Report on COST supported Short Term Scientific Mission entitled

Development of multi-dimensional excitation pulses for in vivo hyperpolarized $^{13}$C imaging using surface coils

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Introduction:

Hyperpolarization partially overcomes the intrinsic limitation of NMR, namely its poor sensitivity, allowing new applications in molecular and metabolic imaging$^{1,2}$. For an optimal use of the large out-of-equilibrium magnetization which is available following dissolution DNP, tailor-designed pulse sequences are required. The specific constraints of hyperpolarized NMR are related to the single-shot nature of the experiments due to the unavoidable decay of the enhanced polarization. For in vivo imaging experiments, the challenge is to acquire spatial, spectral and temporal information in a time window on the order of one minute.

Various acquisition strategies have been developed to rapidly image the spatial distribution of multiple compounds in order to track the metabolism of hyperpolarized substrates in vivo, including echo planar spectroscopic imaging (EPSI)$^3$, spiral CSI$^4$ or compressed sensing MRSI$^5$. Some of the techniques use the inherent frequency selectivity of MRI sequences by adopting multi-echo approaches$^6$ or SSFP based techniques$^7$. Other approaches use RF pulses properties to design interleaved acquisition of different substrates by frequency-specific excitation$^8$ or even multi-band excitation schemes$^9$.

Hybrid spatiotemporal encoding (SPEN) sequence is a new alternative for ultrafast acquisition that in recent studies was demonstrated as able to provide higher immunity to $B_0$ inhomogeneity compared to EPI$^{10}$. In addition, SPEN sequence allows spectral imaging with no extra cost$^{11}$. These features can be exploited especially in hyperpolarized dynamic imaging, which requires fast acquisition and usually includes few spectral peaks. In the context of in vivo studies where surface coils are used for both transmission and reception SPEN sequences can offer a new alternative to compensate for the $B_1$ inhomogeneity.

A typical SPEN sequence employs a linearly-swept “chirped” RF pulse in the presence of a magnetic field gradient. The “chirped” pulse has a frequency which varies linearly with time. At each instant the pulse has a well-defined instantaneous frequency $\omega_c(t)$ which affects spins with a precession frequency close to that resonant frequency. When applying a magnetic field gradient along a direction $r$, a frequency axis $\omega(r)=\Omega_0+\gamma Gr$ is generated (where $\Omega_0$ is the chemical shift frequency, $\gamma$ is the gyromagnetic ratio and $G$ is the gradient applied along $r$). Hence when a chirped-pulse is applied together with a magnetic field gradient the same chemical sites are no longer homogeneously triggered but rather in a spatially heterogeneous manner, so that their resonance frequency $\omega(r)$ matches the pulse frequency $\omega_c(t)^{10}$. When a surface coil is used for the excitation, also the amplitude of the pulse becomes position dependent. SPEN schemes can be exploited to correct for this $B_1$ inhomogeneity. Instead of using uniform pulse amplitude, the $B_1(t)$ profile of the pulse can be modified according to the $B_1$ field generated by the coil. An additional $B_1$ correction can be applied during data processing by integrating the coil receiver profile into the Super Resolution reconstruction$^{12}$.

The aim of the present study was to explore the correction of $B_1$ inhomogeneity using SPEN sequences in an experimental setup that includes a surface coil for both excitation and detection.
Methods:

Measurements were carried out on a cylindrical phantom (15.9/14.4 mm outer/inner diameter) containing H$_2$O. Data was acquired in a 7 T Varian VNMRS vertical imaging system (Varian Associates, Inc., Palo Alto, CA) at the Weizmann Institute, Rehovot, Israel, using a custom-designed single loop 10-mm-diameter quadrature $^1$H surface coil$^{13}$ built at the EPFL, Lausanne, Switzerland. Coil and phantom were embedded in a dedicated holder (see Figure 1).

Figure 1: Experimental setup used for the experiment including quadrature surface coil, holder and the phantom.

Results:

To map the B$_1$ field created by the coil, we used the double flip angle method$^{14}$. Two gradient echo multi-slices images were acquired once with 10° (Fig. 2a) and 20° (Fig. 2b) flip angles and TR = 3 s. The spatial distribution of flip angle was calculated from the ratio of the two images (Fig2c) and fitted (Fig 2d). As a first approximation we correct only for the direction of the chirp pulse: by summing the map along the direction orthogonal to the SPEN direction we reduced the two dimensional B$_1$ distribution to a single one (Fig2e).

Scan parameters: FOV=4x4 cm$^2$, resolution 0.62x1.25 mm$^2$, slice thickness 2mm, TE=1.3 ms, TR=3 s, N$_{averages}=10$.
We have mainly examined $B_1$ correction using a spin-echo 2D hybrid SPEN/k-space imaging sequence in which the first 90°-pulse spatiotemporally encodes the spin evolution along the so-called phase encode direction and the 180°-pulse is used for slice selection. See Figure 3.

Figure 3: Sequences scheme of Hybrid SPEN using 90° chirp pulse

Figure 4 demonstrates how the $B_1$ inhomogeneity compensation is integrated into the amplitude profile of the chirped pulse. The commonly used ‘wurst’ envelope (Fig. 4a) is replaced by an amplitude profile calculated from the measured $B_1$ map (Fig. 4b).

Figure 4: amplitude profile of the chirped pulse without (a) and with (b) B1 correction. Noticed the in this case the chirped sweep direction is from the bottom to top of the image presented in figure 2.

A comparison between the images obtained using the Hybrid SPEN with 90° chirp pulse with and without integrating the $B_1$ correction is presented in figure 5. It can be seen from the 1D projection that the $B_1$ corrected SPEN shows improved image profile.

Figure 5: $B_1$ correction included in the excitation chirp pulse and SR reconstruction. a) Hybrid SPEN with 90° chirp pulse without correction (left) and with correction (middle) and 1D profile comparison (right). Scan parameters: FOV=4x4 cm, acquired points 70x70, resolution 0.57x0.57 mm, slice thickness 5 mm, $T_{90}=30.8$ ms, $G_90=0.5G/cm$, TE=5.67 ms.
The performance of the surface coil as both transmitter and receiver for executing rapid imaging techniques was examined. Figure 6 shows the EPI image acquired on the system (Fig. 6a) as well as hybrid SPEN without and with $B_1$ compensation (Fig 6b and 6c).

**Figure 6**: Images comparison: a) EPI acquisition b) Hybrid SPEN with 90° chirp pulse without correction, c) Hybrid SPEN with 90° chirp pulse with $B_1$ correction. Common scan parameters: FOV=4x4 cm$^2$, number of acquired points 70x70, resolution 0.57x0.57 mm$^2$, slice thickness 5 mm, $T_{acq}$=30.8 ms. EPI parameters: $T_E$=52 ms, Hybrid SPEN with 90° chirp pulse parameters: $T_{90}$=30.8 ms, $G_{90}$=0.5 G/cm, $T_E$=5.67 ms, Hybrid SPEN with 180° chirp pulse parameters: $T_{180}$=15.4 ms, $G_{180}$=0.25 G/cm, $T_E$=34.65 ms.

**Summary:**

Our initial results demonstrate the potential to improve image profile by incorporating $B_1$ correction in the chirp pulse when using SPEN acquisition scheme. Signals that were reduced due to the non-uniform performance of the surface coil can be significantly restored (Fig. 5). Additionally, even when no $B_1$ compensation was applied, SPEN sequence shows better immunity to the $B_1$ inhomogeneity as compared to EPI sequence (Fig. 6). Yet, optimization of this type of correction should still be examined, especially regarding improvement in the $B_1$ mapping.

**Future work:**

**Synergies within the whole collaborative project:**

*Frydman Lab - Weizmann institute of Science (WIS) - R. Schmidt*

Design and Program of the SEPN sequences and integrate the correction in the super-resolution processing protocol.

*CIBM Lausanne - École Polytechnique Fédérale de Lausanne (EPFL) - M. Mishkovsky*

Implement the optimized sequence on the small animal 9.4T scanner at EPFL (same scanner software (same scanner software version than WIS) and perform

*CIBM Geneva - Hôpitaux Universitaires de Genève (HUG) – J.-N. Hyacinthe*

Implement the optimized sequence on the clinical 3T scanner at HUG (same platform than WIS) for translational molecular imaging using hyperpolarized $^{129}$Xe biosensors.

The current preliminary results together with further elaboration could be summarized in a scientific publication with the tentative title “$B_1$ compensation by spatiotemporal (SPEN) encoding schemes”
References:


