned to ^{13}C at 3T (i.e. 32.14 MHz) and used as a receive array. A ^{13}C birdcage transmit coil (Rapid Biomedical GmbH) was used for all ^{13}C experiments. All coils were connected to the scanner through an RF interface-box with 8 pre-amplified receiver channels (Clinical MR Solutions, WI, USA). Three dimensional sensitivity maps of all four receiver coils were computed in Matlab (The MathWorks Inc., Massachusetts, USA), by applying Biot-Savart law. Fiducial markers were placed in each side of the coils to estimate coil position in image space and used in the simulations (Fig 1). Sensitivity maps were validated by imaging a spherical homogenous phantom.

All imaging experiments were performed on a GE MR750 3T MR scanner (GE Healthcare, Waukesha, WI). *In vivo* images were obtained in a specific pathogen free pig (25 kg) under a protocol approved by the institutional animal care and use committee. The injection was 15 mL of 160 mM pre-polarized [1-^{13}C] pyruvate as described by Lau et al.[2] For anatomical reference, cardiac-gated breath-held SSFP CINE images were acquired in sagittal view (TR = 4.2 ms, TE = 1.8 ms, FOV 24 cm, slice thickness 5 mm, spacing 5 mm, matrix size 224×224) using the body coil. *In vivo* hyperpolarized ^{13}C images of the heart were acquired using the single-shot dual-gated spiral pulse sequence (35 time-resolved images with TR=2.5, FOV=36 cm, 10 mm in-plane resolution, 1 cm slice thickness, 8192 samples over 32 ms with 250 kHz sampling[2]).

To minimize the signal variation through the heart due to blood flow (Fig. 2 columns 1-3) all time points were added together for each coil (Fig. 2 Sum T-f column). Then the sum-of-squares and Roemer-optimal combining were used for reconstruction (Fig. 2 SoS-4ch and ROC-4ch).

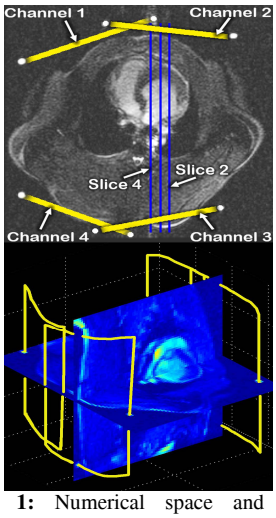

Fig. 1: Numerical space and coil position. **Top**: Axial slice showing the fiducial markers (white dots), coil position (Yellow line) and sagittal slice position (blue lines). **Bottom:** 3d position of all coils for maps calculation.

Results and Discussion: Figure 1 shows the receiver coils position defined by the white circles (fiducial markers) and yellow lines (only for visualization proposes) in the image. Fig. 1 shows the central axial slice and sagittal slice position (blue lines). Fig. 1 Bottom shows the 3d distribution of the channels in the 3D image space used for the calculation of the sensitivity coefficients. Maps of the calculated coefficients agreed with the phantom images acquired.

Figure 2 shows the images of *in-vivo* hyperpolarized ^{13}C pyruvate in the pig heart. To facilitate the comparison all images where divided by the standard deviation of the noise in the background to show SNR maps. All SNR maps were overlaid to the corresponding anatomical images (Slices 2, 3 and 4, Fig. 2 top to bottom). Columns 1 to 3 (from left to right) correspond to time-frames 3, 6 and 8 acquired from channel 1, showing the variability of the signal over time due to the blood flow through the heart. For this reason it's almost impossible to estimate the sensitivity of the coils with time-resolve images of the heart. To partially mitigate this effect the first 15 time-resolved pyruvate images were added together for each coil separately, obtaining a more homogenous image (Fig. 2 column 4 is the sum of all time frames acquired by channel 1 only). Finally column 5 shows the sum-of-squares of all 4 channels and column 6 the Roemer-optimal combining using the sensitivity coefficients calculated numerically. As expected with the sum-of-squares the SNR was higher in the areas close to the chest wall (i.e. where is closer to the coils 1 and 2) due to the coil bias present with this method. When using the coil sensitivity maps in the Roemer-optimal combining method a 100% increase in SNR was measured in distal areas of the heart and up to a 10% increase in some areas closer to the chest wall.

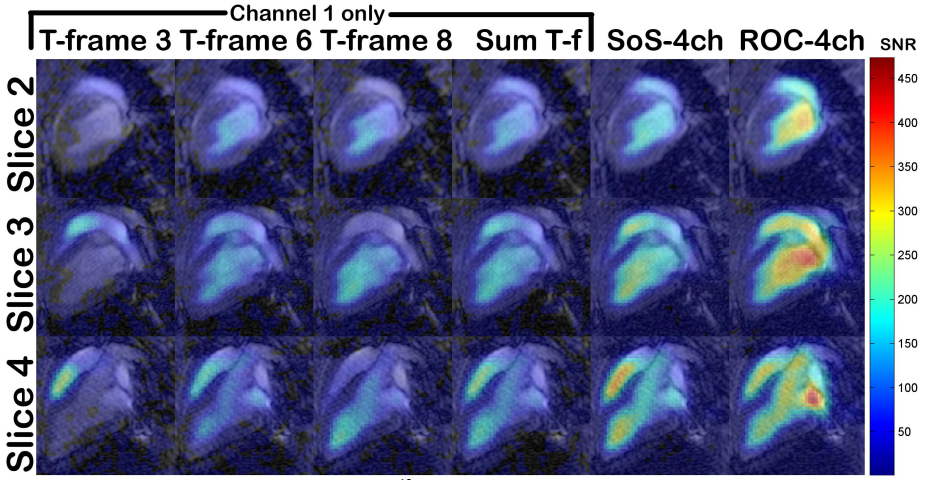

Fig. 2: SNR maps of *in-vivo* hyperpolarized ^{13}C pyruvate of the pig heart. All SNR maps were overlaid onto the corresponding anatomical images (Slices 2, 3 and 4 from top to bottom). Columns 1 to 3 (from left to right) correspond to time frames 3, 6 and 8 acquired by channel 1. Column 4 is the sum of all time frames acquired by channel 1. Column 5 shows the sum-of-squares of all 4 channels and column 6 the Roemer-optimal combining using the sensitivity coefficients. SNR improvement and signal homogeneity are noticeable in the Roemer-optimal reconstruction.

Conclusions: Coil sensitivity coefficients were numerically calculated in Matlab and used for Romer-optimal reconstruction with *in vivo* measurements. SNR improvements of up to a 100 % in areas closer to the base of the heart were demonstrated by using the Roemer reconstruction, as compared with sum-of-squares. This coil array and image reconstruction scheme may be suitable for human cardiac ^{13}C studies in the near future.

References:

1- Golman et al. Cardiac metabolism measured noninvasively by hyperpolarized 13C MRI. MRM (59) 2008. **2-** Lau et al. Rapid multislice imaging of hyperpolarized 13C pyruvate and bicarbonate in the heart. MRM (64) 2010. **3-** Dominguez-Viqueira et al. A five channel receive array for cardiac imaging using Hyperpolarized 13C at 3T. ISMRM (4496) 2013. 4- Roemer, P.B., et al., The NMR phased array. MRM, 1990. 16(2): p. 192- 225.