Design of a 13-Channel Hybrid Array System for Foot/Ankle Magnetic Resonance Imaging at 7T/300MHz

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Abstract—Microstrip lines are being used in MR applications due to their unique properties, such as reduced radiation loss, high-frequency capability, and reduced perturbation of sample loading to the RF coil compared to conventional coils. Here, we present the design of the 13-channel hybrid array consisting of 12 Microstrips, 1 volume half birdcage coil placed on the foot/ankle phantom, and high permittivity materials to cover the maximum area of the subject at 7T/300MHz. We demonstrate using electromagnetic simulations, magnetic field distribution, SAR performance, and the coupling performance of the array elements. This work provides an ultrahigh field multichannel RF solution to lower extremity MR imaging with excellent imaging coverage and field uniformity.

I. INTRODUCTION

Magnetic resonance imaging (MRI) \cite{1, 2} is widely used to detect various abnormalities, injuries, and diseases in bones and soft tissues, such as cartilage degeneration, bone marrow edemas, osteoarthritis, osteoporosis, and ligament/tendon injuries \cite{3-15}. The Magnetic resonance imaging modality has the upper hand in the early detection of abnormalities related to bones and soft tissues \cite{16-26}. The Ultra-high field MRI imaging at static magnetic fields greater than or equal to 7T (≥300 MHz) offers increased Signal-to-noise ratio (SNR) and spatial and contrast resolution \cite{27-43} but also has some drawbacks related to physiological side effects, increased specific absorption rate, challenges in RF hardware design, image degradation artifacts and heavy computations resulting from advanced data \cite{10, 11, 39, 44-62}. Most MRI scanners used for MR foot/ankle imaging operate at 1.5 or 3 Tesla. The development of new RF systems and scanners operating at ultra-high field strength is increasing rapidly due to the promise of signal-to-noise ratio (SNR) gain \cite{8, 57, 63}. Given the critical role of RF transceiver arrays in SNR, irregular geometry of the anatomy, and complexity of RF magnetic field (B1) at ultrahigh fields, it is crucial to develop efficient RF coil array systems for foot/ankle imaging with sufficient B1 homogeneity and coverage in the specific area of interest while reducing the local specific absorption rate (SAR) \cite{55, 64-68}. There are very few foot array coils available for UHF MR imaging, and the available array coils fail to produce uniform field distribution in the geometrically irregular human foot. To address the disadvantage mentioned above, we propose to design the 13-channel hybrid array system for foot imaging at 7T using mixed array elements of microstrip resonators and half-volume birdcage coil. Additionally, we used the high dielectric material’s quality to manipulate the B1 field distributions to produce the uniform field distribution in the human foot-shaped phantom.

Microstrip transmission lines (MTL) are promising in high-frequency RF coil designs for MR applications at ultrahigh fields due to their unique advantages such as reduced radiation loss, distributed-element circuit, high-frequency capability, and reduced perturbation of sample loading to the RF coil in high-frequency range over conventional coils \cite{58, 66, 69-83}. Microstrips are purely distributed and consist of a thin strip conductor, which can be silver or copper. Microstrip has a ground plane separated from the strip conductor by a low-loss dielectric material with a certain thickness. Microstrips provide a higher Q-factor and excellent decoupling performance over the conventional loop coils, require no shielding, have lower costs, and are easy to fabricate \cite{44, 45, 77, 82, 84-88}. The frequency of the conventional MTL resonator can be calculated using the following equation \cite{44, 45, 81, 85, 86, 89-91}:

\[ f_r = \frac{nc}{2L\sqrt{\varepsilon_{eff}}}, (n = 1,2,3...). \]

The capacitively terminated MTL resonators are similar to the conventional MTL resonators. The termination capacitors can be connected to either one or both ends of the conductor. The termination capacitors increase the electrical length,
making the microstrip line resonate at the desired frequency [44, 45, 82, 84-88, 92].

The following equation is used to calculate the effective dielectric constant of the MTL:

$$\varepsilon_{\text{eff}} = \left[ 1 + \frac{H_1 - H}{H}(\sqrt{\varepsilon_r} - 1)(\xi^+ - \xi^- \ln \frac{W}{H})^2 \right]$$

Where

$$\xi^+ = \left(0.5173 - 0.1515 \ln \frac{H_1 - H}{H}\right)^2$$

$$\xi^- = \left(0.3092 - 0.1047 \ln \frac{H_1 - H}{H}\right)^2$$

The characteristic impedance of the MTL is calculated using the following equation:

$$z_0 = \frac{60}{\sqrt{\varepsilon_{\text{eff}} \ln \frac{H}{W}}} \Xi + \sqrt{1 + \left(\frac{2H}{W}\right)^2}$$

Where

$$\Xi = 6 + \frac{2(\pi - 3)}{\exp\left(30.666H\right)^{0.7528}}$$

Where W is the width of the strip conductor, H is the height of the substrate.

Finally, the resonant frequency of the MTL resonator terminated by one capacitor is calculated by using the following equation:

$$f_r = \frac{-1}{2\pi Z_0C_t} \tan\left(\frac{2\pi l\sqrt{\varepsilon_{\text{eff}}}}{c}f_r\right)$$

And the resonant frequency of the MTL resonator terminated on both sides is calculated using the following equation:

$$f_r = \frac{(2\pi f_r Z_0)^2 C_t C_{t1} - 1}{2\pi Z_0(C_t + C_{t1})} \tan\left(\frac{2\pi l\sqrt{\varepsilon_{\text{eff}}}}{c}f_r\right)$$

$Z_0$ is the characteristic impedance, $\varepsilon_{\text{eff}}$ is the effective permittivity, $l$ is the length of the strip conductor, and $C_t$ & $C_{t1}$ are the termination capacitors [45].

There are various types of RF coils that can be classified based on the working principle. One of the most commonly used RF coils is Birdcage volume coils. The birdcage coil provides excellent signal-to-noise ratio and B1 field uniformity and is considered safe for MRI applications. A birdcage coil consists of two circular rings called end rings and are connected by several legs or rungs of equal length. The end rings and legs are made of a conductive material, and the legs have capacitors connected to them. The birdcage coil can be tuned at its resonant frequency by selecting the appropriate capacitors [64, 93-96].

II. METHODS

Twelve capacitively terminated microstrip transmission lines[44, 45, 84, 85] and one half-birdcage volume coil[64, 93-100] make up the proposed improved version. The dimensions and material properties of the human foot/ankle-shaped phantom were altered to match the human foot closely. We used eight 11.6 cm long microstrips arranged in a circular pattern over the ankle area of the human foot/ankle-shaped phantom. The other four microstrips were 20 cm long and placed over the metatarsal and phalanges regions of the phantom's human foot/ankle. We used a single half-birdcage coil to replace the surface coils and wrapped it around the heel of the human foot/ankle-shaped phantom. For all microstrips, the strip conductor width is 1 mm, the substrate width is 1 cm, and the substrate height is 1 cm. 7 rungs/legs and two end rings make up the half-birdcage coil. Each leg measures 9.2 centimeters in length and 1 centimeter in width, and the end rings are 4mm in diameter. Below the foot phantom, we added a 4 mm thick dielectric layer [101-105]. The simulation model’s layout and design are shown in the following diagrams.

Fig. 1 (a) The Geometry of the modified Human foot/ankle-shaped phantom and dimensions. (b) The structure of the 13-channel hybrid array system.
The capacitors were added using lumped elements, and each channel was excited using lumped ports. The circular arrangement of microstrip lines was excited with equal amplitude and a phase difference of 45° for each microstrip line. The metatarsal and phalangeal microstrip lines were excited with the same amplitude with no phase difference. The half-birdcage coil's legs were excited with the same amplitude and a 45° phase difference. Two 6.15pF termination capacitors were used to tune the 11.6 cm long Microstrip lines to 300MHz, and two 2.7pF termination capacitors were used to tune the 20cm long Microstrip lines at 300MHz. The capacitor values for the microstrip lines were tested using the Microstrip resonant frequency calculator. We evaluated the dielectric sheet's performance at the following relative permittivity values: 300, 500, 700, and 1000. The magnetic field distribution, decoupling performance, and SAR studies of the 13-channel hybrid array device were tested using electromagnetic simulations with and without the dielectric sheet.

**A. Substrate**

The material used as the substrate for the MTL resonator is commercially available as RO4003C Laminate. The dielectric material properties of the substrate were $\varepsilon_r = 3.38$, $\sigma = 0$ s/m.

**B. Phantom**

In our simulation model, we used one human foot/ankle-shaped phantom. The dielectric material properties were set to $\varepsilon_r = 39$, $\sigma = 0.49$ s/m to reflect the human foot/ankle properties. Figure 1 shows the model using the human foot/ankle-shaped phantom.

**C. High Dielectric Sheet**

We placed a high dielectric sheet with a thickness of 4mm below the foot phantom to evaluate the dielectric sheet's effect on the field distributions. The high dielectric sheet's relative permittivity was varied to test the array system's performance at different values. Figure 1 shows the dielectric sheet placed beneath the foot/ankle phantom.

**D. Simulations**

We performed electromagnetic simulations using COMSOL Multiphysics software. We computed the frequency domain method to compute our array system's frequency response at 7T/300 MHz. Coupling performance and Specific absorption rate were also calculated using simulation studies.

**F. Data Analysis**

We exported the B field maps, current density plots, and S-parameters directly using COMSOL Multiphysics software. The magnetic field distribution was displayed using the following expression:

$$20 \times \log_{10}(\text{emw. norm}B)$$

The current density plots were constructed using the following expression:

$$\text{emw. norm}J$$

Finally, the S-parameters were evaluated using the following AWE expression:

$$\text{abs} (\text{comp1.emw.S21})$$

**III. Results**

**A. Decoupling Performance/ S-parameters Evaluation**

We tested the coupling between microstrip lines in a circular and planar configuration. We used two microstrip lines in this experiment, but only one was excited while the other was held as a passive element. In the circular arrangement, the gap between neighboring microstrip line elements was 2.7 cm, while in the planar configuration, it was 1.9 cm. The S11 and S21 parameters for circularly placed microstrip lines were -41.5 and -43 dB, respectively. In planar positioning, the S11 and S21 parameters for microstrip lines were -38 and -26 dB, respectively. Our findings demonstrate excellent decoupling between the Microstrip transmission line channels without using any decoupling techniques.
Fig. 3. The decoupling performance of the MTL resonators in a circular configuration. (a) $S$ parameters evaluation (b) Electric fields, (c) magnetic fields, and (d) currents induced in the passive element from the active component.

Fig. 4. The decoupling performance of the MTL resonators in a planar configuration. (a) $S$ parameters evaluation (b) Electric fields, (c) magnetic fields, and (d) currents induced in the passive element from the active component.

C. Magnetic Field Distribution

The magnetic field distribution in decibels was shown on a logarithmic scale. The following equation was used: $20 \log_{10}(\text{emw. } \text{normB})$. Our findings indicate that a dielectric layer with a high dielectric constant increases $B_1$ field uniformity. Magnetic field distribution and coverage were significantly improved using dielectric sheets with relative permittivity of $\varepsilon_r$: 500 and 700. However, as the relative permittivity value is increased further to an acceptable value, the findings show that any field cancellation is developing in the region of interest. As a result, determining the dielectric sheet's suitable relative permittivity [101-105] is crucial.

Fig. 5 Magnetic field distribution produced by the proposed 13-channel hybrid array system with (a) No dielectric sheet (b) dielectric sheet, $\varepsilon_r$: 300 (c) dielectric sheet, $\varepsilon_r$: 500 (d) dielectric sheet, $\varepsilon_r$: 700 (e) dielectric sheet, $\varepsilon_r$: 1000

Fig. 6 Axial slices of the Magnetic field distribution in the human foot phantom produced by the proposed 13-channel hybrid array system with (a)
No dielectric sheet (b) dielectric sheet, \(\varepsilon_r: 300\) (c) dielectric sheet, \(\varepsilon_r: 500\) (d) dielectric sheet, \(\varepsilon_r: 700\) (e) dielectric sheet, \(\varepsilon_r: 1000\)

**D. Specific Absorption Rate**

![Image](image_url)

Fig. 7 Specific Absorption Rate map in a sagittal slice of the human foot/ankle-shaped phantom produced by the proposed 13-channel hybrid array system with (a) No dielectric sheet, (b) dielectric sheet, \(\varepsilon_r: 300\) (c) dielectric sheet, \(\varepsilon_r: 500\) (d) dielectric sheet, \(\varepsilon_r: 700\) (e) dielectric sheet, \(\varepsilon_r: 1000\).

The specific absorption rate induced in the area of interest, the human foot phantom, was evaluated using electromagnetic simulations. The expression used was as follows: \((\text{emw. SAR})\). The local SAR values are under the permissible FDA guideline limits, and hence, the proposed array can be considered safe for Ultrahigh field MR applications.

**IV. CONCLUSION AND DISCUSSION**

We designed and simulated a novel RF coil array system for ultra-high field foot/ankle magnetic resonance imaging applications in this study. According to the findings, our designed array system could produce magnetic field distributions that covered the whole region of interest. As capacitively terminated microstrip transmission lines are arranged in an array, they exhibit excellent decoupling efficiency. In addition, the 13-channel hybrid array system’s magnetic field coverage and uniformity were increased by using a high dielectric sheet. In the future, Bench tests may be carried out by building array systems and testing their success in a realistic setting. Accurate safety studies could help make more design changes. To improve the field distributions, individual analysis can be performed to precisely calculate the relative permittivity of the dielectric sheet used in the array system.

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