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Assessment of the specific absorption rate and calibration of decoupling parameters for proton decoupled carbon-13 MR spectroscopy at 3.0 T

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Abstract

A strategy for proton decoupled carbon-13 MR spectroscopy ($\{^1H\}$-^{13}C MRS) with a strong static magnetic field (3.0 T) in vivo was investigated. The proton decoupling improves the signal-to-noise ratio, however, the effect of the decoupling power on the human body, especially in strong magnetic fields, should be considered. In order to establish a technique for monitoring the metabolism of glucose in the liver using $\{^1H\}$-^{13}C MRS at 3.0 T, two phantom experiments were performed. To assess whether the decoupling energy conformed to SAR limits defined by the IEC, temperature rises inside an agar gel phantom were monitored during a $\{^1H\}$-^{13}C MRS experiment. Then, the decoupling conditions of a glucose solution phantom were systematically optimized with combinations of decoupling bandwidth and power. The reliability of this procedure was discussed in conjunction with IEC guidelines.

Keywords: ^{13}C MRS; Proton decoupling; 3.0 T; SAR

1. Introduction

Broadband proton decoupling is a useful technique for carbon-13 magnetic resonance spectroscopy (^{13}C MRS) in vivo [1,2]. By irradiating protons with a strong decoupling radio frequency (rf), the spin–spin coupling between a proton and ^{13}C is eliminated (decoupled) and a set of split ^{13}C signals turns into one larger peak. The irradiation also induces nuclear Overhauser enhancement (NOE) with an increase in ^{13}C signals of up to three-fold [3].

Since the gyromagnetic ratio of ^{13}C is about a quarter that of proton and the natural abundance of ^{13}C is only 1.108%, the signal-to-noise ratio (SNR) is much reduced in ^{13}C MRS. One possible way to improve the SNR may be to use a stronger magnetic field. However, since the decoupling power demanded correlates with a square of the Larmor frequency, safety issues must be considered. For example, a quadruple increase in rf energy is needed for proton decoupling at 3.0 T compared to that required at 1.5 T. Hence, input, the transmission and reception circuit, and the design of the decoupling coil should be optimized to avoid thermal tissue damage from excessively high rf energy and minimize electrical noise. As a safety guideline for the MR system, the International Electrotechnical Commission (IEC) has provided safety standard 60601-2-33 (2002), in which the limits of the specific ab-

Abbreviations: FID, free induction decay; $\{^1H\}$-^{13}C MRS, proton decoupled carbon-13 magnetic resonance spectroscopy; IEC, International Electrotechnical Commission; NOE, nuclear Overhauser enhancement; rf, radio frequency; SAR, specific absorption rate; SCE, second rf channel exciter; SNR, signal-to-noise ratio

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sorption rate (SAR) and temperature are defined as follows: an upper limit of the local SAR of 10 W/kg in the head and trunk, and 20 W/kg in the extremities, and a maximum permissible spatially localized temperature limit of 38 °C in the head, 39 °C in the torso and 40 °C in the extremities in the normal operating mode at an environmental temperature of below 24 °C.

Several attempts have been made to discuss the technical measurements of the effects of rf energy on the human body in computer simulations [4–6]. However, computer simulation is not perfect since it evaluates pre-defined characteristics of the circuit using equations, and unpredictable factors may potentially remain. Therefore, it is still indispensable to directly evaluate the rf characteristics of the prototype coils. Bergh et al. worked to evaluate the SAR during proton decoupling protocols with experimental approaches, and determined the skin surface temperature changes in volunteers using fluoroptic probes [7,8].

In this paper, we present a safety assessment procedure for in vivo proton decoupled ^{13}C MRS ($\{^1$H$\}$-^{13}C MRS) with a clinical 3.0 T MR system using two phantoms. During a $\{^1$H$\}$-^{13}C MRS experiment, in which decoupling power was within the limits of the SAR, the temperature rises inside an agar gel phantom were monitored to evaluate safety levels of rf power in the human body. Then, the decoupling conditions in a glucose phantom with various combinations of bandwidth and power were systematically investigated.

2. Materials and methods

2.1. MR systems for the $\{^1H\}$-^{13}C MRS experiments

All MRI and MRS experiments were performed with a 3.0 T clinical MR system (Signa VH/i 3.0 T, GE Medical Systems, Milwaukee, WI) equipped with a second rf channel exciter (SCE) for proton decoupling. Proton decoupling was performed using a WALTZ-4 sequence with bi-level irradiation [2]. The set proton decoupling power of the SCE was applied during the ^{13}C free induction decay (FID) signal acquisition, and a value of 10% was used during the remaining time before the next pulse to induce NOE. In the SCE, three parameters for proton decoupling were variable: (1) the rf center frequency, (2) the power (W) and (3) the 90° pulse length of WALTZ-4.

All MR images and spectra were obtained using a dual transmit/receive surface coil of external dimensions 195 mm × 130 mm, doubly tuned to 127.90 Hz for proton and 32.16 MHz for ^{13}C. The circuit traces were copper ribbons of width 6 mm, on a Teflon backing (RT/duroid, Rogers Corp., Chandler, AZ). The loop dimensions for the proton and ^{13}C resonators were 185 mm × 110 mm and 85 mm × 75 mm, respectively. The ^{13}C loop was situated inside the proton loop concentrically, and was electrically decoupled by means of a small parallel trap circuit tuned to 127.90 MHz. The room temperature and humidity in the MR scanner room were maintained at 23 °C and 55%, respectively.

2.2. Phantom preparation

An agar gel phantom for temperature monitoring was prepared by mixing 2% per wt. of agar (Taguchi Corp., Osaka, Japan), 0.22% sodium chloride (Aldrich Chemical Company, Milwaukee, WI) and 0.1% sodium azide (Aldrich Chemical Company) as preservatives with 5.4 l of distilled water. To adjust the SAR distribution of the phantom to that of human muscle at 128 MHz, the phantom composition was referenced from the hyperthermia guidelines of the Japanese Society of Hyperthermic Oncology. The concentrations of agar and sodium chloride, which determine the electrical conductivity and the relative permittivity, respectively, were finely adjusted [9]. The compound was heated to 90 °C to dissolve the agar and poured into a plastic container (28 cm × 20 cm × 9 cm). Air bubbles were expelled from the agar gel under a 10^{-1} Torr vacuum in a de-aerator under cooling.

A glucose solution phantom was prepared to employ the ^{13}C peak from glucose as an indicator of decoupling conditions. One hundred and fifty grams of non-enriched D(+)-glucose (Nacalai Tesque, Kyoto, Japan) was dissolved in 500 g of water (1.67 mol/kg), and poured into a spherical plastic container 10 cm in outer diameter.

2.3. MR experiments

Proton MR images and spectra were used for shimming and spectral localization. All ^{13}C spectra were acquired with a 248 μs hard pulse for excitation without spatial localization. Sixteen dummy scans were preformed to achieve a steady state of magnetization. Data were analyzed on a workstation (IRIX O_2: Silicon Graphics, Mountain View, CA) using the SA/GE software package (GE Medical Systems). Each averaged FID was processed with a 10 Hz exponential function, zero-filling to double the sampling points, fast Fourier transform and phase correction.

2.3.1. Determination of the proton decoupling period

The goal is to obtain a maximum decoupling effect with minimum decoupling rf power, which was derived by multiplying the decoupling period by the power in a unit of time. The proton decoupling period was synchronized to the ^{13}C FID acquisition period. The acquisition period was determined by multiplying the ^{13}C FID signal sampling points by the reciprocal of the ^{13}C observation bandwidth. From the spectra of the ^{13}C liver without proton decoupling from two healthy volunteers who gave written informed consent (one male: 41 years, one female: 32 years), it was confirmed that all peaks of glucose metabolites and derivatives can be covered within the 8 kHz width of ^{13}C spectra. The decay time of ^{13}C FID was about 0.050 s (unpublished results). With these