A CRYO-COOLING MICROFLUIDIC CHANNEL DEVICE FOR A MAGNETIC RESONANCE (MR) MICROSCOPY SYSTEM

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ABSTRACT

The development of a cryo-cooling microfluidic device for reducing the resistive noise of a magnetic resonance (MR) microcoil to improve its signal-to-noise ratio (SNR) in MR microscopy applications is presented. The radiofrequency (RF) spiral coil was cryo-cooled to liquid nitrogen temperature (-196ºC) by the integrated microfluidic channels carrying liquid nitrogen for decreasing the thermal noise of the coil. Our prototype had a Q factor increase of 1.78 folds while preventing the imaging sample from freezing.

KEYWORDS: Cryogenic cooling, Magnetic Resonance Microscopy, Signal to Noise Ratio (SNR), Micro spiral coil

INTRODUCTION

Magnetic resonance image (MRI) or nuclear magnetic resonance (NMR) are powerful analysis methods in the fields of medicine, biochemistry, and materials science. Magnetic resonance spectroscopy is generally considered to be a signal-to-noise ratio (SNR) limited technique, particularly in the case of MR microscopy. If a voxel size decreases by a factor of 10 in each direction and all other parameters remain constant, the SNR decreases by a factor of 1000 because the SNR is proportional to the number of spins in a given voxel. SNR can be enhanced by using signal averaging, higher magnetic field strengths, or modified MR sequence design. However, those methods require longer acquisition time or more expensive systems. Therefore, several efforts have been made to reduce the noise of MR coils using cryogenic cooling or superconducting materials to enhance the SNR [1-2]. However, high-temperature superconducting coils have disadvantages in terms of simplicity and cost when compared to copper coils. Also, the large size of thermal insulating layers of conventional cryostats makes them not suitable for microscale surface coils where the SNR exponentially drops with increasing coil-to-sample distances.

Here we developed a cryo-cooling microfluidic device integrated with surface microcoils. It minimizes the coil-to-sample distance without freezing samples to be imaged while cryo-cooling the coils.

THEORY

The SNR gain by cooling a metal coil is shown in the following equation [1],

$$SNR_i = \sqrt{\frac{R_{unload,room}T_{room}+R_{sample}T_{sample}}{R_{unload,cooled}T_{cooled}+R_{sample}T_{sample}}} \qquad (1)$$

where R_{unload} is the resistance of the coil itself without samples loaded and R_{sample} represents the resistance of samples. If the temperature of the coil decreases from room temperature (T_{room} = 27ºC) to liquid nitrogen temperature (T_{cooled} = -196ºC), the resistivity of copper coils drops eight folds, resulting in a theoretical SNR improvement of 2.82 times considering that the copper loss is the dominant loss factor in most microscopy coils.

EXPERIMENTAL

The cryo-cooling microfluidic device is composed of three parts: a spiral surface microcoil, a cryo-microfluidic channel, and an imaging surface structure (Figure 1).

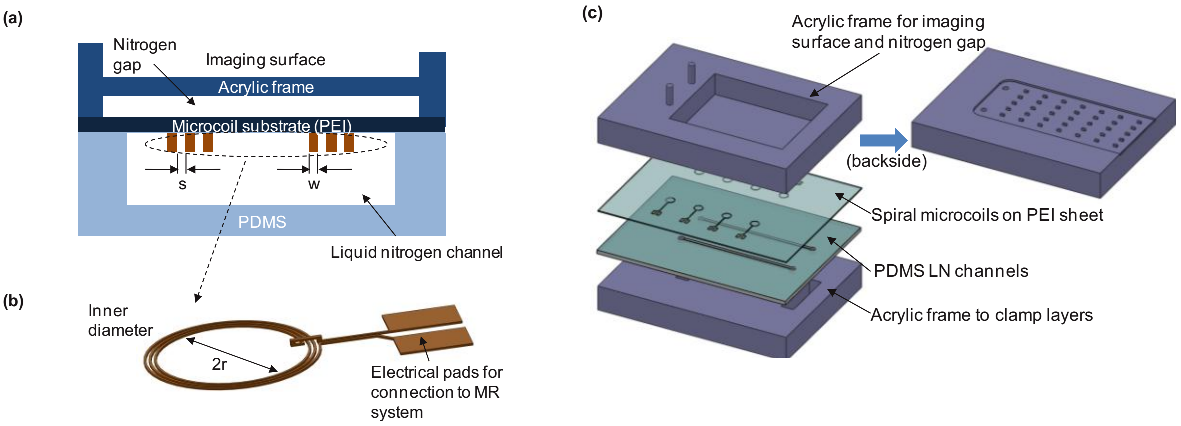

Figure 1: Schematics of the cryo-cooling microfluidic device with integrated MR surface microcoils. (a) Cross section view of the integrated device. (b) Spiral coil: r is the inner radius, w the trace width, s the spacing between traces. (c) Illustration showing each layer composing the device.

The imaging surface structure on which target samples can be placed had a 1 mm nitrogen gap between the surface and the coil substrate through which nitrogen gas could flow, disturbing the heat transfer and convection, hence functioning as an insulation layer. Simulation through finite element method (FEM)-based models (COMSOL Multiphysics®) shows that the temperature of the imaging surface is kept above the water freezing temperature of 0ºC (Figure 2).

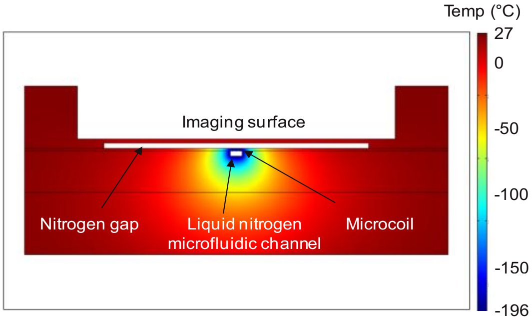

Figure 2: FEM simulation result showing the temperature gradient of the device during cryo-cooling.

A microcoil with a thickness of 25 µm was fabricated on a 0.5 mm polyetherimide (Ultem® PEI) substrate through copper electroplating (Figure 3a). This polymer substrate has lower thermal conductivity (0.22 W/mK) than silicon (1.6 W/mK) or glass (1.1 W/mK). Three-turn coils (2 mm inner diameter) with 40 µm width and 30 µm spacing were designed by referring to the coil dimension which Massin *et al.* fabricated for micro scale NMR spectroscopy [3]. The microfluidic channel structure was fabricated with poly(dimethylsiloxane) (PDMS) through soft-lithography (Figure 3b), which will locally cryo-cool the microcoil with minimum use of liquid nitrogen. Then the microfluidic channel structure was permanently bonded to the microcoil substrate using O_2 plasma treatment. An acrylic frame having the imaging surface and the 1 mm high nitrogen gap was fabricated in an acrylic block using a rapid prototyping machine (MDX-40). For the final assembly step, the acrylic frame and the microcoil substrate were tightly clamped using non-magnetic plastic screws and the integrated device was connected with polyethylene tubing through which liquid nitrogen was supplied from a 20 liter dewar. After a phantom filled with 0.1% cupric sulfate solution ($CuSO_4$) was placed on the imaging surface of the device, the device was ready for testing [4].

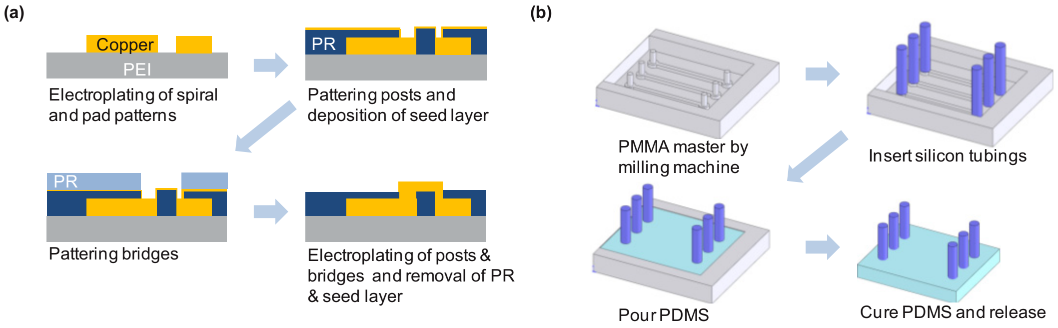

Figure 3: Fabrication steps for the (a) spiral coil and (b) cryo-cooling microfluidic channel structure.

RESULTS AND DISCUSSION

The fabricated microcoils and the integrated device are shown in Figure 4. Temperature change of the imaging surface was measured while supplying liquid nitrogen through the microfluidic channel and flowing nitrogen gas through the nitrogen gap that separated these microcoils from the imaging surface. Figure 5 shows successful thermal isolation of the imaging surface during cryo-cooling.

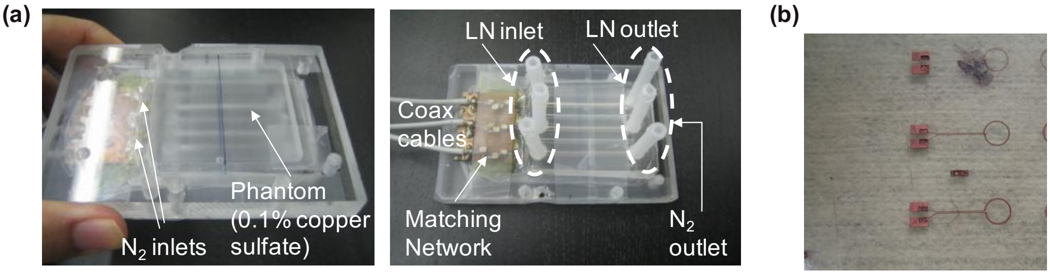

Figure 4: (a) The integrated device and (b) the fabricated spiral microcoils

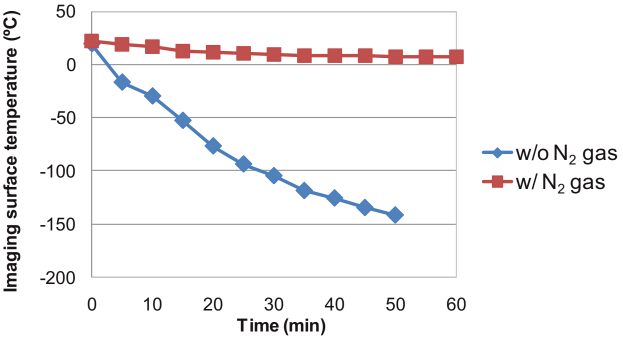

Figure 5: Temperature profiles of the imaging surface with and without nitrogen gas flowing through the nitrogen gap.

The resistance of the fabricated microcoils was characterized at room and liquid nitrogen temperature by using a multimeter (Fluke 8840A), and was measured to drop 8 folds from 0.88 Ω to 0.11 Ω, directly correlating with the copper's resistivity at room and liquid nitrogen temperature. The inductance of the microcoils measured using a network analyzer (HP4395A) was 40.4 ± 3 nH at 200.128 MHz, which is the center frequency of the 4.7 T magnet used here.

The Q factor of the microcoil with a matching network was measured by the VSWR 2:1 bandwidth measurement method using the network analyzer. The Q factor was calculated according to $Q = \frac{\omega_0}{\Delta\omega}$, where $\Delta\omega$ is the bandwidth between points where the voltage response drops to 0.707 of its peak value. To measure the Q factor of the cryo-cooled microcoil with a matching network, liquid nitrogen was flowed through the microfluidic channel from a 20 liter liquid nitrogen dewar. The measured Q factor was 1.78 times higher than the Q factor of the microcoil without cryocooling, and the estimated SNR improvement was 1.3 to 1.4 folds. SNR enhancement was smaller than the theoretical value of 2.82 times (according to Eq. 1). This is because the matching network was not optimized and not cryo-cooled as well as because the resistance of the network was still higher than just the microcoil's resistance, resulting in lower Q factor enhancement of the overall microcoil system.

CONCLUSION

A cryo-cooling microfluidic device for MR microscopy was developed and it was demonstrated that the Q factor of the cryo-cooled microcoils could be improved. The device effectively cooled the microcoil and made it possible to minimize the distance between the coil and the imaging surface without freezing samples on the imaging surface. As the SNR increase is roughly proportional to the square root of the Q increase, we would expect an SNR increase in the range of 1.3 to 1.4, a potentially significant improvement. The next step in this work is to evaluate the SNR improvement of the coils.

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