Available online at www.sciencedirect.com
ScienceDirect
Methods 43 (2007) 54–67
METHODS
www.elsevier.com/locate/ymeth

Technical aspects: Development, manufacture and installation of a cryo-cooled HTS coil system for high-resolution in-vivo imaging of the mouse at 1.5 T

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Accepted 27 March 2007

Abstract

Signal-to-noise ratio improvement is of major importance to achieve microscopic spatial resolution in magnetic resonance experiments. Magnetic resonance imaging of small animals is particularly concerned since it typically requires voxels of less than $(100\ \mu m)^3$ to observe the small anatomical structures having size reduction by a factor of more than 10 as compared to human being. The signal-to-noise ratio can be increased by working at high static magnetic field strengths, but the biomedical interest of such high-field systems may be limited due to field-dependant contrast mechanisms and severe technological difficulties. An alternative approach that allows working in clinical imaging system is to improve the sensitivity of the radio-frequency receiver coil. This can be done using small cryogenically operated coils made either of copper or high-temperature superconducting material. We report the technological development of cryo-cooled superconducting coils for high-resolution imaging in a whole-body magnetic resonance scanner operating at 1.5 T. The technological background supporting this development is first addressed, including HTS coil design, simulation tools, cryogenic mean description and electrical characterization procedure. To illustrate the performances of superconducting coils for magnetic resonance imaging at intermediate field strength, in-vivo mouse images of various anatomic sites acquired with a 12 mm diameter cryo-cooled superconducting coil are presented.

Keywords: Superconducting; Coil; In-vivo; Micro-imaging; Mouse; Whole-body

1. Introduction

1.1. SNR and spatial resolution

Signal-to-noise ratio (SNR) is most important in biomedical magnetic resonance (MR) applications and must be maximized to achieve high spatial-resolution images within conveniently short acquisition times. The SNR stands for the total amount of detected MR signal normalized to the overall noise power involved in the MR experiment. The contribution of the radio-frequency (RF) coil that detects the MR signal to the achievable SNR for a given experimental protocol is represented by the RF sensitivity factor of the coil, S_{RF}, expressed as:

$$S_{RF} = \frac{\omega(B_1/I)}{\sqrt{4k_B R_{eq} T_{eq}}} \tag{1}$$

k_B is the Boltzman's constant. B_1/I is defined as the magnetic coupling coefficient of the coil and represents the magnetic field it produces per supplied unit current when used as a transmission coil. The term $R_{eq}T_{eq}$ is the sum of the equivalent, temperature-weighted, noise resistance induced in the coil. It represents the total noise power involved in the MR experiment. The main sources of noise that primarily limit the SNR in MR imaging (MRI) are the internal noise of the RF coil and the noise inductively

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1046-2023/$ - see front matter
doi:10.1016/j.ymeth.2007.03.011

coupled to the coil by the sample [1]. For most routine MRI applications, as large regions of interest are observed with large copper coils, a sufficient amount of MR magnetization is carried in each encoded elementary volume (voxel). The resulting MR signal overcomes the overall noise power and a high SNR is obtained. In MRI of small rodents, very small structures have to be observed and high spatial-resolution images are then required to assess the information contained at microscopic scale and to avoid partial volume effect [2]. The voxel size reduction produces a strong decrease of the MR signal and consequently reduces the achievable SNR.

1.2. Static field consideration

To address this sensitivity problem, an early solution has been to increase the static field intensity of MR scanners. High-field scanners achieve a high SNR because of the frequency-dependent, linear increase of the nuclear magnetization. High-field systems have been widely used for small animal microscopy in many biomedical applications [3,4] calling to reduced-size equipment. Microscopic voxel encoding is also facilitated due to higher gradient strengths currently available with small-scale systems. Such MRI scanners with field strengths now reaching 17.6 T have been successfully developed to perform in-vivo mouse microscopy [5–8].

However, MR experiments with high-field systems presently have some drawbacks regarding the expensive cost of the MRI unit, safety considerations, non-uniform penetration of the RF field and technological constraints imposed to the rest of the hardware. Increasing the static field intensity also affects the relaxation mechanisms of biological tissues leading to MR images that present radically modified contrast and may not be usable to perform biomedical analysis to be transposed to human investigations on lower-field whole-body systems. In addition, other frequency dependent effects, such as chemical shifts or field gradients induced by local susceptibility differences inside the sample, may produce significant image artifacts and disallow accurate MR signal quantification.

Beside the continuous development of very high-field systems, few recent in-vivo MRI investigations on small rodents were preferably conducted at commonly used intermediate field strengths (1–3 T). Indeed, commercially available whole-body scanners are now equipped with enhanced gradient systems with amplitudes exceeding 50 mT/m. In this field range, contrast mechanisms are familiar to those encountered in clinical applications and standard imaging protocols can be easily transferred from mouse to human imaging. Valuable images with microscopic spatial resolution were demonstrated at 3 T for rat brain studies [9]. At 2 T, evaluation of atherosclerotic plaque development in the aorta was made possible using a contrast-enhanced protocol with isotropic voxel size of 90 μm [10]. The entire mouse was also imaged at 1.5 T using a specifically designed RF coil to improve the sensitivity of the MRI experiment [11]. Another advantage of MRI at intermediate field strength is the wide bore providing spare room for animal handling or additional RF accessories such as cryo-cooling equipment. Recent developments of parallel imaging techniques have allowed to benefit from the spare room and implement multiple-mouse imaging strategies [12,13].

1.3. Coil improvement

An alternative solution to the high-field approach is to improve the sensitivity of the RF detection coil. Primarily, this can be done using smaller coils that detect both a higher signal coming from a stronger magnetic coupling with the sample and a lower noise coming from a smaller volume of tissue viewed by the coil. The use of micro-coils is particularly advantageous for very small samples investigated at high-field strengths [14–16]. However, sensitivity improvement provided by the coil size reduction is very efficient as far as the sample-induced noise is dominant over the internal coil noise. Once the floor of the coil noise has been reached, the improvement becomes less effective since it now only comes from the increase of the magnetic coupling coefficient and no longer from the reduction of the induced noise. In specific MRI applications such as micro-imaging with small rodents at intermediate field strength, the internal noise of the coil may actually be considerably greater than the sample-induced noise, setting a strong limit to the achievable spatial resolution and SNR.

With dominant coil noise, further SNR improvement can still be achieved by using cryo-cooled MR coils, made of either copper or high-temperature superconducting (HTS) material. Cooling copper coils reduces the equivalent noise of the coil by lowering the resistance of the coil windings in addition to the direct reduction of electrical charges motion provided by the lower temperature.

Only few investigations have been reported with cooled copper coils for in-vivo imaging at intermediate field strength. Wright et al. [17] used a 10 mm radius surface copper coil cooled to 77 K for in-vivo imaging of the human finger at 1.5 T, leading to a SNR gain of 2.4–3 depending on the position for signal measurement. This study also demonstrated the potential interest of such a coil for small rodents imaging, achieving a SNR gain up to 2.5 on rabbit eye images acquired in-vivo. Wecker et al. [18] developed a liquid nitrogen (LN) cooled copper coil in view of in-vivo investigations on small animals at 7 T, already providing a SNR gain of 1.9 on phantom images. Smith et al. have employed a LN-cooled copper coil to perform mouse brain imaging at 3 T, improving image quality obtained in-vivo by a factor of 2 [19]. Very recently, a cryogenically-cooled RF detection system [20] was developed by Bruker for small animal MRI at 9.4 T and a SNR gain of 2.4 was obtained as compared to standard coil technology. However, small-sized copper coils cooled at LN-temperature may still present significant internal noise. Indeed