Comparison of B_1^+ Field and Specific Absorption Rate (SAR) between Birdcage, Transverse Electromagnetic and Microstrip Coil for Ultra High Field MRI at 9.4 Tesla

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Abstract— The RF coil is an essential part of MRI systems. In ultra-high field (UHF) MRI, the design of RF coils is a challenging task. The RF coil should resonate at a particular frequency (the Larmor Frequency) and must provide a highly homogeneous B_1^+ field as well. It must be safe to use by maintaining a low specific absorption rate (SAR) value. Homogeneity of the B_1^+ is a supremely important factor in MRI systems. A homogenous B_1^+ allows the spin in different mediums having different electromagnetic properties to see the same B_1^+ field value. When the field-tissue interaction takes place, the spin interacts differently in a unique manner making it possible for materials to be imaged. Generally speaking, this allows higher resolutions images with high contrast increasing therefore the sensitivity of the MRI system. The specific absorption rate is a safety indicator. It is an indicator that reflects how much electromagnetic energy is absorbed in the biological tissue. SAR value must be kept as low as possible. The task of this paper is to provide a quantitative comparison between three common volume RF coils at 9.4 Tesla. The comparison is held in terms of the homogeneity of the B_1^+ both in the loaded and unloaded cases and also as a function of the SAR. Additionally, a comparison with the performance of 7 Tesla published earlier to quantify the gain of increasing the frequency. Before comparing the coils, the coils must be built first. A novel design for each type of coils is shown. Before comparing the coils, the coils must be first built. A novel design for each type of coils is shown. The S-parameter as a clue of resonance at the Larmor frequency is presented accompanied with a comparison with measurements performed. A quantitative approach to assess the interaction between the electromagnetic fields and phantoms is provided and discussed in the context of dielectric resonance. Additional visual clues are provided. A detailed statistical study of the local homogeneity/inhomogeneity is performed. This makes it possible to conduct local field corrections, increasing therefore the homogeneity and consequently the sensitivity of the MRI system.

1. INTRODUCTION

High signal to noise ratio (SNR) and high contrast mechanism are very attractive features of UHF MRI systems [2]. On the other hand, the homogeneity (heterogeneity) of the B_1^+ field and the safety issues remains to be of major concern at high frequencies [5]. The complex structure of the human head leads to highly inhomogeneous current distribution on the coils forming therefore nonuniform B_1^+ field [8]. Consequently, different coils structures tend to have different B_1^+ field homogeneities. Another important quantity is the specific absorption rate (SAR) which has to be maintained as low as possible [1].

In this paper, a comparison in terms of B_1^+ field homogeneity and SAR is drawn between three-well known types of volume coils namely the birdcage, transverse electromagnetic TEM and microstrip coils at 9.4 Tesla; an extension to a previous work conducted at 7 Tesla [3]. The target is to establish a systematic knowledge about these types of coils as a function of field homogeneity and safety.

2. MATERIALS AND METHODS

At 9.4 Tesla the corresponding resonance of the RF coils is exactly 399.69 MHz which is the Larmor frequency [1]. Each type of the RF coils must therefore resonate at this particular frequency.

The Birdcage RF coil consists of two parallel end rings and a number of conductive rungs [2]. 16 legs with 10 mm width and 200 mm length are chosen. The end-rings are made of cooper with 10 mm width. The legs as well as the end-rings are 1 mm thick. 32 capacitors are located on each of the end-rings. With such setup resonance is possible at 400 MHz as can be seen in Figure 1. Two excitations are required and are placed perpendicularly to each other between the RF shield and the end ring. This means a 90° phase shift is required to achieve a circular polarized magnetic field. The TEM and the microstrip RF coils have totally different working principle as compared

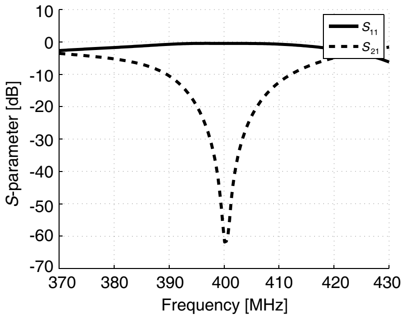

Figure 1: Resonance of the birdcage coil.

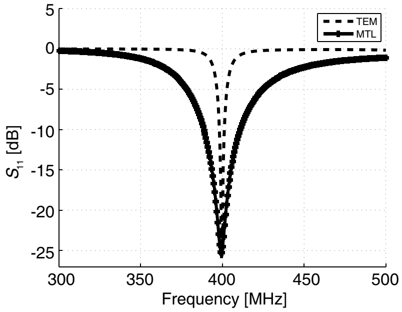

Figure 2: Resonnace of the TEM and the MTL coils.

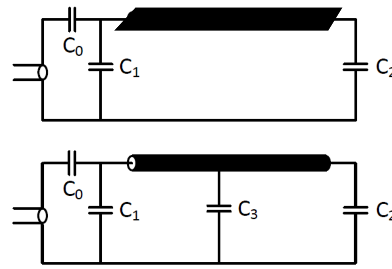

Figure 3: Equivalent circuits of the MTL (top) and TEM (bottom) coils.

to the birdcage coils. The MTL and the TEM are multi-channel RF coils [2]. The coil structure consists of a number of resonators (Figure 3) each of which is excited individually. Such structures provide in general low SAR values and allow better control over the B_1^+ field, making them very attractive for the MRI community.

The transverse electromagnetic (TEM) coil is formed of 16 cylindrical rods of copper each with 5 mm radius and 201 mm length. On each rod, an RC circuit in mounted at the end side with a resistor of 20 Ω and a capacitor of 1.95 pF. An "L-type" matching circuit is used with two capacitors of 2.2 pF and 2 pF respectively.

The microstrip transmission line (MTL) coil is composed of 16 curved strips with 180 mm length, 0.36 mm thickness and arc perimeter of 25.5254 mm placed on a cylindrical Plexiglas holder with a radius of 135 mm and 5 mm thickness. Performing the matching and the resonance was difficult. The capacitances as well as the inductances are not solely determined by the lumped elements but also with by the geometrical setup of the structure. For instance, the gap between the strips and the ground in the TEM structure is in fact a capacitor. Computing the partial inductance/capacitance for such geometry is a supremely difficult task [7]. The problem has been solved by using lumped inductors in series with the capacitors responsible for resonance. As a consequence, an RLC circuit is placed at the end side with a resistance of 50 Ω an inductor with 278.75 pH and a capacitor of 1.8 pF. An "L-type" matching circuit is used with two capacitors each with 2.45 pF. As 16 elements are used, 22.5° phase shift between the elements is required to achieve a circular polarized magnetic field. The resonances of the TEM and the MTL coils are shown in Figure 2. An 8-channels prototype for the MTL coil is shown in Figure 4. A comparison between the S_{11} parameter between the prototype and the simulated model is provided in Figure 5. A good agreement between the measurement and the simulation results is shown. The resonance for the prototype occurred at 403.84 MHz. At 400 MHz, the prototype has an attenuation of 12.7 dB.

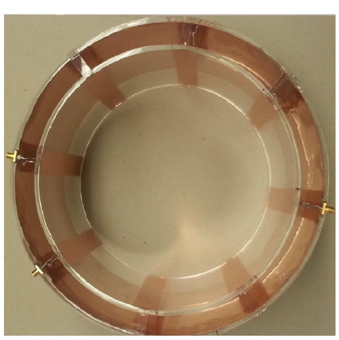

Figure 4: Eight-channels MTL RF coil prototype.

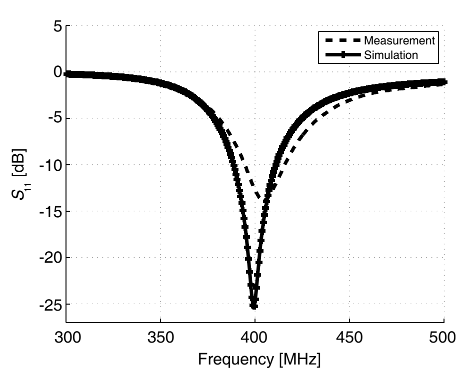

Figure 5: Comparison between simulated and measures S_{11} parameter.

3. RESULTS AND DISCUSSION

The B_1^+ field is the component of the magnetic field that rotates in a plane perpendicular to the static magnetic field in the MRI system [2, 6] and is defined as [2]:

$$B_1^+ = \frac{B_{1x} + jB_{1y}}{2}$$

To produce the desired circular polarized magnetic field, all coils are excited simultaneously with the corresponding phase shift mentioned above. Then by applying Equation (1), the 3D B_1^+ is calculated. A 2-D transversal cut of the 3-D B_1^+ field shows that indeed good levels of homogeneity are achieved, as can be observed in Figure 6. Figure 6 parts ((a), (b) and (c)) represent the unloaded case and the lower parts ((d), (e) and (f)) correspond to the loaded one. In the birdcage and the MTL coils, very strong peak appeared at the center of the phantom while for the TEM coil, the edges of the phantom shares good amount of electromagnetic energy with the center. To make the comparison clearer, the field is evaluated on a line located in the transversal plane perpendicular to the coil direction [3] with a length of 19.2 cm. The B_1^+ field is normalized over the field value at the center as suggested in [3], which is also the maximum field value. In the unloaded case, high levels of homogeneity are expected. Figure 7 provides a closer look. For the unloaded case in the birdcage, the field variation over the whole line is 3.24%. In the TEM coil, this variation reads 6.1%. In the MTL coil, the field does not change more than 11.18%.

The comparison between the field homogeneity of the three types of coils presented here (i.e., at 9.4 Tesla) are in agreement with the results for the 7 Tesla RF coils published in [3]. The birdcage coil is not only able to provide better homogeneity but also to score the highest field value of about 7.0212 Tesla. For the comparison reasons, all the B_1^+ fields calculated are normalized to 1 kW of stimulated power as referred in [2]. These results are summarized in Table 1.

Table 1: Variation of the B_1^+ field amplitude.

	9.4 Tesla		7 Tesla (Ref. [3])
Coil Type	Field Variation [%]	Maximum Value [μT]	Field variation [%]
Birdcage	3.24	7.02	15
TEM	6.12	4.50	23
MTL	11.18	4.10	38

Now, the coils are loaded with water phantoms with a diameter of 19.2 cm. The permittivity, permeability and the conductivity are maintained constant providing therefore a homogeneous medium $\epsilon_r = 81$, $\mu_r = 0.9991$ and $\sigma_e = 0.957$ (S/m). The electromagnetic field must interact with the phantom placed in the coils and consequently dielectric resonance is observed [4–6]. This results in strong maxima and minima [4, 5]. The B_1^+ field becomes locally inhomogeneous [6]. The remaining level of homogeneity is now evaluated on a local basis. Numerical electromagnetic simulators discretize Maxwell's Equations. The inherent discrete structure of the solution permits statistical

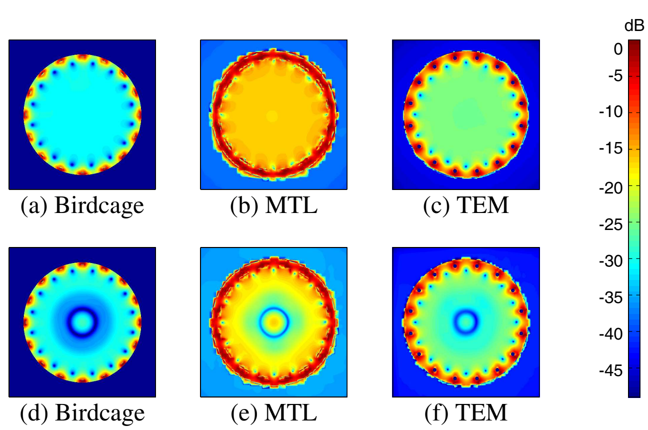

Figure 6: 2-D B_1^+ field distribution (top: unloaded, bottom: loaded).

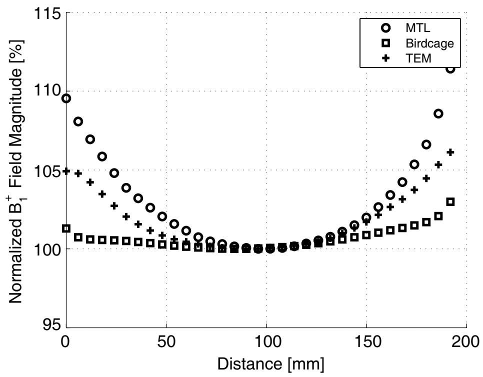

Figure 7: B_1^+ field distribution for the transversal direction for the unloaded coils.

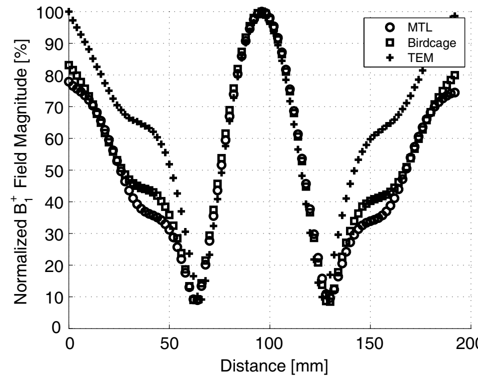

Figure 8: B_1^+ field distribution for the transversal direction for the loaded coils.

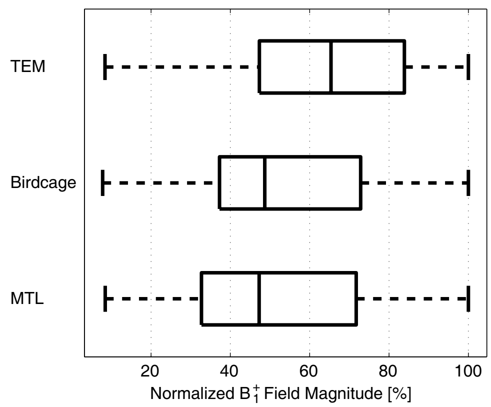

Figure 9: Statistical B_1^+ field distribution for the transversal direction for loaded coils.

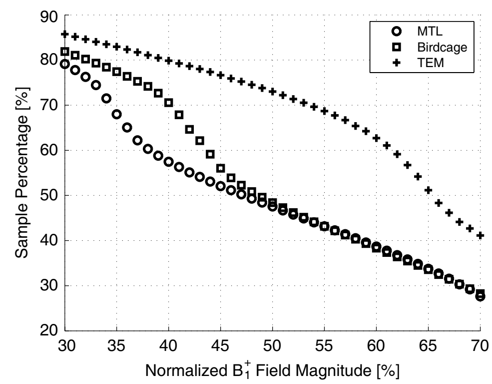

Figure 10: Performance analysis of the coils as a function of B_1^+ field homogeneity.

analysis. When a field is evaluated on a curve, it is actually sampled over this line. For statistical analysis, better induction is drawn if the number of samples is high enough. In this case, 19202 samples are considered for each coil. The distribution of the B_1^+ field amplitude as a function of the number of samples is better represented in a box plot. The birdcage and the MTL behaved similarly despite the high level of homogeneity of the birdcage in the unloaded case. This can be seen in Figures 8 and 9. The percentages of the samples having the same normalized field values share similar portion in the boxplot for the birdcage and the MTL. The birdcage is slightly better. The 75th percentile for the birdcage and the MTL are similar. So does the 25th percentile, the median and the lowest values. The TEM shows to be better in distributing the value of the B_1^+ field amplitude; the edges still have high field values. A performance analysis graph is shown in Figure 10. The idea here is simple; the x-axis shows the preserved value of the normalized B_1^+ field amplitude and the y-axis shows the percentages of the samples that were able to preserves a particular field value. Higher values mean better performance. One can see clearly that the TEM coil has the best performance followed by the birdcage and finally by the MTL coil. The TEM coil was slightly better in the low field values and much better at high field values (i.e., higher than 45% of the maximum field values). The Birdcage up to 45% of the maximum field value was better than the MTL coil. One interesting conclusion is that designing a coil with high B_1^+ field homogeneity in the unloaded cases does not necessarily imply high homogeneity in the loaded case.

The specific absorption rate or SAR is defined as the rate over which the energy is absorbed by the human body when exposed to an RF electromagnetic field. It is calculated by taking the time derivative of the incremental energy dW absorbed by an incremental mass dm contained in a volume element dV of a given mass density ρ using the following formula: $\mathrm{SAR} = \frac{d}{dt}\frac{dW}{dm} = \frac{d}{dt}\frac{dW}{\rho dV}$. A fully featured, highly detailed 'Voxel Model' with 5 mm voxel resolution is used as a phantom because the SAR is related to safety and requires as accurate modeling as possible. 50 W (rms) are fed into the coils as stimulated power. Different coils have different power acceptance capabilities giving rise to various power loss densities inside the tissues. It has been observed that the SAR value is highest close to the surface of the phantom facing the incident wave. The birdcage has the highest SAR followed by the TEM and the MTL. The Birdcage is a fully coupled structure. The electromagnetic energy is highly concentrated in spots also called 'hot spots'. As the SAR is proportional to the electric field, coils must de-emphasize the electric field for the sake of the magnetic field. The TEM coil acting as a transmission line, appears to have uncontrolled interference of the electric field implying therefore the ability to form hot spots in the phantom. This can be seen in Figure 11. The birdcage forms multiple hot spots and so does the MTL. The red spots appear only at the surface of the phantom in the MTL case. The maximum SAR for the birdcage coil is 6.499 W/kg for 50 W excitation averaged over 10 g. For the same excitation power, the maximum SAR for the MTL coil is 2.627 W/kg and for the TEM coil is 4.646 W/kg. All the SAR calculations have been performed according to the IEEE/IEC 62704-1 standard. In terms of SAR, the MTL has the best performance which is in accordance with [3].

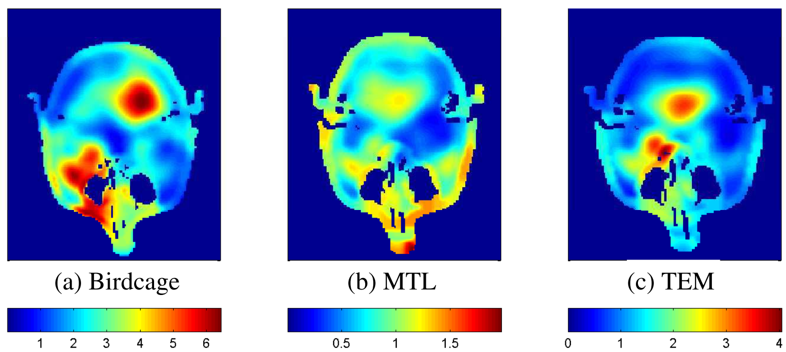

Figure 11: Transversal cut of the SAR in [W/kg].

4. CONCLUSION

The B_1^+ field homogeneity and SAR has been evaluated for the birdcage, TEM, and MTL volume coils. The results were compared to a previous work performed at 7 T. According to the simulation results, the birdcage coil has the best unloaded B_1^+ field homogeneity and the TEM has the best loaded B_1^+ field homogeneity exactly as concluded in [3]. In terms of the SAR, the MTL has the lowest SAR values and therefore it is the safest to use.

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