Subject-specific knee SAR prediction using a degenerate birdcage at 7T

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Abstract—We performed a study to predict global and local subject-specific Specific Absorption Rate (SAR) exposure in 7T Musculoskeletal (MSK) acquisition sequences. Such prediction, that is not available in current Magnetic Resonance (MR) exams, is possible combining sequences SAR exposure simulated on the generic anatomical model with subject-specific measured $B^+{}_1$ maps. The procedure has been implemented with a degenerate birdcage coil specifically designed for knee exams. Results show a good agreement between simulated $B^+{}_1$ and $B^+{}_1$ magnitude measure in-vivo, while values of global and local SAR calculated are below the recommended limit, respectively 8 W/kg and 20 W/kg.

Keywords—SAR, Magnetic Resonance, Ultra High Field, Multiphysics simulations, B_1 maps.

I. INTRODUCTION

The monitoring of the SAR in MR analysis is a critical issue for MR safety, in particular at ultra-high field (UHF) where, due to the RF field produced at higher working frequency, an increase of the energy deposition and an inhomogeneity of its distribution in the patient is observed [1][2]. Current MR scanners provide global SAR evaluation, empirically computed on emitted and reflected power from the RF coil and patients weight: this allow, during MR exams, a real time monitoring of SAR exposure, that must remain below the regulatory limit imposed by the International Electrotechnical Commission (IEC), as reported in the standard IEC-60601-2-33 [3]. These limits have been introduced to limit the increase of tissue temperature to safe values. However, current scanners are not able to predict SAR exposure (they only give SAR estimation in real time) before an exam, evaluation does not take into account subject-specific anatomy and position in the RF coil of the body part being investigated, and local SAR is not evaluated. Moreover, since SAR estimation routines differ from system to system, they should not be taken as the primary and only way for MR safety [4][5].

In order to have a subject-specific SAR evaluation, simulations must be performed for radio frequency (RF) fields and SAR analysis. In this work we compare simulated and measured B^{+}_{1} maps on an agar-agar phantom to verify the simulation algorithm, then we combine SAR simulations performed on and generic anatomic models with subject-specific measured B+1 maps, predicting local SAR during exam acquired on the knee using a degenerate birdcage for MSK applications. More in details, the coil is a 7T 1H eight-channel degenerate birdcage for the human limbs, with dedicate Tx/Rx switches and Butler matrix. The coil, described in [6], can be split into two half cylinders, as required for application to patients.

TABLE I.

CHARACTERISTICS OF THE AGAR -AGAR CYLINDRICAL PHANTOM

Quantity	Value
Heat capacity (c)	4.2kJ/K/Kg
Dielectric permittivity (ε_r)	77.52
Electric conductivity (σ)	1.886 S/m
Mass density (ρ)	1054 Kg/m^3

II. MATERIALS AND METHODS

A. *Electromagnetic simulations.*

We used the Finite Element Integration Technique (FIT) in the CST MW Suite (CST-Computer Simulation Technology AG, Darmstadt, Germany). We simulated the 1H 298 MHz degenerate birdcage coil described in [6], loaded firstly with an agar-agar cylindrical phantom (height 12.5 cm, radius 3 cm) with characteristic reported in Table 1 [7]. The phantom was positioned in the center of the coil with the main axis parallel to the static magnetic field (Fig. 1, top), and the B +1 field was calculated in an axial slice crossing the center of the phantom (Fig. 1, bottom). Then, the coil was loaded with a human knee model (Fig. 2, top), derived from the 2×2×2 mm3 voxel-size anatomic model Ella (adult, 59 kg, Virtual Population, ITIS foundation); in the human model the B+1 was calculated in an axial slice crossing the patella (Fig. 2, bottom). The maximum local (averaged for 10 g of tissue) SAR [W/kg] for the following MR sequence was calculated in the knee model: Axial “Zero” Time-of-Echo (ZTE) sequence (“SILENT”) [8], 384 FA=4° hard pulses of 12 μs length, 5 inversion and saturation pulses per Time Repetition (TR=525 ms). Next, we simulated various knee positions (moving the knee of ±1 cm, ±2 cm along the z axis) recording SAR and rSAR worse case.

B. *Measurements*

Measurements were acquired on a GE MR950 7T human system (GE HealthCare, Milwaukee, WI, USA) using the coil described above. The phantom used in this work is obtained by dissolving agar (7 g/L), NaCl (10 g/L) and $CuSO_4$ (1 g/L) in hot water and then allowing the solution to cool down and solidify in the cylindrical plastic former [7]. B^{+}_{1} maps in the phantom were acquired with a

Bloch-Siegert sequence [9] on 7 axial slices, centered on the slice corresponding to that used in the simulation. Sequence parameters are: TR=33 ms, TE=15 ms, RBW=15.6 kHz, thk=3.5 mm, matrix-size 64×64, square FOV 22 cm, 2 nex (total acquisition time: 9 s per slice), spacing 1 cm. For the in-vivo measurements considered in this experiment, we acquired B^+_1 maps in 5 adult patients, whose data are reported in Table 2, on 7 axial slices, centered on the slice used in the simulation, with the same sequence used for the phantom. For each slice where $|B^+_{1,map}|$ was measured, a coefficient C, proportional to avg($|B^+_{1,map}|$)/$B^+_{1,nominal}$, was calculated and used to scale the SAR simulated on the anatomic model [10].

III. RESULTS

Fig. 1, on the bottom, shows the magnitude of the simulated B+1 field for an input of 1W per channel, CP mode, in the central axial slice of the phantom. Fig. 2, on the bottom, shows the simulated B+1 magnitude map in the human knee model, for the same input, in an axial slice crossing the patella. The average of B^+_1 magnitude are respectively 2.07 μT, with a normalized standard deviation of 0.27, and 1.56 μT with a normalized standard deviation of 0.24. These two maps have been used to calculate the B^+_1 maps for a FA=90° sinc-pulse in the phantom and in the knee model.

Fig. 3 shows a comparison between simulated (on the top) and measured (on the bottom) B^+_1 field for a FA=90° sinc-pulse. The average value of simulated B^+_1 is 7.2 μT (i.e. the nominal B^+_1 for a FA=90° sinc-pulse of 3.2 ms length), the nominal B^+_1 for a FA=90° sinc-pulse of 3.2 ms length), while the average value of measured B^+_1 field is 7.13 μT with a normalized standard deviation of 0.32.

Fig. 4 shows SAR distribution (top) and B^+_1 field map for a FA=90° sinc-pulse (bottom): all of them are evaluated in an axial slice crossing the patella. The maximum local SAR in the considered slice is 2.6 W/kg, while the average of B^+_1 field is 7.2 μT i.e, as in the phantom simulations, the nominal B^+_1 for the FA=90° sinc-pulse of 3.2 ms length. It has to be noted that the maximum local SAR in the whole knee model is not in the considered slice, but is localized approximately 2 cm below the considered slice, but is localized approximately 2 cm below the considered slice. In Fig. 5 are reported, as example, the B^+_1 maps measured on the axial slice corresponding to the slice simulated, acquired in the 5 patients considered in this study. For each patient, the average of B^+_1 magnitude in the central slices in Fig. 5, the predicted global and maximum local SAR for "SILENT" sequence are reported in Table 2.

TABLE II.

DATA OF ACQUIRED PATIENTS

#	**Gender**	**Age [y]**	**Weight [Kg]**	**Avg (B^+) [μT]**	**Max SAR [W/Kg]**	**Global SAR [W/Kg]**
1	Male	44	80	7.45	5.13	0.7
2	Male	54	85	5.53	2.82	0.39
3	Female	53	62	7.04	4.54	0.62
4	Female	46	70	6.88	4.3	0.58
5	Male	53	62	6.33	3.68	0.5

IV. DISCUSSION AND CONCLUSION

In this study we propose a procedure which allows the prediction of global and local subject-specific SAR exposure for commonly used 7T sequences in knee. Prerequisites for such prediction are: sequences SAR exposure simulated in the generic anatomical model and subject-specific measured B^{+}_{1} maps. Validation of the coil electromagnetic model has been previously reported [6]. Comparison between simulated and measured B^{+}_{1} field maps in the phantom (Fig. 3) shows a good agreement of the two distributions, despite a slight asymmetry of the measured B^{+}_{1} distribution, given by the not exactly central position of the phantom inside the coil. However, this comparison confirms the accuracy of the simulation software in the calculus of the B^{+}_{1} distribution. Concerning the anatomical model, there is a good visual agreement between simulated B^{+}_{1} and B^{+}_{1} magnitude measured in-vivo. In the measurement, the flow artefact is clearly visible. Limits on global and local SAR, 8 W/kg and 20 W/kg respectively, were met for the sequence here considered.

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FIGURES

Figure 1. *Simulated birdcage coil loaded with agar-agar phantom (top) and simulated B^+_1 map in the axial slice in the phantom for an input of 1W per channel (bottom). Mean value of B^+_1 magnitude in the slice is 2.07µT.*

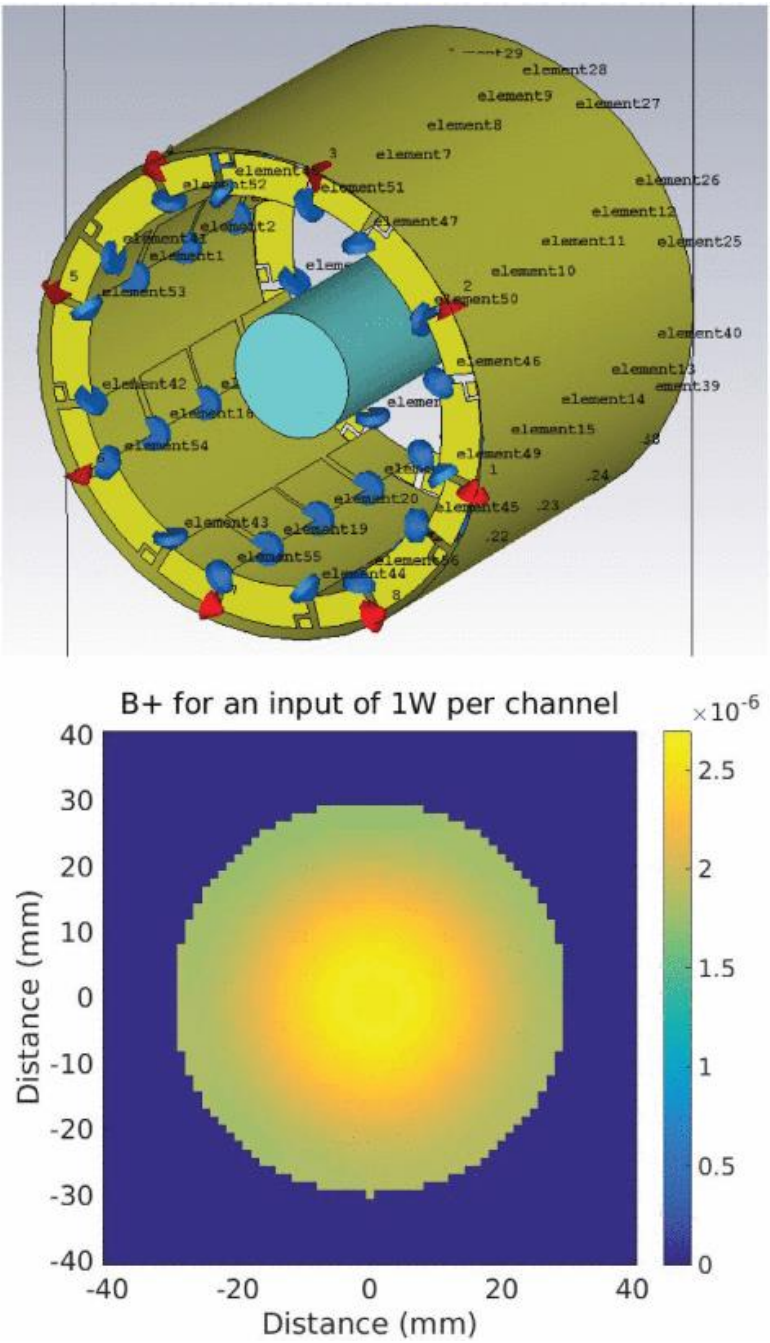

Figure 2. *Simulated birdcage coil loaded with the human knee model (top) and simulated* B^{+}_{1} *map in the knee model in an axial slice crossing the patella for an input of 1W per channel (bottom). Mean value of the* B^{+}_{1} *magnitude is 1.56* μT.

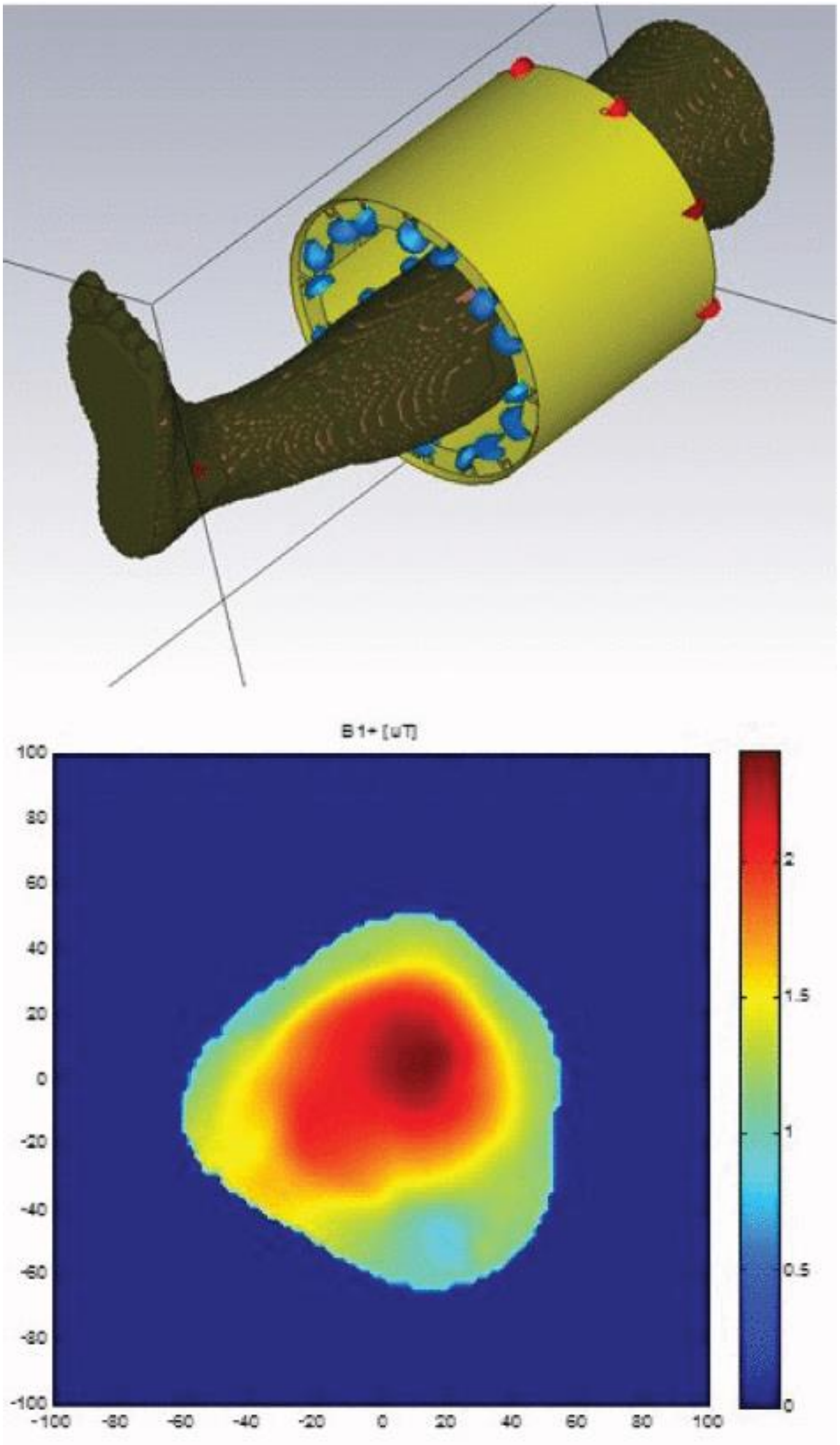

Figure 3. *Simulated (top) and measured (bottom) distribution of B^+_1 field in the cylindrical phantom for a FA=90° sinc-pulse. Simulated and measured average values of B^+_1 are respectively 7.2 μT and 7.13 μT. There is a good visual agreement between simulated and measured field, despite a small asymmetry of the measured B^+_1 map, due to a not central positioning of the phantom in the coil.*

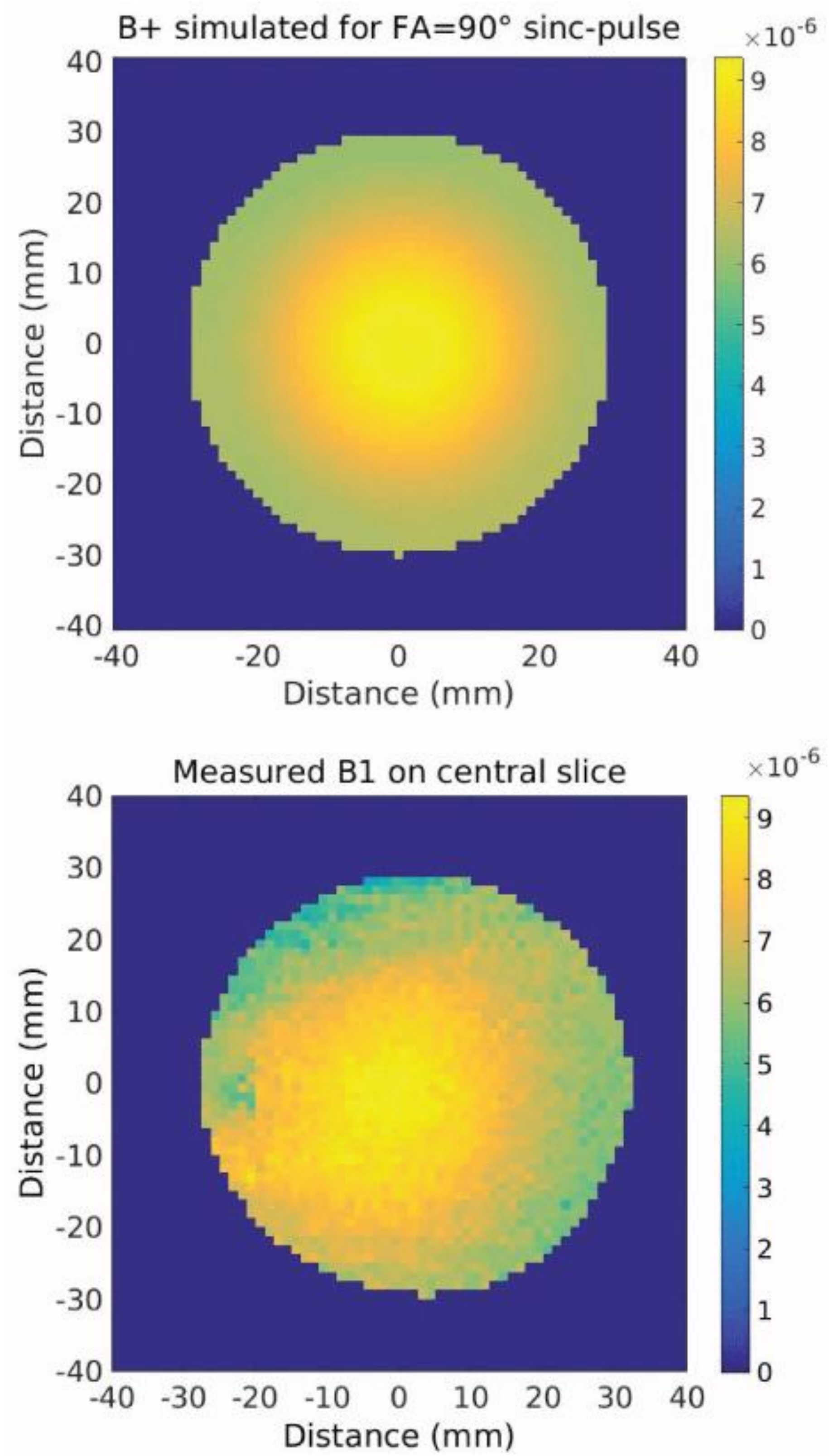

Figure 4. *Simulated map of SAR for an input of 1W per channel (top) and of B^+_1 magnitude for a FA=90° sinc-pulse (bottom) in the knee model. Maximum value of SAR is 2.6 W/kg, average value of B^+_1 field is 7.2 μT.*

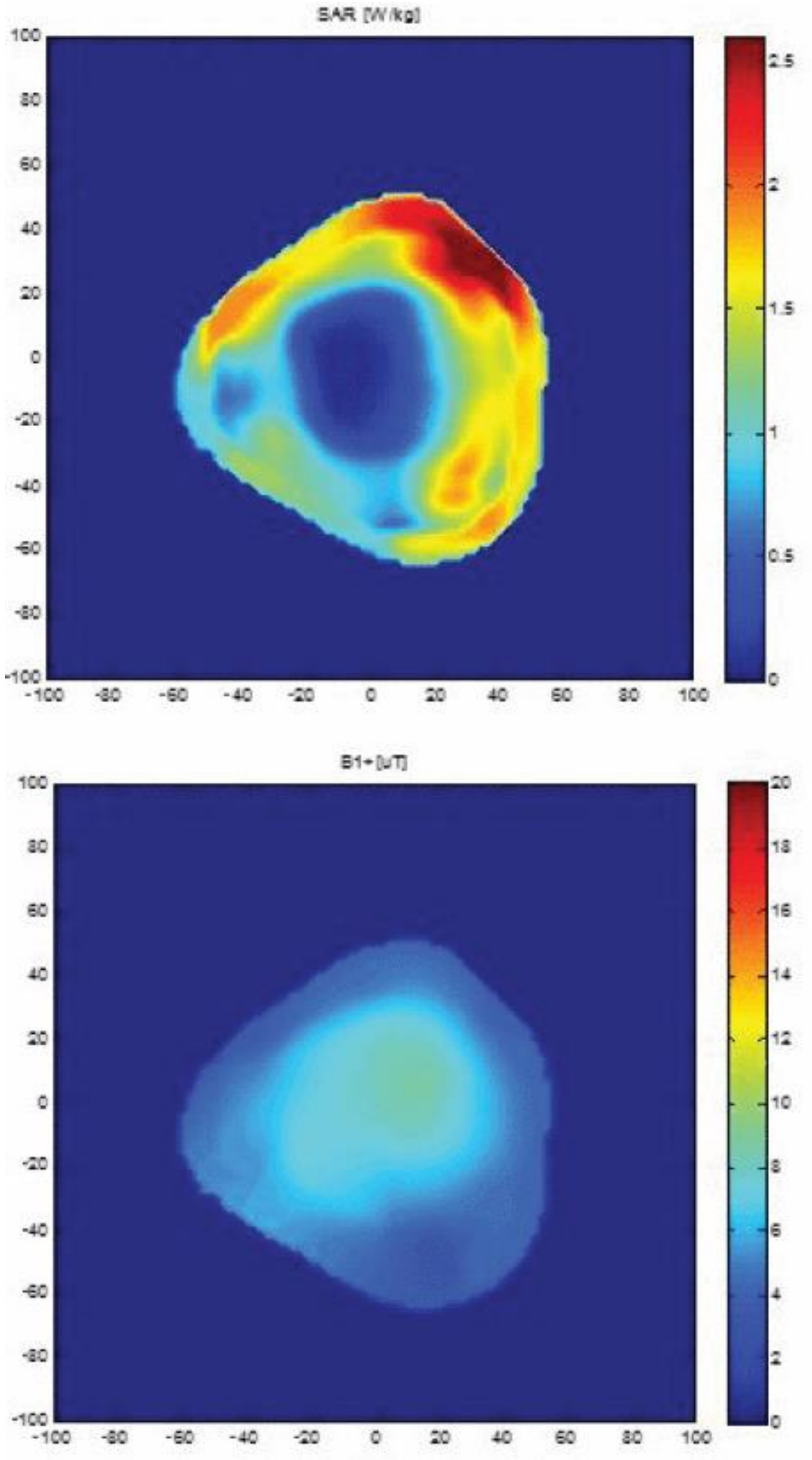

Figure 5. *Central axial slice B^+_1 magnitude map acquired for each patient examined in this work, corresponding to the slice used in the simulation. Values of B^+_1 field are expressed in μT. Average values of B^+_1 are reported in Table 2 for each patient.*