Three-Line Microstrip Array for Whole-Body MRI System at 7 T

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Abstract: This paper proposes the use of a triple-line microstrip array for transmitting a magnetic field ($|B_{1+}|$) into the whole body for magnetic resonance applications at ultra-high field strength, such as 7 T. We explored some technologies that can potentially be applied for whole-body 7 T magnetic resonance imaging, as there is ongoing research on this topic. The triple-line microstrip transmission line (t-MTL) array consists of 32 channels. Each channel has a t-MTL, comprising a main conductor line and two adjacent coupled lines. The adjacent lines are not connected directly to the source. This configuration resulted in increased intensity and a centered $|B_{1+}|$-field. We compared the proposed structure and some reference radiofrequency (RF) transmitters, such as a patch antenna, using a magnet bore as a waveguide and a whole-body birdcage coil. We evaluated the performance of the t-MTL using cylindrical phantoms. We computed the $|B_{1+}|$-field from each RF transmitter inside a 3D human model containing more than 200 tissues. We compared their uniformity and field intensity and proposed a t-MTL array that yielded better performance. The proposed design also showed a lower specific absorption rate compared with a patch antenna.

Keywords: MRI; three-line microstrip array; RF transmitter; full-body MRI

1. Introduction

Magnetic resonance imaging (MRI) has been a useful tool for diagnosing health problems and studying the functions of the human body [1–3]. MRI technology has continued to improve to achieve better image resolution and reduce the scan time. As a result, studies on the use of MR scanners, such as 7 T, are increasing. As these strong main magnetic ($|B_0|$)-field systems receive approval by the safety authorities for clinical use, some aspects of the radiofrequency (RF) transmission and hardware still need to be investigated, such as the use of whole-body systems [4–7].

The use of whole-body MRI (wb-MRI) has been recommended for early cancer detection [8], bone marrow malignancies [9], angiography, and cardiac function [10,11]. To obtain these types of images, an RF transmitter that can produce a uniform magnetic ($|B_{1+}|$)-field across the whole body is necessary. In addition to a uniform $|B_{1+}|$-field, the RF transmitter should also exhibit lower energy absorption in the body (specific absorption rate (SAR)), which is the main reason that 7 T MRI systems are not yet fully approved for clinical use.

A birdcage coil is one of the reference systems for imaging at a lower field strength of 4 T and below, as it can produce a uniform $|B_{1+}|$-field. However, at 7 T, the field produced by the birdcage coil decreases, given that the operational frequency is higher, and thereby reduces the wavelength. The reduction in the wavelength is further affected by interaction with human tissues [12,13].

One method that has been proposed for whole-body imaging at higher frequencies is the use of patch antennas and waveguide with the bore of a magnet [14,15]. However, this technology depends on the geometry and the modes that can be created. The use of microstrips for 7 T MRI has also been proposed, which has shown promising results [16,17].

In this study, we investigated the use of a modified conventional microstrip line set in an array configuration. We proposed the use of a triple-line microstrip-transmission line (t-MTL) in which the main line is connected to a voltage source and the adjacent lines are
coupled. As a result, the transmitted field can be increased in a wider area. We compared the performance of the proposed array with those of the reference birdcage coil and the traveling wave antenna. The use of a triple-line t-MTL is a novelty application for MRI, as it has only been applied for microwave line couplers. The use of the MTL array has the advantage that it allows adjustment to the magnetic field propagation, so that it can be more uniform when it interacts with the human tissues.

The paper will first introduce the theory of t-MTL, followed by a comparison between different configurations to demonstrate the reason for the design. The second part of the method section describes the array of the triple-line microstrips compared with two other configurations: a travel wave patch antenna and a whole-body birdcage coil. We present the $|B_1^+|$-fields from each configuration in the results section.

2. Methods

In this study, we investigated a new design for a microstrip array for the whole body using a 7 T MRI system and compared it with existing whole-body RF transmitters. The t-MTL consists of a ground plate, a dielectric material, and a conventional conductor line to which the voltage source is connected. However, in our design, we included additional lines next to the main TL. The adjacent lines are highly coupled to the main line, and the proposed design is expected to increase field propagation uniformity. One of the adjacent lines is terminated with a short circuit to increase the field strength. The two adjacent lines are not connected to the source voltage. The use of a t-MTL array has been previously proposed and analyzed as line couplers for microwave applications [18,19]. The solution to the TL equations is obtained from the above study using a $3 \times 3$ matrix. The voltage $[V]$ and current $[I]$ equation is given by

$$\frac{d[V]}{dx} = -[z][I]$$

where $[z]$ represent the $3 \times 3$ matrix of the impedance of the line, and the solution to this equation is found in [20].

Here, we modified the matrix structure to indicate that the center line is the one carrying the current, as depicted in Figure 1, with the tag L1.

$$z = \begin{bmatrix}
z_{11} & z_{12} & z_{12} \\
z_{12} & z_{22} & z_{23} \\
z_{12} & z_{23} & z_{22}
\end{bmatrix}$$

The solution is given as

$$\gamma_1 = z_{22} - z_{23}$$

$$\gamma_2 = \frac{z_{11}}{2} + \frac{z_{22}}{2} + \frac{z_{23}}{2} - \frac{1}{2} \sqrt{z_{11}^2 - 2z_{11}z_{22} - 2z_{11}z_{23} + 8z_{12}^2 + z_{22}^2 + 2z_{22}z_{23} + z_{23}^2}$$
\[
\gamma_3 = \left[ \frac{z_{11}}{2} + \frac{z_{22}}{2} + \frac{z_{23}}{2} + \frac{1}{2} \sqrt{z_{11}^2 - 2z_{11}z_{22} - 2z_{11}z_{23} + 8z_{12}^2 + z_{22}^2 + 2z_{22}z_{23} + z_{23}^2} \right]
\] (5)

An analysis of the coupling of the t-MTL array can be found in [21,22]. In the case of antennas and couplers, the use of t-MTLs was found to be useful for combining two signals into one without any interaction with the signal source. However, by reciprocity, the radiated field can reach a larger area in a constructive manner in the present application for MRI. The \(|B_1^+|\)-field required for transmission in MRI is given by the x- and y-components of the magnetic field as follows:

\[
B_1^+ = B_x + jB_y
\] (6)

Figure 1 shows a single t-MTL with the corresponding geometry. It should be noted that only the center line is connected to the voltage source, and the adjacent lines are narrower by approximately 15%. The separation between the lines was included to improve coupling between the lines based on the theory in [18]. To determine the best configuration of the t-MTL that can deliver a more uniform \(|B_1^+|\)-field, we tested four different configurations to justify the use of a triple-line. The first configuration is a simple microstrip with a width of 32 mm and a length of 384 mm. Teflon was used as the dielectric material (height \(= 10\) mm, relative permittivity \(\varepsilon_r = 2.08\)); this configuration ensured resonance at 300 MHz.

The second configuration is a triple-line with a center line of 32 mm and adjacent lines of 5 mm. The lengths of the lines are 384 mm. The dielectric material is also Teflon with a height of 10 mm; in this case, all the lines were terminated with an open circuit. The third configuration consisted of terminating one of the adjacent lines with a short circuit with the same geometry as the microstrip.

We performed electromagnetic simulations to compute the \(|B_1^+|\)-field in a target area of a \(400 \times 300 \times 100\) mm block with conductivity \(\sigma\) and \(\varepsilon_r\) of 0.0764 S/m and 11.745, respectively; these values correspond to the electrical properties of fat at 300 MHz. Figure 2 shows the \(|B_1^+|\)-field for each of the cases described. For the single and wide strip line, the field distribution was off-center and focused on the right part of the line, and the mean and standard deviation of the \(|B_1^+|\)-field were 0.080 and 0.013 \(\mu\)T, respectively. For the \(|B_1^+|\)-field from the triple-line with open end shown in Figure 2b, the mean and standard deviation were 0.065 and 0.0216 \(\mu\)T, respectively. This configuration shows an improvement in the centering of the field. Figure 2c shows the \(|B_1^+|\)-field for the triple microstrip with only one adjacent line short-circuited; for this case, the mean and standard deviation were 0.070 and 0.02 \(\mu\)T, respectively.

**Figure 2.** The computed \(|B_1^+|\)-field for (a) a single microstrip, (b) the triple-line microstrip transmission line (t-MTL) with open circuit terminated, and (c) the triple-line microstrip with one line short circuited, and the field profile (d) for each of the computed \(|B_1^+|\)-fields.
It can be observed that the field is aligned to the center. Figure 2d shows the line profile for the three fields produced by the different configurations. The kurtosis metric was used to measure the alignment of the fields to the center of the phantom. For this case, the metric values were 2.66, 2.96, and 3.74, for the single microstrip line, triple microstrip line with open terminations, and triple microstrip line with only one adjacent line shorted, respectively. It can be observed that the use of one shorted line produces a better focused field to the middle of the phantom, which is desirable in MRI applications. Although the single microstrip produces higher field intensity, it has a narrower field penetration compared with the triple microstrip with only one shorted line.

We performed a phantom analysis to design the t-MTL geometry. The first study comprised an evaluation of the effect of the height of the dielectric. We used dielectric heights of 20, 30, 40, and 50 mm. We evaluated the resulting $|B_1^+|$-field inside a cylindrical phantom with electrical properties of fat, with a conductivity ($\sigma$) of 0.0764 S/m and a permittivity of $\varepsilon_r$ 11.745 at 300 MHz. The analysis is depicted in Figure 3. The field maps and the line profile plotted in Figure 3e indicate that changes in the dielectric height produced a small difference in the field intensity, with the 20 mm dielectric having the lowest field intensity and the 50 mm dielectric having the highest field intensity.

We also explored the effects of the coupled adjacent lines to the conductor line. For this evaluation, we varied the distance between the main conductor line and the adjacent coupled lines to 4, 12, and 17 mm. The field distribution for this analysis is shown in Figure 4. The field maps indicate that a larger distance between the adjacent lines and the main conductor line favor field penetration, as indicated by the plotted line profile.
We also investigated the array performance of the t-MTL, by placing eight elements around a cylindrical phantom with a radius of 120 mm and a length of 300 mm. The phantom was assigned electrical properties equal to those of fat at 300 MHz, with a conductivity ($\sigma$) of 0.0764 S/m and a permittivity of $\varepsilon_r$ 11.745. The t-MTL array was compared with a high-pass birdcage coil with a radius of 150 mm and a length of 320 mm. The birdcage coil was driven in circular polarized (CP) mode; each capacitor on the ring was considered as a voltage source, with the corresponding phase difference. Figure 5 shows the computed $|B_1^+|$-field for the cylindrical phantom and the SAR average 10 g maps. The mean and standard deviation of the $|B_1^+|$-field for the BC were 0.013 and 0.008, and for the t-MTL they were 0.015 and 0.006, respectively. The mean and maximum SAR values for the BC were 0.110 and 0.20, and for t-MTL they were 0.112 and 0.24 mW/kg, respectively.

![Figure 5](image)

**Figure 5.** Computed $|B_1^+|$-field for the (a) BC and (b) t-MTL array. SAR maps for the (c) BC coil and (d) t-MTL array.

In this study, we compared the use of three types of RF transmitters for the whole body in 7 T MRI. The two reference structures are a patch antenna using a magnet bore as a waveguide and a birdcage coil. The proposed design is an array of t-MTLs. The patch antenna used in the waveguide is depicted in Figure 6a. We used a cylinder with a length of 3000 mm and a radius of 300 mm corresponding to the bore of an MRI system. The cylinder used as the waveguide was selected as a perfect electric conductor (PEC). The patch antenna was designed to have a circular shape with a diameter of 406 mm and a dielectric height of 10 mm, corresponding to Teflon. The geometries of the waveguide were selected to produce a transverse electric TE mode at 300 MHz. The second reference RF device was designed as a whole-body birdcage coil. Although a birdcage coil is known to have deficiencies in high-frequency MRI applications, we considered it necessary to compare it with the reference. The geometry of the birdcage coil is shown in Figure 6b; it has a length of 2000 mm and a diameter of 520 mm. It is based on a bandpass type with 12 legs; each leg has a width of 30 mm and an end-ring of 30 mm.
Figure 6. The geometry of each of the array configurations for the whole body in sagittal and axial views, for the (a) patch antenna, (b) birdcage coil, and (c) t-MTL array.

The proposed array structure consists of 32 t-MTLs, distributed in four arrays along the z axis, with each array having eight elements. The elements were evenly distributed along the circumference of a circle with a diameter of 500 mm. Each t-MTL used Teflon as the dielectric material, and the length, width, and height of each element were 284, 80 mm, and 30 mm, respectively. The width of the main conductor line was 32 mm, whereas the width of the two extra conductor lines was 5 mm; the separation to the main line was 17 mm. The geometry of the t-MTL was designed following the transmission line theory equations to produce a microstrip with electrical length of 180 degrees. The distance along the z axis between arrays was 90 mm in order to ensure coverage of the whole-body model.

We used the human model, Duke, as shown in Figure 6, which is composed of over 200 well segmented tissue materials, with the values of the electrical properties corresponding to the frequency of use; the complete list of tissues with their corresponding conductivity, electrical permittivity, and tissue density values can be found in [23]. The human model belongs to the virtual family collection [24]. The model is based on a young adult of 34 years with a height of 1.77 m, a weight of 70.2 kg, and a body mass index (BMI) of 22.4 kg/m$^2$. The human model is composed of bones and soft tissue, including segmented organs such as white matter, gray matter, spinal cord, stomach, eyes, and fat. We moved the arms of the human model so they are closer to the body to avoid an empty space between the body and the arms. We also decreased the distance between the legs, as much as physically possible, in the model to ensure that the body model has a more uniform shape. The tissue models have been certified with ISO 10,974 for MR compatibility, and a model from the same virtual family has been used for validation studies on SAR for ultra-high field MRI [25,26].

In order to compare the statistics of the field maps, we will use the coefficient of variation (CV), which is a standardized measure of dispersion. The CV is computed by taking the ratio between the standard deviation and the mean.

3. Results

We computed the $|B_1^+|$-field and SAR from the human model using computer aided analysis and an electromagnetic simulator provided by the commercial software, Sim4Life (Zurich). This software used the finite-difference time-domain (FDTD) method to perform numerical analysis to find solutions to electromagnetic equations. The $|B_1^+|$-field was extracted from the human model after being excited using the patch antenna, birdcage coil, and the proposed array of t-MTLs. All simulations were performed at a central
frequency of 300 MHz and bandwidth of 600 MHz, and all the conductors were selected as a PEC. The conductors were assigned 0 mm of thickness to reduce the simulation time and increase the effectiveness of the analysis. The simulation was done with a matrix grid of $284 \times 284 \times 940$ cells. The electrical properties of Teflon used for the patch antenna and t-MTL are as follows: $\sigma$ of 0.000462 S/m and $\varepsilon_r$ of 2.08. The TE mode for the patch antenna and waveguide was selected to operate at 300 MHz. The birdcage coil was excited in a quadrature mode, the tuning was made by using ring capacitors of 0.621 pF and leg capacitors of 65 pF, for which a S11 value of -20 dB was obtained before applying a matching circuit. The simulations were normalized to an input power of 1 W. The phase difference between each t-MTL elements in the xy plane array was 45°, to make the CP mode.

Figure 7 shows the $|B_{1+}|$-field in the sagittal view (yz plane) for each of the transmission cases. The slice was selected to be off center to show the whole body. Figure 8 shows the $|B_{1+}|$-field in the axial view (xy plane) at different locations along the human model and for each RF transmitter.

![Figure 7](image1.png)

**Figure 7.** The computed $|B_{1+}|$-field inside the human model in sagittal view, for (a) the path antenna, (b) birdcage coil and (c) the array of triple-line microstrips.

![Figure 8](image2.png)

**Figure 8.** The axial view of the computed $|B_{1+}|$-field for, (a) the path antenna, (b) birdcage coil, and (c) the array of t-MTL. The left column is an axial slice on the knee, middle on the torso, and right column is a slice inside the brain.

We also computed the SAR in the whole body, as shown in Figure 9. To display the SAR map, we used a projection view of the maximum SAR value in the sagittal and axial
views. This type of display can indicate the location of the highest level of SAR produced by the respective transmitter.

**Figure 9.** The computed projected maximum SAR maps in sagittal and axial views, for (a) the path antenna, (b) birdcage coil, and (c) the array of triple-line microstrips.

Table 1 summarizes the mean and standard deviation of each $|B_1^+|$-field in Figure 7 and Figure 8, and the SAR maps in Figure 9.

| RF transmitter | Mean/CV | Mean/Max |
|---------------|---------|----------|
|               | $|B_1^+|$ [μT] | Sagittal slice/yz-plane [μT] | Axial slice/Legs [μT] | Axial slice/Torso [μT] | Axial slice/Head [μT] | SAR whole body [W/kg] |
| Patch antenna | 0.066/0.60 | 0.073/0.17 | 0.063/0.11 | 0.067/0.08 | 0.143/0.13 | 0.019/1.283 |
| Birdcage coil | 0.036/1.12 | 0.036/0.16 | 0.041/0.15 | 0.038/0.27 | 0.063/0.12 | 0.009/0.355 |
| t-MTL array   | 0.078/0.55 | 0.073/0.14 | 0.071/0.07 | 0.069/0.09 | 0.103/0.08 | 0.013/0.120 |

It can be observed from the sagittal view of the magnetic field inside the whole body that the use of the proposed t-MTL can produce a more uniform and stronger $|B_1^+|$-field compared with the patch antenna and birdcage coil. The patch antenna can deliver a uniform $|B_1^+|$-field inside the head; however, as the field propagates into the body, the intensity and uniformity are lowered. The use of a patch antenna results in a higher SAR value in the head area.

The birdcage coil also exhibits low field uniformity, as the field is highly diminished, particularly in the abdominal area. The field in the brain is centered and focused, but it has low intensity in the brain periphery.

The proposed arrangement of t-MTL can produce a uniform field with an intensity similar to that of the BC coil along the whole body; although the uniformity is not perfect, it is better that those of the reference systems. In particular, the $|B_1^+|$ field demonstrates better uniformity in the abdominal and torso area. In terms of the SAR, the proposed array of t-MTLs also exhibits lower values and smaller peak values. It should also be noted that the peak values are separated and far from each other, whereas those of the patch antenna are close to the same position. The highest values of the SAR are located near the elbows and upper legs. This is because the microstrips are close to these areas. Figure 10 shows the $|B_1^+|$ field and SAR at different positions in the body for the proposed array. Figure 10 also includes a histogram of the distribution of SAR per m$^3$ of the human model. Table 2 shows some of the SAR values for specific tissues that present a greater safety concern.
Figure 10. The computed $|B_1^+|$-field and SAR maps in axial views, for (a) the brain, (b) torso, and heart, as well as (c) the histogram of the SAR distribution per volume $m^3$ in the whole human model.

Table 2. Mean and maximum SAR.

| RF transmitter | Eyes       | Spinal Cord | White matter | Heart  | Stomach  |
|----------------|------------|-------------|--------------|--------|----------|
| Patch antenna  | 102/362    | 8.9/47.8    | 49.6/142     | 9.5/64 | 11.7/7.2 |
| Birdcage coil  | 8.1/14.0   | 1.2/6.4     | 7.2/17.1     | 1.0/6.2| 2.1/11.0 |
| t-MTL array    | 9.8/14.8   | 7.3/30.7    | 8.6/20.0     | 1.9/6.9| 5.2/18.4 |

In this work we presented only the performance of the t-MTL in terms of $|B_1^+|$-field. However, some limitations can occur depending upon the interaction of the microstrips with ground plates and the gradient coils, which can add parasite currents. We also limited our study to a generic, average-size, 3D human phantom.

The development cost of the proposed t-MTL array would match, or be lower than, that of a birdcage coil, since the amount of the acryl used to support the coil is less than the birdcage coil. The t-MTL has a planar shape that is easy to manufacture, compared to the cylindrical shape of the birdcage coil. The implementation of the microstrip array presented in this work has its resonance frequency generated from the geometry and does not require the use of lumped elements, such as capacitors, as in the case of the birdcage coil.

4. Conclusions

In this work, we proposed the use of a triple-line microstrip in an array configuration for whole-body MRI applications. We first investigated the properties of the triple-line microstrip by performing simulations using tissue phantoms. The proposed array configuration is capable of producing a field intensity slightly higher than that of the BC coil across the whole body, with better uniformity than that produced by the whole-body patch antenna and the whole-body birdcage coil. In terms of SAR, the proposed array exhibited fewer hot spots than the patch antenna, especially in the brain region. The maximum SAR can be observed in the elbow regions, since these are closer to the t-MTL elements.

Although the proposed array is not perfect, it is a viable design for whole-body RF coil development in MRI.

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