Investigation of SAR for Low-Frequency Hyperpolarized Gas MRI of the lung

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INTRODUCTION: Magnetic resonance imaging of the human lung using hyperpolarized gas (HPG) can be performed at low magnetic field [1-5] to avoid certain disadvantages that accompany the technique at conventional field strengths (B_o ~ 1.5 T). In particular, operation at lower field allows the use of rapid pulse sequences that would otherwise exceed safe power absorption limits. For example, a very fast repetition CPMG sequence (i.e. sequential π-pulses) has been employed at very low field (B_o ~ 3 mT, f_o ~ 100 kHz) to measure the oxygen-limited T_1 relaxation of hyperpolarized ^{3}He in the human lung [2,4]; this technique provides a direct means of tracking pulmonary O_2 concentration and its uptake rate into the blood. The extension of such novel pulse sequences toward still faster repetition rates and their potential use at intermediate field values is of interest. As a result, it is important to have a thorough knowledge of the specific absorption rate (SAR) of RF power over the range of frequencies that are relevant to this new class of MR experiments. Here we present results of in vivo SAR measurements over the frequency range f = 0.1 - 1.2 MHz; the results are discussed in terms of π-pulse amplitude.

METHOD: A birdcage-like coil (Figure 1) was employed for this series of cavity perturbation measurements; it was originally designed as a transmit coil to produce very homogeneous oscillating magnetic fields over the volume of a human thorax [6]. The coil was connected to a low loss variable capacitor to form an isolated LRC tank circuit. Small, well separated transmit (T_X) and receive (R_X) coils were weakly coupled to the resonant circuit so that its frequency response could be measured in transmission. Data from these experiments were fit to a model of the transfer function for the circuit comprising three free parameters: an amplitude scaling factor related to the coupling between the T_X and R_X coils and the resonant structure, a resonant frequency f_0, and an effective series resistance R. Cavity perturbation measurements [7] were performed with a human subject inside the coil and the absolute change in the effective series resistance was determined. We refer to this difference as the effective resistance of the body $R_S = R_L - R_U$, where R_L and R_U denote the loaded and unloaded effective series resistances of the resonant structure. Experiments involving the use of five healthy subjects were performed with institutional ethics approval.

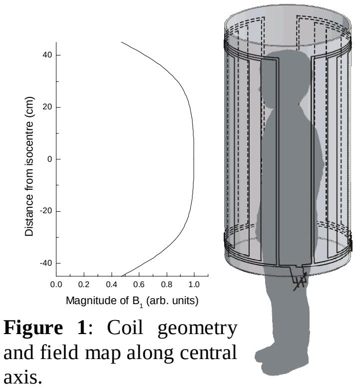

Figure 1: Coil geometry and field map along central axis.

RESULTS AND DISCUSSION: The effective resistance of all subjects was observed to scale as f^2 over the range f = 0.2 - 1.2 MHz (Figure 2); below this frequency experimental resolution was insufficient to distinguish R_S from zero. The average value of the quadratic coefficient R_S / f^2 was found to be 4.8 x10^{-15} Ω Hz^{-2} per kilogram. The absolute value of R_S / f^2 is specific to coil geometry and depends on the square of the coil-constant $\chi = B_1 / I$, where I is the current necessary to produce a magnetic field B_1. However, the power $P = I^2 R_S = (B_1 / \chi)^2 R_S$ that is dissipated in a sample by induced currents depends only on B_1; as a result we can calculate a frequency-dependent SAR value suitable for use with any transmit (B_1) coil that produces a uniform field over a comparable fraction of the human body. Taking into account that fraction of the body mass that is outside the nominal field produced by our coil, we arrive at a conservative value for the instantaneous specific absorption rate SAR = 5.4 x 10^{-5} $f^2 \cdot B_1^2$ W/kg (MKS units). SAR levels inferred from our data are shown in Figure 3 for the operating frequencies of the five low-field ^{3}He MR experiments that have been reported to date in the published literature [1-5]. Note that field amplitudes have been expressed in terms of an equivalent π-pulse duration $T_\pi = 2\pi/(\gamma B_1)$ [8]. These results imply that very fast (sub-millisecond) π-pulses can be used without exceeding SAR limits [9] when operating at frequencies of a few MHz or less.

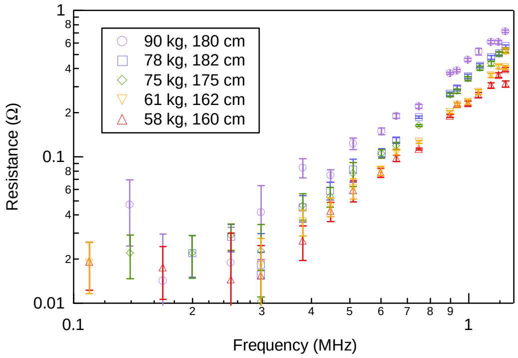

Figure 2: Effective resistance R_S versus frequency. The heights and weights of the five human subjects are given in the legend.

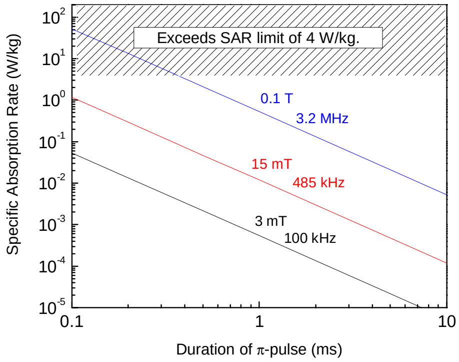

Figure 3: SAR as a function of π-pulse duration for magnetic fields B_0 = 3 mT [2,4,5], 15 mT [3], and 0.1 T [1]. The latter relies on extrapolation of our data with the assumption that the quadratic frequency dependence of R_S is valid up to 3.2 MHz.

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