On SNR performance of sequence designs for dynamic imaging of hyperpolarized ^{13}C compounds

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Introduction: Hyperpolarized metabolically active substances provide a promising approach to investigating in vivo metabolism in real time[1,2]. However, due to the transient life time of hyperpolarization and fast metabolic conversion of injected substances such as ^{13}C labeled pyruvate, suitable fast dynamic spectroscopic imaging sequences are required. Several methods have been proposed for efficient spatiotemporal encoding for dynamic imaging of hyperpolarized compounds[3-7]. The current work presents a theoretical framework to compare three frequently used pulse sequence designs for ^{13}C labeled pyruvate in terms of signal to noise ratio (SNR) performance. A compartment based signal model is assumed and effects of multiband excitation and data acceleration techniques are discussed.

Methods: Considering a given voxel size, concentration and nucleus, the SNR dependency of a single frame n_d of a dynamic scan can be written as:

$$SNR(n_d) \propto \frac{\sum_{n=0}^{N_{enc}-1}\left(e^{-\frac{n\cdot TR}{T_1}}\sin(\alpha)\cos^n(\alpha)\cdot e^{-\frac{n\cdot\Delta TE_{MultiEcho}}{T_2^*}}\right)}{\sqrt{N_{enc}}}\cdot\frac{\sum_{n_p=0}^{N_p-1}e^{-\frac{TE_{ge}+n_p\frac{1}{BW}}{T_2^*}}\cdot e^{-\frac{TE_{st}}{T_2}}}{\sqrt{BW\,N_p}}\cdot M_z(n_d) \qquad (1)$$

Encoding steps | Readout

where T_1, T_2 and T_2* are the relaxation time constants, α flip angle, N_{enc} number of signal encoding steps per time frame n, N_p number of points acquired during readout, TR repetition time, $\Delta TE_{MultiEcho}$ echo time shift (multi-echo), TE_{ge} echo time (gradient echo), TE_{st} echo time (spin echo) and BW bandwidth. A two compartment model is assumed for the magnetization $M_z(n_d)$. Restricting to the forward reaction from pyruvate P(t) to bicarbonate B(t) two differential equations result: $\frac{dP}{dt} = -\left[k_{PB} + \frac{1}{T_1} + \left(1-\cos(\alpha_P)^{\frac{Nenc}{\Delta t}}\right)\right]P(t)$ $\frac{dB}{dt} = k_{PB}P(t) - \left[\frac{1}{T_1} + \left(1-cos(\alpha_P)^{\frac{Nenc}{\Delta t}}\right)\right]B(t)$ with $P(0)=1$ and $B(0)=0$ (ideal bolus at $t=0$). For all simulations a k_{PB} value[3] of 0.018s^{-1}, T_1 of 30s and T_2* of 10.6ms was used. Spatial-spectrally (SPSP) selective excitation with a single shot EPI readout[4], echo planar spectroscopic imaging (EPSI) gradient echo[5] and a multi-echo (MultiEcho) acquisition in with single shot readout[6] were simulated (Figure 1, Table 1). The acquisition duration was chosen optimally (1.26xT_2*). SNR in every time frame and mean SNR of the first 20 dynamics were compared.

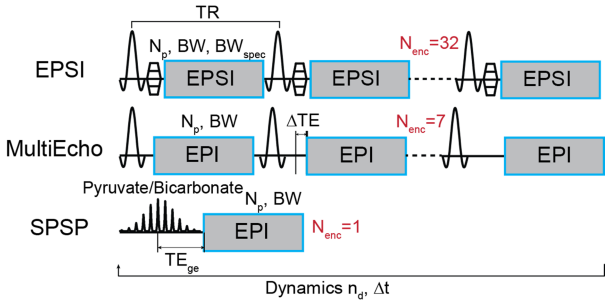

Figure 1: Schematics of simulated pulse sequences for dynamic imaging of hyperpolarized metabolic active substances.

Sequence	Parameters							
	N_p	N_{enc}	TE_{ge} [ms]	ΔTE [ms]	TR [ms]	BW[a] [Hz]	BW_{spec} [Hz]	Δt [s]
EPSI	32x38	32	1	-	15	90 957	2842[b]	3
MultiEcho	32x32	7	1	0.38	15	76 595	-	3
SPSP	32x32	1	2.3[c]	-	-	76 595	-	3

[a]for 1/BW = 1.26 T_2*
[b]BW_{spec} was chosen to cover a BW from lactate to bicarbonate at 9.4T
[c]based on a SPSP pulse with 11 sublobes and ≈300µs spacing

Table 1: Parameters used for numerical simulations of the pulse sequences.

Results: Figure 2a shows the maximum SNR of pyruvate and bicarbonate dependent on the flip angle. In case of the SPSP selective excitation SNR optimal flip angles for bicarbonate were considered. The EPSI sequence provides the highest SNR for pyruvate, based on short echo times TE_{ge} and ΔTE. For bicarbonate SPSP selective excitation provides highest SNR for all flip angles. With the condition that the mean SNR is the same for pyruvate and bicarbonate, an optimal flip angle on pyruvate of about 5° was found for the SPSP selective excitation, indicated in Figure 2a, providing a 22% increase in mean SNR on bicarbonate compared to EPSI with a 40% increase at the beginning to 5% increase at time point t = 60s as show in Figure 2b. However, optimal flip angles depend on the dynamic repetition time Δt, the relaxation time T_1, the considered rate k_{PB} and the number of encoding steps per dynamic N_{enc}. Undersampling techniques reducing N_{enc} do not automatically lead to a decrease in SNR in contrast to conventional imaging. If flip angles are adapted to optimal values the SNR will stay the same. For single shot readouts the situation is similar. SNR stays the same if the BW is adapted to the reduced number of points N_p, so that the acquisition time is kept constant. However, if the maximum BW is limited due to technical limits such as maximum slew rate or gradient strength, acceleration techniques allow enhanced image resolution with optimal SNR as shown in Figure 2c.

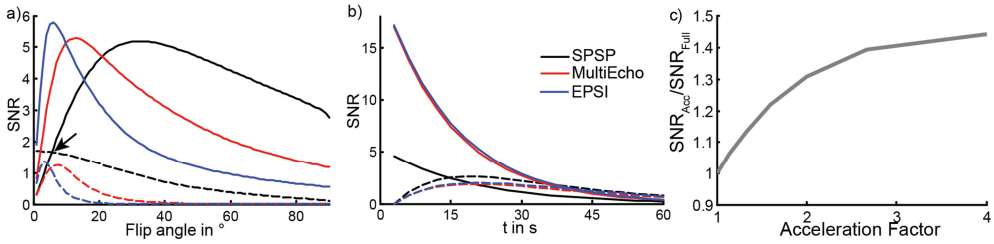

Figure 2: (a) Mean SNR dependent on flip angle on pyruvate (solid line) and bicarbonate (dashed line). Flip angles for maximum signal were found as 3° for EPSI and 7° for MultiEcho. For SPSP a flip angle of 5° was chosen for pyruvate where the mean SNR of pyruvate is the same as for bicarbonate (arrow), excited with an optimal flip angle of 27.5°. (b) Dynamic SNR curves for optimal flip angles according to (a). (c) SNR dependence on the acceleration factor for single shot readouts, if the maximum acquisition bandwidth BW_{acq} is limited by $BW = \frac{BW}{4}$.

Discussion: This work presents a theoretical framework for SNR comparison of sequences for dynamic imaging of metabolic active hyperpolarized substances. For metabolic products SPSP and multiband excitation can be considered most optimal in terms of SNR. Single shot methods provide very short acquisition times, which are beneficial especially in cardiac experiments and should be preferred over phase encoded EPSI sequences. However, high demands on the gradient system may limit the use of SPSP and multiband excitation. In contrast to conventional imaging, undersampling techniques do not automatically decrease SNR compared to the fully sampled case. Undersampling may be beneficial compared to the full sampling, if BW is limited for technical reasons.

References: 1. Schroeder et al., Circulation 2011. 2. Kurhanewicz et al., Neoplasia 2011. 3. Lau et al., MRM 2012. 4. Cunningham et al., JMR 2008
5. Wiesinger et al., MRM 2012. 6. Weiss et al., AMR 2012. 7. Larson et al., MRM 2011.