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Multichannel transceiver dual-tuned RF coil for proton/sodium MR imaging of knee cartilage at 3 T

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Abstract

Sodium magnetic resonance (MR) imaging is a promising technique for detecting changes of proteoglycan (PG) content in cartilage associated with knee osteoarthritis. Despite its potential clinical benefit, sodium MR imaging in vivo is challenging because of intrinsically low sodium concentration and low MR signal sensitivity. Some of the challenges in sodium MR imaging may be eliminated by the use of a high-sensitivity radiofrequency (RF) coil, specifically, a dual-tuned (DT) proton/sodium RF coil which facilitates the co-registration of sodium and proton MR images and the evaluation of both physiochemical and structural properties of knee cartilage. Nevertheless, implementation of a DT proton/sodium RF coil is technically difficult because of the coupling effect between the coil elements (particularly at high field) and the required compact design with improved coil sensitivity.

In this study, we applied a multitransceiver RF coil design to develop a DT proton/sodium coil for knee cartilage imaging at 3 T. With the new design, the size of the coil was minimized, and a high signal-to-noise ratio (SNR) was achieved. DT coil exhibited high levels of reflection S11 (~−21 dB) and transmission coefficient S12 (~−19 dB) for both the proton and sodium coils. High SNR (range 27–38) and contrast-to-noise ratio (CNR) (range 15–21) were achieved in sodium MR imaging of knee cartilage in vivo at 3-mm^3 isotropic resolution. This DT coil performance was comparable to that measured using a sodium-only birdcage coil (SNR of 28 and CNR of 20). Clinical evaluation of the DT coil on four normal subjects demonstrated a consistent acquisition of high-resolution proton images and measurement of relative sodium concentrations of knee cartilages without repositioning of the subjects during the same MR scanning session.

Keywords: Sodium MR imaging; Dual-tuned coil; Multitransceiver coil

1. Introduction

Knee osteoarthritis (OA) is a common cause of disability in the aging population. It is a complex, heterogeneous condition that is associated with degeneration of articular cartilage [1,2]. At the initial stage of OA progression, cartilage loses proteoglycan (PG) content, and subsequent changes in cartilage collagen and morphology soon follow [3–7]. Various magnetic resonance (MR) imaging methods have been proposed to detect changes in PG in cartilage at early OA, such as sodium (^{23}Na) imaging [4], proton density [8,9] and relaxation time mapping [3,8]. Since sodium atoms are closely associated with high fixed-charge density of PG sulfate and carboxylate groups of the cartilage, the measurement of sodium concentration in cartilage is reported to closely correlate to detect small variation of PG content [10].

Sodium MR imaging in vivo is technically more challenging than proton MR imaging because of intrinsically low sodium concentration, low MR signal sensitivity and fast T_2 signal decay (e.g., 2 to 10 ms in normal cartilage) [11–14]. In addition, to facilitate the use of sodium MR imaging into a clinically useful OA biomarker, it is preferred to scan both structural and sodium concentration changes of knee cartilage without repositioning the subject. Thus, for the acquisition of both sodium and proton morphologic MR images in a single setting, a dual-tuned (DT) radiofrequency (RF) coil is required [15].

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In general, a volume RF coil is preferred to achieve a high degree of field homogeneity [16], whereas a surface RF coil is superior to acquire a high signal-to-noise ratio (SNR) [17]. To take advantage of these complementary properties, a transmit-receiver array coil configuration (i.e., a receiver-array coil combined with a separated transmit volume coil) has been used in high-SNR single-nuclei MR imaging studies [18–20]. However, this two-separate-coils setting is not suitable for a DT RF coil system. Voluminous proton and sodium transmit-receiver configurations cause the DT coils to become bulky and also complicate the coupling (conductive or inductive) between different nuclei coil elements. The increased distance between the receiver coil and the object would likewise reduce the coil sensitivity. As an alternative design, a dual-frequency RF coil employing a single loop or a birdcage (BC) type has been reported [21–24]. Although this approach offers a good efficiency for both nuclei, it is geometrically constrained and does not allow for separate optimization of the proton and sodium imaging. Considering these published study results and based on our previous experiences, we postulate that the multitransceiver array DT coil technique would be optimal for imaging of the knee (a relatively small field of view of <150 mm). This technique takes advantages of both surface and volume coil effects and offers high SNR and homogeneity [20]. Thus, the purpose of our study was to develop a highly sensitive and highly efficient DT proton/sodium RF coil and interface system based on a multichannel transceiver RF design for imaging human knee cartilage in vivo.

2. Materials and methods

2.1. Coil system configurations

Wilkinson power divider (e.g., two-way and four-way divider) [25] and transmission/reception (Tx/Rx) switches were made for multitransceiver array design (Fig. 1A and B). For the proton and sodium MR imaging, a single RF power input was split into four and eight transmission outputs with an equal amplitude and phase. To improve the homogeneity

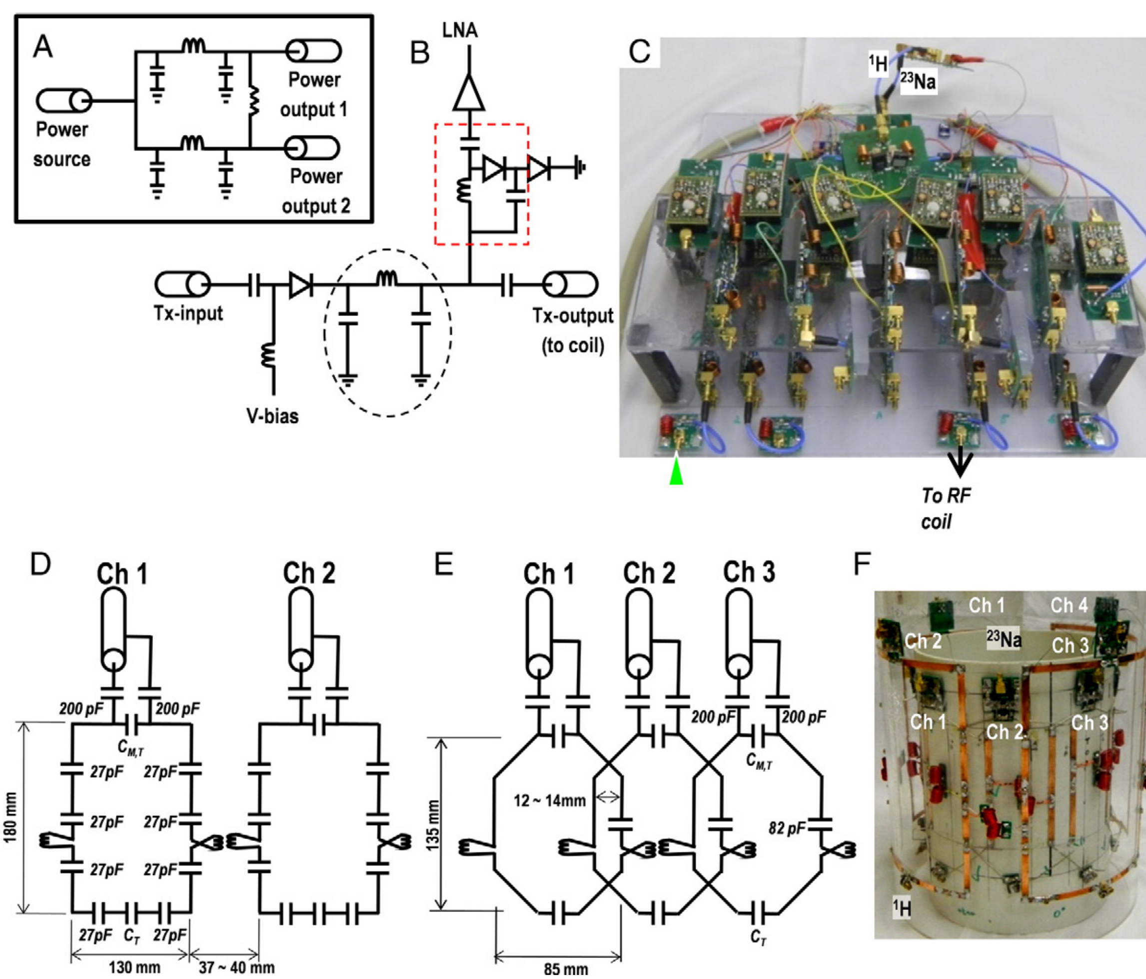

Fig. 1. Coil interface circuit. Two-way Wilkinson power divider (A) and T/R switch (B). Series resonance and band-stop filter (red-dotted rectangle) was inserted to retain high and low impedance during Tx and Rx period. Phase shifter was inserted for the in-phase betweens of Tx outputs (black-dotted circle) (B). Assembled coil interface box. Phase shifter was inserted at the terminal stage (green arrowhead) to produce CP mode (C). Four-channel proton-only coil circuit (only two channels shown) (D) and eight-channel sodium-only coil circuit (only three channels shown) (E). Assembled DT proton/sodium RF coil (F).