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Original contribution

A target field design of open multi-purpose RF coil for musculoskeletal MR imaging at 3 T

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ABSTRACT

Musculoskeletal MR imaging under multi-angle situations plays an increasingly important role in assessing joint and muscle tissues system. However, there are still limitations due to the closed structures of most conventional RF coils. In this study, a time-harmonic target-field method was employed to design open multi-purpose coil (OMC) for multi-angle musculoskeletal MR imaging. The phantom imaging results suggested that the proposed OMC could achieve homogeneously distributed magnetic field and high signal-to-noise ratio (SNR) of 239.04 ± 0.83 in the region of interest (ROI). The maximum temperature in the heating hazard test was 16 °C lower than the standard regulation, which indicated the security of the designed OMC. Furthermore, to demonstrate the effectiveness of the proposed OMC for musculoskeletal MR imaging, especially for multi-angle imaging, a healthy volunteer was examined for MR imaging of elbow, ankle and knee using OMC. The in vivo imaging results showed that the proposed OMC is effective for MR imaging of musculoskeletal tissues at different body parts, with satisfied B1 field homogeneity and SNR. Moreover, the open structure of the OMC could provide a large joint movement region. The proposed open multi-purpose coil is feasible for musculoskeletal MR imaging, and potentially, it is more suitable for the evaluation of musculoskeletal tissues under multi-angle conditions.

1. Introduction

Recently, there has been a growing interest in the multi-angle MR imaging of the joints and muscles under stress and normal conditions [1–3]. With multi-angle and (or) dynamic MR imaging, situations of musculoskeletal tissues under stress and movement can be simulated, and more structural and functional information of joints and muscles can be obtained. Furthermore, the multi-angle MR diagnosis is always desired for some patients such as arthrofibrosis patients who suffer from flexion contracture. Consequently, multi-angle MR imaging can provide better image guidance for rehabilitation of arthritis, diagnosis of muscle inflammation and other diseases [4]. Radio-frequency (RF) coil is an essential component of magnetic resonance imaging (MRI) system. The structures of most commercial RF coils for musculoskeletal MR imaging are closed [5,6], which could not provide adequate joint motion range and only be used for a specific body part. In addition, conventional closed-form RF coils could not be used for some patients with severe flexion loss or locked joints. Therefore, there is a great need for specific RF coil, which is suitable for multi-angle imaging of different musculoskeletal tissues in both clinical diagnosis and research.

In recent years, the concept of open coil has been proposed and attracted more and more attention. Actually, the structure of open coil is non-hermetic and open. It can provide greater range of movement for the musculoskeletal tissues. Meanwhile, comparing to the conventional surface coils, open coils have several vertical planes and thus increase the imaging depth and range, which are suitable for imaging of patients with special shaped joints and for multi-angle imaging based mechanics studies of musculoskeletal tissues [7]. Nevertheless, the magnetic field homogeneity of the open coil remains to be improved.

Specially, Orzada et al. [7] proposed an open, U-shaped eight-channel coil for real-time multi-angle imaging of human ankle. The coil consists of eight microstrip modules, preamplifier and matching network. Although it is feasible for real-time imaging of moving ankle joint in a wide range with high SNR, extra RF shimming system was needed to compensate the poor homogeneities in transmit field caused by open, U-shaped structure, which increases the cost and complexity of this design.

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Apart from the open RF coil, flexible coil design has also been proposed recently [6,8,9,25] and applied in the multi-angle imaging of joints and muscles. However, the former flexible coils can only be applied for imaging of a specific joint or muscle, and the magnetic field homogeneity and SNR may vary significantly under different angles [9]. These weaknesses prevent the wide application of flexible coil design for multi-angle imaging of different joints and muscles.

In this study, as an extension to the method described in Ref. [16], we improved the design of an open multi-purpose coil (OMC) using the time-harmonic target-field approach. The target field approach was firstly proposed to design gradient coil [10,11], and then it was widely used to design shimming coil [12,13] and RF coil [14–18] in MRI system. Based on the time-harmonic target-field method, various RF coils have been designed with high magnetic field homogeneity for imaging of breast, head and so on [14–19].

In this approach, the coil wire winding structure is derived from magnetic field requirement in the region of interest (ROI), ensuring the magnetic field homogeneities of designed open coil. In order to evaluate the B1 field homogeneity and SNR of the OMC, phantom imaging experiments were carried out compared with single-loop coil. To test the heating hazard of the OMC, three separate probes of a fiber optic thermometer were placed on the coil surface closed to tissues to measure temperature during scan. The in vivo imaging of the elbow, ankle, knee joint and muscle tissues of a healthy volunteer (25 years old, male) were performed and the multi-angle imaging of the elbow, ankle, knee joint and muscle tissues by self-made multi-angle support were further conducted to evaluate the SNR and feasibility of the proposed coil for various musculoskeletal imaging, especially for the multi-angle imaging.

2. Materials and methods

2.1. Design OMC with time-harmonic target-Field method

The flowchart of the theoretical model is as shown in Fig. 2.

According to the time-harmonic target-field method [16], firstly, the current densities on the surface of the three planes are expressed in terms of trigonometric basis functions with unknown coefficients. For simplification, the current density is approximately with zero divergence in the present study. The structure of OMC is shown in Fig. 1a. The direction of v is defined as the direction of x on the right plane (R), $-$x on left plane (L) and y on middle plane (M). J_v is set to be zero at the protruding boundary ($v = \pm(A+2B)/2$) of left and right planes, $J_v \neq 0$ at the joining edges ($v = \pm A/2$) of middle plane, and $J_z \neq 0$ at the top and bottom edges ($z = \pm C/2$) of all the planes. Then the current densities on the surface of the three planes can be expressed as follows with unknown coefficients a_{mn}:

$$\begin{cases} J_v(v,z) = \sum_{n=2}^{2N} \sum_{m=1}^{M} a_{mn} \sin(g_n v) \sin(g_m z) \\ J_z(v,z) = \sum_{n=2}^{2N} \sum_{m=1}^{M} \frac{g_n}{g_m} a_{mn} \cos(g_n v) \cos(g_m z) \end{cases} \tag{1}$$

where $g_n = \frac{n\pi}{A+2B}, g_m = \frac{m\pi}{C}$, $m = 1,2,3,\ldots,M, n = 2,4,6,\ldots,2N$.

Based on the (Eq. (1)), the magnetic field at each space field point in the ROI can be derived from the time-harmonic magnetic vector potential.

$$\begin{cases} B_x(x,y,z) = \frac{u_0}{4\pi} \int_{S_0} \left\{ \frac{e^{-jkR}}{R^2} \left(jk + \frac{1}{R} \right) \left[-J_z(v_0,z_0)(y-y_0) + J_y(v_0,z_0)(z-z_0) \right] \right\} ds \\ B_y(x,y,z) = \frac{u_0}{4\pi} \int_{S_0} \left\{ \frac{e^{-jkR}}{R^2} \left(jk + \frac{1}{R} \right) [J_z(v_0,z_0)(x-x_0) - J_x(v_0,z_0)(z-z_0)] \right\} ds \\ B_z(x,y,z) = \frac{u_0}{4\pi} \int_{S_0} \left\{ \frac{e^{-jkR}}{R^2} \left(jk + \frac{1}{R} \right) \left[J_x(v_0,z_0)(y-y_0) - J_y(v_0,z_0)(x-x_0) \right] \right\} ds \end{cases} \tag{2}$$

where R is the distance from the specified space field point to a source point on the current surface

$$R = \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2} \tag{3}$$

(x, y, z) denotes a space field point in ROI and (x_0, y_0, z_0) represents a source point on the current density surface. u_0 is the magnetic permeability of vacuum. $k = \omega\sqrt{u_0 \varepsilon_0}$, ω is the angular frequency, and ε_0 is the dielectric constant of vacuum. S_0 is the distributed area of the current density on the planes.

In this study, the coil is designed to generate a relatively homogeneous field in ROI perpendicular to the main magnetic field in the z direction. We take B_x filed distribution for example and B_y field has the similar condition. For N given points in ROI, if we substitute the current density with (Eq. (1)), the B_x filed distribution can be written in matrix form as:

$$C_X \cdot a = B_X \tag{4}$$

where a symbolizes the column vector of the unknown coefficients in (Eq. (1)), and B_X represents a column vector of magnetic field values along the x-axis of all the N space field points. C_X denotes the matrix derived from (Eq. (2)) after extracting the unknown coefficients.

For solving the unknown coefficients of the current density, an object function is constructed with respect to the total least square

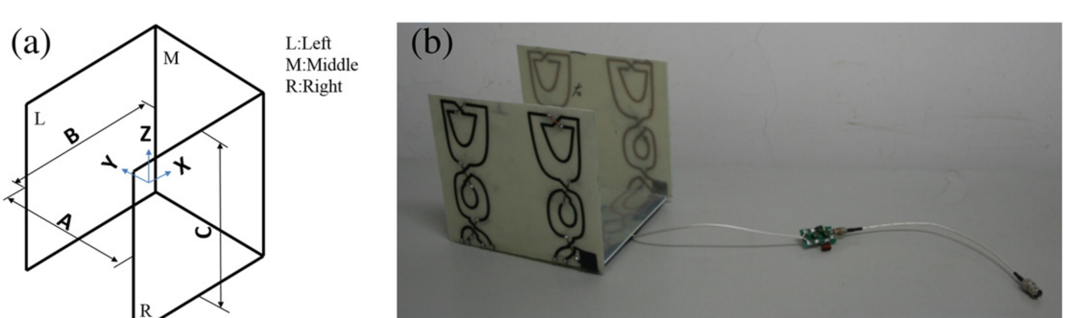

Fig. 1. (a) The structure of the open multi-purpose coil. (b) Photograph of the proposed OMC (10 cm × 10 cm × 10 cm).