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3-Fold SNR Enhancement of Small Animal ^{13}C MRI using a Cryogenically Cooled (88 K) RF Coil

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Synopsis

SNR in hyperpolarized ^{13}C MRI is often limited by the low sensitivity of the receive RF chain at the low Larmor frequency of ^{13}C. In this study we present an RF transparent (non-metallic) cryostat designed for small animal imaging, which allows a coil temperature of 88 K, with a coil-to-sample distance below 3 mm. Performance of the cryostat equipped with a 30 x 40 mm^2 ^{13}C surface coil (3 T, 32 MHz) was tested and 3-fold SNR gain over room temperature coil was achieved.

Purpose

Cryogenically cooled coils have been a long-standing promise for SNR enhancement since the early days of MRI[1]. This is even more relevant nowadays, with the increased interest on imaging of low abundance nuclei with lower Larmor frequencies than protons[2]. However, the increased coil-to-sample distance needed in cryogenic coils can easily neutralize the SNR enhancement obtained by cooling. In this study we describe an MRI transparent cryostat for small animal imaging (Ø 73 mm) which allows a coil-to-sample distance below 3 mm, with the coil temperature reaching 88K while the outer surface being kept at room temperature.

Methods

A schematic of the cryostat is shown in Fig. 1. A separate ceramic (Al_2O_3) cylinder (AdValue, AZ, USA) whose outer diameter matches the inner diameter of the vessel acts as a cold-finger for to-be-cooled RF coil(s). Besides the vacuum thermal insulation, additional Multi-Layer Insulation (MLI) was installed, to reduce radiation heat losses. A combination of traditional (aluminized Mylar) and non-metallic (Kapton) MLI was used, in order to avoid eddy currents close to the RF coil (Fig. 2). The cryostat (ILK, Dresden, Germany) is shown in Fig. 3a, while the cold-finger (with the RF coil attached) is shown in Fig. 3b. Temperature sensors were attached to the cold-finger, and to the outside the cryostat (at the animal position). The temperatures were monitored under two different situations: without heat externally applied to the inner bore, and with warm air (50 °C) applied. The approximate amount of LN_2 supplied during the experiment was 6 L. An octagonal 40x30 mm^2 RF coil made of flat copper (thickness 1.2 mm) was glued to the cold finger using thermally conductive epoxy, and its Q-factor measured at room temperature and when cooled down inside the cryostat. A reference measurement with the coil immersed in LN_2 was also performed. The coil includes tuning, matching and active decoupling as described in[3]. The SNR performance was measured with a combination of a spectrum analyzer (Keysight, CA, USA) and a signal generator (Rohde&Schwarz, Munich, Germany). A small pickup loop was placed inside the cryostat bore, at a distance of 38 mm to the coil, and excited with -100 dBm. The received signal was measured for two different cases: room temperature (290 K) and cooled (88K), and the SNR calculated.

Results

The measured temperature inside and outside the cryostat is shown in Fig. 4, where the warm air was applied for 5 min from minute 70 to 75, and later for a longer period of 50 min (from minute 100 to 150). It can be appreciated that the application of warm air, increases only minimally the temperature of the cold finger (0.6 K). The coil Q-factor is shown in Fig. 5.a). The Q-factor is increased from 325 to 599 when the coil is cooled, which agrees well with other results reported for coils of similar size[4,5]. The measured SNR is shown in Fig. 5.b.

Discussion

The measured temperature at the coil position was 88 K (-184 °C), and this temperature could be kept stable for several hours (not shown in Figure 4). The temperature at the sample position was slightly decreased after some minutes to a stable value of about 10°C. This could be corrected by applying warm air at 50 °C, with a minimal effect on the temperature of the cold-finger (and therefore on the coil). The relatively small difference between the measured Q-factor of the coil inside the cryostat, compared to the coil immersed in LN_2 shows that the coil is indeed very close to the LN_2 temperature (77 K). A 3-fold SNR enhancement was measured, which agrees well with the theoretically predicted value when sample losses are negligible $\left(\Delta SNR = \frac{\sqrt{Q_{88K}\cdot 290}}{\sqrt{Q_{290K}\cdot 88}} = 2.6\right)$. The extra factor from 2.6 to 3 can be attributed to the noise reduction in the matching network, which was observed to effectively decrease the noise levels when cooled down.

Conclusion

Cryogenically cooled RF receive coils can be the means to significantly improve SNR in ^{13}C MRI, where sample noise is not very important. This is so, as long as the coil-to-sample distance is not increased excessively due to the thermal insulation needed to provide a warm environment at the sample position. In this study we describe a small animal cryogenic coil setup, where the coil can be kept at a distance below 3 mm from the sample, while keeping the sample position at room temperature. A 3-fold SNR enhancement is reported for a small 30x40 mm^2 octagonal coil for ^{13}C at 3T (32 MHz), which agrees well with the theoretically predicted value.

Acknowledgements

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Figures

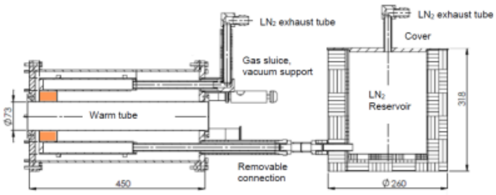

Figure 1. Schematic of the proposed cryostat: the LN_2 flows from the reservoir (on the right), to the vacuum-insulated cylindrical vessel (on the left). The vessel is thermally connected a cold-finger made of Al_2O_3, which has the RF coil attached (showed in orange color in the figure). Dimensions are shown in mm.

Figure 2. MLI added around the inner tube of the cryostat to prevent heat losses through radiation. It contains a part with regular aluminized Mylar, and a smaller part with Kapton film.

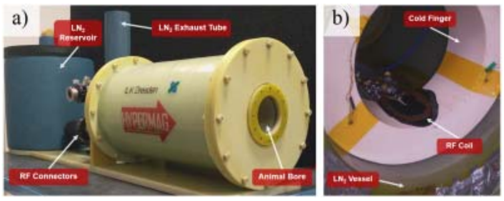

Figure 3. a) Fabricated cryostat and b) detail of the cold-finger with the receive RF coil attached.

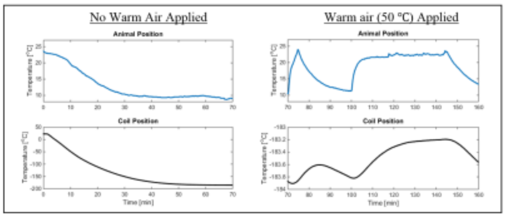

Figure 4. Measured temperature of the animal and coil positions of the cryostat over time, with and without applying warm air through the inner bore. Warm air was applied first for 5 min (min 70 to 75) and later for 50 min (min 100 to 150).

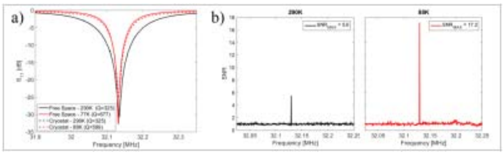

Figure 5. a) Measured S_{11} and Q-factor of the coil (in free space, and mounted in the cryostat) and, b) SNR measured with the coil mounted in

the cryostat. The signal for the SNR measurements was generated with a 15 mm diameter pickup loop placed 38 mm away from the receive coil, and fed with an input power of -100 dBm. Measurements were performed in a partially shielded room, with insignificant noise levels 32 MHz.