



Synthetic signal injection using inductive coupling

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ABSTRACT

Conversion of MR signals into units of metabolite concentration requires a very high level of diligence to account for the numerous parameters and transformations that affect the proportionality between the quantity of excited nuclei in the acquisition volume and the integrated area of the corresponding peak in the spectrum. We describe a method that eases this burden with respect to the transformations that occur during and following data acquisition. The conceptual approach is similar to the ERETIC method, which uses a pre-calibrated, artificial reference signal as a calibration factor to accomplish the conversion. The distinguishing feature of our method is that the artificial signal is introduced strictly via induction, rather than radiation. We tested a prototype probe that includes a second RF coil rigidly positioned close to the receive coil so that there was constant mutual inductance between them. The artificial signal was transmitted through the second RF coil and acquired by the receive coil in parallel with the real signal. Our results demonstrate that the calibration factor is immune to changes in sample resistance. This is a key advantage because it removes the cumbersome requirement that coil loading conditions be the same for the calibration sample as for experimental samples. The method should be adaptable to human studies and could allow more practical and accurate quantification of metabolite content.

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1. Introduction

A practical and robust method for converting signals into units of metabolite content would greatly improve the accuracy, information content, and utility of MR measurements. Quantification of metabolite content, a process often referred to as absolute quantification, requires accurate determination of the proportionality factor between the quantity of excited nuclei associated with that metabolite within the measurement volume and the integrated area of the corresponding spectral peak in the processed data. In general, a very high degree of diligence is required to account for all of the parameters that affect this calibration factor. As a result, nearly all MR results are presented in terms of arbitrary units or as ratios, which can be difficult to interpret and of limited clinical and experimental utility.

We have developed a method that eases the burden of the quantification process. Our approach utilizes a small RF coil (the injector coil) that couples inductively with the RF coil used for signal acquisition. The purpose of the injector coil is to stimulate a robust synthetic signal (the pseudo-signal) in the receiver coil at the same time that the real signal is acquired from the sample.

The amplitude, frequency and linewidth of the pseudo-signal are first set relative to a real peak corresponding to a known metabolite concentration. The same pseudo-signal is then injected during subsequent measurements and used as a reference signal for converting the real signals into standard units of concentration.

The key innovation of this approach is that the pseudo-signal is introduced to the receiver coil via inductive coupling. Since this is also the mechanism by which the local B_1 field (B_{1m}) arising from excited nuclei in the sample couples with the receiver coil, any subsequent manipulations of the data have an equal effect on both signals. This makes the calibration factor immune to changes in coil loading conditions, receiver gain settings and data processing methods.

We have built and implemented a prototype probe and we have conducted *in vitro* experiments to verify that the pseudo-signal and the real signals are completely independent of each other—a necessity for accurate quantification—and that the ratio of the pseudo-signal and real signal is immune to variations in coil loading. Our approach could allow more practical and accurate quantification of metabolite content using non-invasive MR techniques.

2. Experimental

All experiments were conducted on a 4.7 T Bruker horizontal bore magnet equipped with a Varian Inova spectrometer and

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VNMR version 6.1. The pulse sequence and RF coil were modified to allow injection of a pseudo-signal during acquisition of the real signals, as described below. Before each measurement, the tune and match capacitors were adjusted to yield $50\ \Omega$ impedance, the B_0 field was optimized by manually adjusting the shims, and the flip angle was set to maximize the real signal. The integrated areas of the spectral peaks generated by the real and pseudo-signals were determined using the Advanced Method for Accurate, Robust and Efficient Spectral (AMARES) time domain fitting algorithm [1] as included in the Java-based Magnetic Resonance User Interface (jMRUI) software package [2].

Signal excitation and acquisition were achieved using a 2 cm diameter surface coil. The experiments were specifically designed to avoid potential errors in quantification caused by the highly non-uniform B_1 field generated by the surface coil. This eliminated the need for spatial calibration measurements. A simple pulse-acquire sequence was used for all measurements and the repetition time was always much longer than the T_1 of the samples. This eliminated the need to compensate for differences in relaxation times for different samples.

2.1. Probe design

Our prototype probe consisted of a 2 cm diameter surface coil (C1 in Fig. 1) and a 1.5 mm diameter, 2-turn injector coil (C2), both formed from copper wire. C1 was tunable to both ^1H and ^{31}P frequencies, 200.4 and 81.2 MHz, respectively, and was operated in both transmit and receive modes. The injector coil was used solely to inject the pseudo-signal into the surface coil during data acquisition. To minimize coupling between the injector coil and the sample, C2 was oriented perpendicular to the plane defined by C1.

A straightforward circuit analysis provides insight into how the probe satisfies the key constraints described in Section 3. Fig. 2A shows the main components of the probe, the voltage source used to inject the reference signal, and the preamplifier used to acquire the signals as the components are used during signal acquisition.

As shown schematically in Circuit A of Fig. 2, the injector coil and the main RF coil were placed in close proximity to each other (1 mm separation between them) so there was mutual inductance, M , between them. The mutual inductance is defined as, $M = k(L_1 L_2)^{1/2}$, where k is a scalar that depends on the geometric arrangement of the two coils. In our probe, the injector coil was rigidly mounted to the main RF coil so k was a constant. This is a key feature of the design because it ensures that M is a constant and, therefore, that the pseudo-signal remains in calibration when the probe is repositioned in the magnet to accommodate different samples. Any change in M during the course of the study would have been obvi-

ous because it would have required breaking the bonds holding the probe together.

As shown in Circuit B of Fig. 2, the elements comprising the voltage source and the injector coil can be replaced with an equivalent voltage source and resistor, e'_r and R'_r , respectively, where

$$e'_r = \frac{j\omega M}{R_r + R_i + j\omega L_i} e_r \quad R'_r = \frac{\omega^2 M^2}{R_r + R_i + j\omega L_i}. \quad (1)$$

The parameters on the right-hand sides of these two equations are constants determined by fixed physical characteristics of the hardware that do not change after the calibration session. By summing the voltage drops around the two loops in Circuit B, two simultaneous equations can be generated. These can be solved in order to determine the detected signal, V_p ,

$$V_p = \frac{R_p}{D} (e_s + e'_r) \quad D = \left\{ 1 + \frac{C_t}{C_m} + j\omega C_t R_p \right\} \left\{ R_s + R'_r + R_c + j\omega L_c + \frac{1}{j\omega C_t} \right\} - \frac{1}{j\omega C_t}. \quad (2)$$

Note that the sample-dependent variables, R_s , C_t , and C_m , are all in the denominator, D , and they act in equal proportion on the two terms in the numerator, e_s and e'_r . In this analysis, we have assumed a single value for the frequency, ω . In practice, the frequency for the injected signal, ω_r , will be deliberately set to a slightly different frequency from the metabolite frequency, ω_s , so that the peaks in the processed spectrum do not overlap. The difference between ω_r and ω_s , which is on the order of a few kilohertz, is much smaller than the resonant frequency, which is at least tens of megahertz, so this will introduce a negligible error into the analysis but it also allows the acquired signal to be divided into two components,

$$V_p = V_s(\omega_s) + V_r(\omega_r) \quad (3)$$

$$V_s(\omega_s) = \frac{R_p}{D} e_s(\omega_s) \quad V_r(\omega_r) = \frac{R_p}{D} e'_r(\omega_r)$$

where V_s arises from the sample and V_r is the voltage of the injected reference signal.

This analysis demonstrates that the calibration factor, $V_r(\omega_r)/V_s(\omega_s) = e'_r(\omega_r)/e_s(\omega_s)$, is independent of the sample-dependent parameters that affect coil loading so, after it is set during the calibration session, it remains constant.

2.2. Properties of the injector coil

The analysis above assumes that the only coupling mechanism between the injector circuit and C1 is inductive. The injector coil

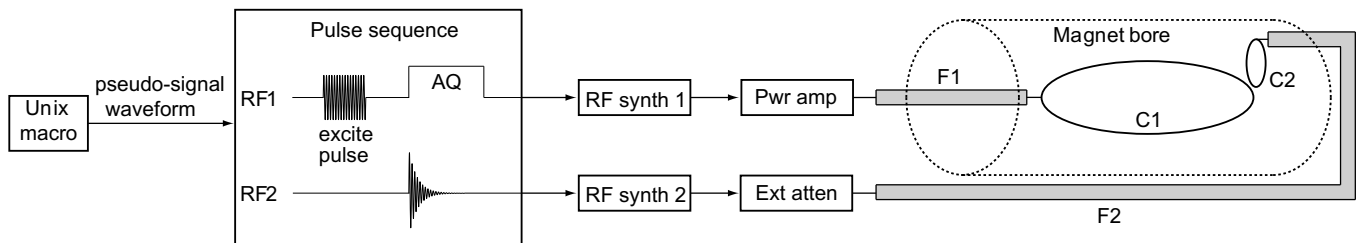


Fig. 1. This schematic depicts the key components required to implement the quantification protocol. Prior to execution of the pulse sequence, a Unix macro was used to create a digitized waveform describing the desired pseudo-signal. The pulse sequence read the waveform and sent it to the second RF channel (RF2). The pseudo-signal was transmitted through an RF synthesizer (RF synth 2) and passed through an external attenuator (Ext atten) before being fed through an RG-223 coaxial cable (F2) to the injector coil (C2). The diameter of C2 was much smaller than C1 and it was oriented perpendicular to the surface of the sample. To prevent cross talk between the two coaxial cables (F1 and F2), the distance between them was maximized by feeding them in through opposite ends of the magnet bore. During sequence execution, C1 was operated in transmit/receive mode while C2 was used only to transmit the pseudo-signal during the acquisition window (AQ). The main RF channel (RF1) and the components linking it to C1 were operated as they would be for a typical pulse sequence. We show a simple pulse-acquire sequence and a pseudo-FID but more sophisticated sequences and pseudo-signals can be implemented.

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