Development of Cryogen-Free Ultra-Low Field MRI Instrument

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Abstract

In-vivo MR imaging at very low fields using superconducting quantum interference device (SQUID) magnetometry and pre-polarizing field cycling technique has been demonstrated recently and many advantages have been noted. Although the expensive superconducting magnet can be essentially eliminated in a pre-polarizing low field SQUID MRI system, expendable cryogens and its maintenance service, required to cool the low temperature detector, are still placing increasing burden on the operational cost. We have built a prototype cryogen-free SQUID MRI system. Here we present its design, noise characterizations and the first phantom image.

Methods

The system consists of (1) a cryocooled SQUID and a superconducting gradiometer in a non-magnetic dewar, (2) a polarizing coil, a measurement field coil and gradient coils, and (3) readout electronics and software system. Figure 1 shows a schematic block diagram of the system. We used a commercial two-stage pulse tube cryocooler to cool the SQUID detector and the superconducting gradiometer. The dewar is a home-built design using a fiber-glass material. The prototype instrument is utilizing several new novel elements. The superconducting gradiometer (diameter=7.4 cm) is an inexpensive, home-built wire using internal copper skeleton wire surrounded by an external lead-tin alloy coating (a commercial soft solder wire). The internal copper wire provides a good thermal conduction to reach temperature below the superconducting transition temperature of the external lead-tin coating. The outer superconducting layer provides both shielding of thermal Johnson noise from the copper wire and superconducting persistent loop with the SQUID input coil. A special Nb-PbSn superconducting joint is made for connection to the Nb SQUID input coil. The gradiometer is designed and aligned symmetrically to the polarization field to minimize the coupling. The low frequency suppression coil minimizes the residual low frequency power-line noise, which is picked up by the gradiometer without loss of the MR signal at higher frequencies. A separate set of coils surround the entire apparatus to provide earth field cancellation allowing us to capture signal at 132 μT (5.7 kHz). An un-tuned excitation coil is used for NMR induction. To avoid thermal Johnson noise pick-up, thermal radiation shields are made by using electrically insulating materials (alumina and IR absorbing cellulose).

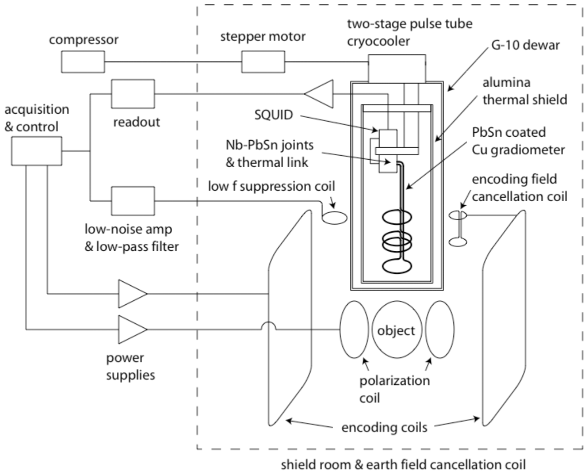

Figure 1. Block diagram of the cryogen-free ULFMRI system.

Discussion

The operation of the pulse-tube cryocooler introduces a pick-up noise to the system. To minimize the cryocooler operation pick-up noise, we synchronize the operational cycle such that the data can be taken during the quite period. At this time, the system overall noise near 5.7KHz (our current measurement field) is approximately three folds higher than the SQUID detector noise limit, approximately 10 Φ_0/sqrt(Hz). In the figure 2, we show a schematic drawing of the synchronized pulse sequence and a 2-D image of a water phantom (diameter = 6.4 cm). The pre-polarizing field used for the imaging is 10 mT. The measurement frequency used for the test is 5.7 kHz. The typical resolution of the phantom image is 3.5 mm x 3.5 mm. We expect a significant SNR improvement by using more powerful polarizing magnet. In principle, magnitude of the polarization field is limited by the need to avoid unacceptable magneto-stimulation as the field is cycled rapidly down to the measurement field. We anticipate that 0.2 Tesla will be a practical limit for our system. This is more than twenty fold higher than our current operating point. Image data taken using our previous passive dewar system indicated that the SNR of the system will be ultimately limited by the commercial SQUID intrinsic noise. To enhance the detector sensitivity, we have designed and built a new SQUID detector with low junction capacitance to improve the energy resolution by factor of 8. The potential of successful cryogen-free, ultra-low field imaging devices includes an order of magnitude reduction in end-user cost, the ability to operate units at very low power, the availability of imaging within the operating theater that does not interfere with normal patient access, the opportunity to deliver imaging to the field in emergency situations and a host of other advantages.

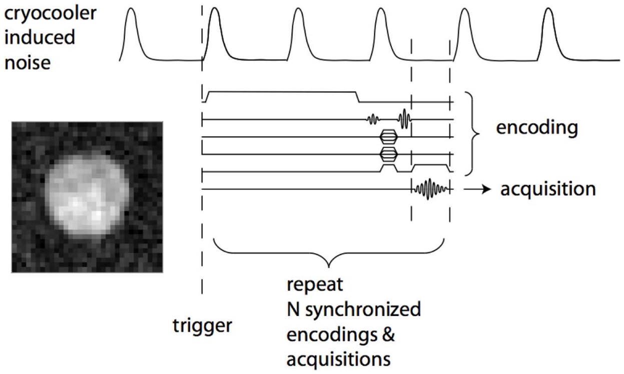

Figure 2. A water phantom 2-D image (diameter=6.4 cm) and schematic drawing of the MR pulse sequence to eliminate the noise associated with the cryocooler.