Precise flip angle calibration for hyperpolarized ^{13}C scans

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Introduction

The introduction of hyperpolarization techniques for ^{13}C labeled molecules [1] could promote MRI to a new role of metabolic imaging modality. The particularities of the hyperpolarized signals, however, pose new technological challenges. Many imaging pulse sequences rely on precise flip angle calibration to create high SNR, artifact-free images, and such calibration might become difficult with little or no signal prior to agent injection, and with time-varying signal following injection. We present here a method for precise flip angle setting at the ^{13}C frequency prior to injection, based on flip angle calibration at the ^{23}Na frequency. ^{23}Na is present in most biological tissues at relatively high concentrations (10-140mM), and resonates extremely close to ^{13}C at 1.5T. The same transmitter/receiver chain can be used for both nuclei, and only minor modifications are needed for a coil to be able to pick up both signals. We demonstrate here, in phantoms and *in vivo*, that flip angle calibration with accuracy of 0.01dB is possible at the ^{13}C frequency using this approach.

Methods

A 16 rung, 1.5T low-pass birdcage rat coil with one of its modes tuned to the ^{13}C frequency (16.06MHz), and the other mode tuned to the ^{23}Na frequency (16.89MHz) has been built using an approach similar to the one described in [2]. More precisely, the symmetry of the system was broken, and the existence of 2 linearly polarized fields was imposed through a change in the capacitor values of C_4, C_8, C_{12} and C_{16}. To have the same flip angle on both channels (assuming equal length excitation pulses), in theory, one can write $B_{1^{13}C} = B_{1^{23}Na} \cdot \gamma_{^{23}Na} / \gamma_{^{13}C} = 1.05 B_{1^{23}Na}$. In practice, due to factors such as non-linearity of the RF amplifier or non-identical tuning and matching of the 2 modes, the proportionality coefficient c_1 (with $B_{1^{13}C} = c_1 B_{1^{23}Na}$) can be slightly different than its theoretical value of 1.05.

To calibrate the transmit power for a given flip angle, one typically adjusts the transmit gain (TG) in a prescan step. TG represents the transmit power expressed in units of 0.1dB (1TG unit=0.1dB). As the power needed for a given flip angle is proportional to the square of the B_1 field, one can write

$$P_{^{13}C}[mW] = P_{^{23}Na}[mW] \cdot c_1^2$$

(here c_1 is the above constant, and we assumed pulse widths at both frequencies), or alternatively

$$P_{^{13}C}[TG\ units] = P_{^{23}Na}[TG\ units] + 200 \log c_1 \qquad [1]$$

Ten different phantoms of 500ml each (2 concentric cylinders, containing 10-100mM concentrations of NaCl on the outside, and 7M ^{13}C labeled sodium acetate on the inside) were built to simulate (and exceed) different coil loadings seen *in vivo*. The inversion TG's (iTG's) (TG's for the 180 degree flip angles) were recorded at both the ^{13}C and ^{23}Na frequencies, and a linear fit was performed to extract c_1 (a coil characteristic) according to Eq. [1]. Four rats were also scanned, and the "theoretical" iTG at the ^{13}C frequency (determined using Eq. [1] -and the experimentally measured ^{23}Na frequency iTG) was compared to the experimentally measured TG at the same ^{13}C frequency (when ^{13}C signal was at all visible).

Results and discussion

Figure 1 presents the images at the ^{23}Na (Figure 1a) and ^{13}C (Figure 1b) frequencies of the phantoms described above, using the dual tuned birdcage coil and a gradient echo pulse sequences on a 1.5T GE scanner.

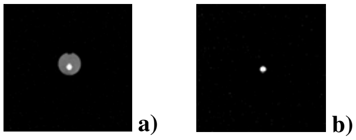

Figure 1: a) *^{23}Na and* ***b)*** *^{13}C image using the dual tuned birdcage coil*

Figure 2a presents the experimental phantom data relating the iTG at the ^{23}Na frequency to the iTG at the ^{13}C frequency. A linear fit to the data (according to Eq. [1]) yields a constant c_1=1.19. Frequency dependent amplifier response, variable T/R switch frequency response, and different tuning/matching of the 2 channels of the coil can easily explain the difference between the fitted value of 1.19 and expected value of 1.05.

Figure 2b presents *in vivo* experimental data acquired from 4 rats (three positioned twice within the coil, to landmark the head and the mid-body) confirming the in vitro experiments. Here, the predicted ^{13}C iTG vs ^{23}Na iTG is shown as a line (calculated according to the calibration for this coil, $TG[^{13}C] = TG[^{23}Na] + 15.1$), together with the in vivo measurements. As noted from Fig. 2b, the error in measuring the iTG at the ^{13}C frequency in vivo is very large. Typically, this uncertainty is on the order of ±10TG units, though, when the landmark is set on the head of the rat, this uncertainty can go as high as ±20TG units. Moreover, in one of the cases, no ^{13}C signal could be measured from the head of a rat. This was expected, as no significant amount of lipids (providing enough natural abundance ^{13}C signal for measurements) is present. By comparison, the error in measuring the iTG at the ^{23}Na frequency was less than one TG unit. It is to be noted in Fig. 2b that all the measured inversion TG's at the ^{13}C frequency are within the predicted values from the previous coil calibration.

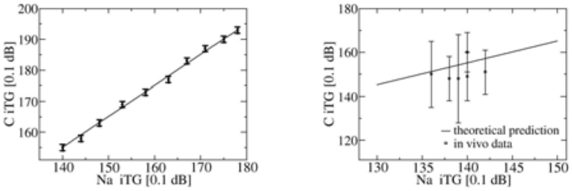

Figure 2: a) ^{13}C vs ^{23}Na inversion transmit gain (iTG) for the 10 loading phantoms **b)** ^{13}C vs ^{23}Na iTG for 4 rats. The theoretical prediction is also shown as a line.

Conclusions

We have presented evidence demonstrating that calibrating the transmit power for a ^{13}C scan at the ^{23}Na frequency is very accurate. We have also shown an implementation of a practical coil (a birdcage coil with one of the modes tuned to the ^{23}Na, and the other one tuned to the ^{13}C frequency) suitable for this calibration in vivo. Alternatively, a low pass coil can be envisioned, having the same capacitors for both frequencies, but slightly longer rungs for the ^{13}C frequency. The additional rung length can be added using varactor diodes. Such implementation will offer quadrature drive, therefore a 40% signal to noise improvement for imaging at both frequencies.

References

1. Golman et al, PNAS, **103(30),** 11270 (2006); **2.** P. Joseph et al, IEEE Trans on Med Im, 286 (1989).