Microtesla MRI detected with a superconducting quantum interference device

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Introduction

We use a low transition temperature (T_c) Superconducting QUantum Interference Device (SQUID) to perform magnetic resonance imaging (MRI) at magnetic fields B_0 ~130 µT, corresponding to proton Larmor frequencies of about 5 kHz. In such low fields, broadening of the nuclear magnetic resonance lines due to inhomogeneous magnetic fields and susceptibility variations of the sample is minimized. In contrast to conventional high-field MRI, where the signal amplitude scales as B_0^2, in our experiment the signal amplitude is independent of B_0. This is achieved by prepolarizing the spins in a magnetic field up to 300 mT and detecting the signal at a much lower measurement field using an untuned superconducting input circuit coupled to the SQUID. In this approach the homogeneity reqirements for the field coils are very modest, and all magnetic fields can be generated from simple copper wire coils and do not require shimming.

Experiment

The principle of SQUID-detected MRI is shown schematically in Fig. 1. The magnetic field from proton spins precessing around the measurement field B_0 is detected by the lowest coil of a superconducting, second-order axial gradiometer. The gradiometer has a balance of ~100 against uniform magnetic fields, thereby reducing external noise from distant sources. It is connected to a thin film, multiturn input coil coupled to the SQUID, which consists of a superconducting loop interrupted by two Josephson junctions. An array of Josephson tunnel junctions protects the input circuit from large transient currents. A 0.6 m radius Helmholtz coil produces B_0, and Maxwell and Golay coils of similar size generate the encoding gradients. To attenuate environmental noise below the 1.7 fT $Hz^{-1/2}$ SQUID noise, the entire experiment is surrounded by 3mm-thick Al plates.

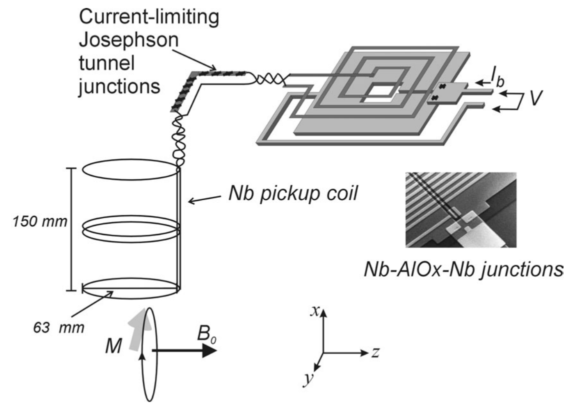

Fig 1. Measurement configuration of SQUID-detected MRI

Results and Discussion

In order to increase the detected signal we apply a prepolarization pulse of up to 300 mT before image encoding. This pulse is turned off adiabatically allowing the spins to orient along the measurement field. After a delay time we employ a standard spin-echo pulse sequence to acquire three-dimensional images in less than 6 minutes. Using encoding gradients of ~100 µT/m we obtain three-dimensional images of bell peppers and water phantoms with a resolution of 2 x 2 x 8 mm³ [Fig. 2(a)]. In its current configuration the system is ideally suited to acquire *in vivo* images of small, peripheral parts of the human body such as hands and arms. Three-dimensional images of a human forearm were acquired at B_0 = 132 µT with an average prepolarization field B_p = 50 mT. Figure 2 (b) shows two 24-mm thick sections of the forearm with a signal-to-noise ratio (SNR) of 10 and an in-plane resolution of 3 mm x 3 mm; the imaging time was 6 minutes.

The combination of prepolarization at fields around 300 mT and detection at ultralow magnetic fields enables us to obtain longitudinal relaxation time (T_1) dispersion curves and T_1-weighted contrast images over five and a half decades in frequency. For this purpose a spin evolution period in a variable field between 1.4 µT and 300 mT is added between prepolarization and detection. As an example we measured the T_1 dispersion of a phantom consisting of 0.25%- and 0.5%-agarose gel. The dispersion curve and T_1-weighted images at 10µT and 300 mT clearly show a substantial T_1-contrast enhancement in low magnetic fields [Fig. 3]. This enhancement might lead to novel applications in specialized clinical imaging of human subjects, for example, low-cost tumor screening. To make such applications feasible further improvements of the SNR and resolution of the system are necessary. By employing a SQUID detector with a lower magnetic field noise and by raising the maximum polarizing field, an improvement of the SNR by an order of magnitude should be possible.

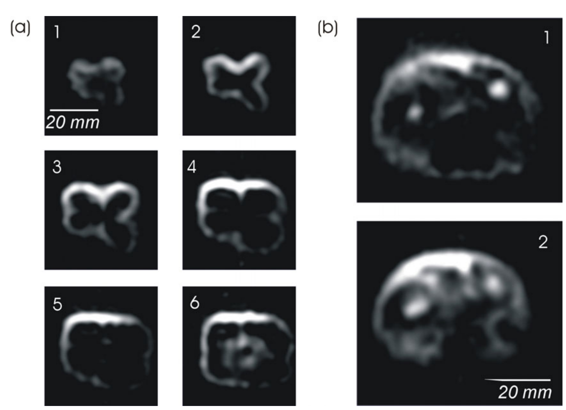

Fig 2. (a) Three-dimensional image of bell pepper showing six cross sections with a thickness of 8 mm, (b) Two 24mm-thick cross sections of a human arm.

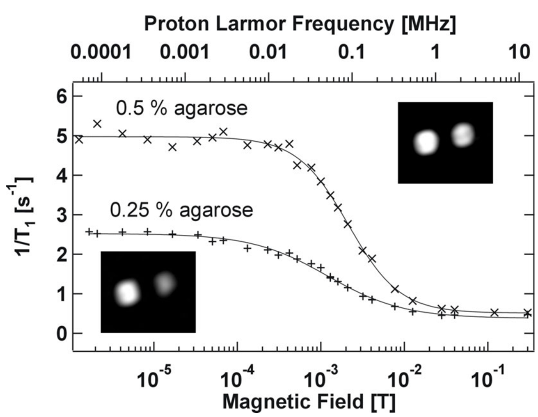

Fig 3. T_1 dispersion for a two-column phantom filled with two different concentrations of agarose gel (left column 0.25%, right column 0.5 %) , insets show T_1-weighted contrast images of the phantom at 10 µT (left) and 300 mT (right)