# Numerical Evaluation of an 8-element Phased Array Torso Coil for Magnetic Resonance Imaging

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## Abstract

*Recently, parallel imaging using multiple RF coils has excited great interest in magnetic resonance imaging (MRI). To help the design of some novel flexible array coils for the human torso, we theoretically investigate the RF field of an 8-element array coil loaded with an anatomically accurate model of the human torso. The RF behaviour is predicted based on a hybrid FDTD/MoM approach. The primary results are reported and simulations demonstrate the feasibility of torso imaging using array coils.*

## 1. Introduction

Radio-frequency (RF) coils are used in MRI as near-field antennas transmitting RF pulses and receiving the nuclear magnetic resonance (NMR) signal. In MRI, a phased array coil generally refers to a set of surface coils whose signals are combined to obtain a uniform image over a region larger than any individual coil could cover while taking advantage of the high signal-to-noise ratio (SNR) available from the smaller individual coils [1-3]. Over the last few years, several parallel imaging strategies such as simultaneous acquisition of spatial harmonics (SMASH) and sensitivity encoding (SENSE), have been proposed, which have the potential to revolutionize the field of fast MR imaging by enabling parallel acquisition [4]. These techniques employ spatial information of individual coils of an array to partially replace spatial encoding which is usually be achieved using magnetic field gradients, and hence reducing scan time [5]. Phased array technology is now having a major impact on standard MR methodologies. Besides the SNR advantage, array coils may also help to reduce the geometrical distortion that occurs due to variation of sample susceptibility. Most studies on mid-high frequency volume coils to date have been limited to the human head, as the shorter wavelength at high frequencies makes it very difficult to produce large volume coils with reasonable homogeneity. This makes array technology an attractive alternative for RF resonators for high field MR imaging of the human body. It is anticipated that at high fields an array can be designed to operate in the transceive mode and provide adequate homogeneity with a higher SNR while reducing power levels and safety concerns [6].

Since the development of the NMR array in the late 1980s, multicoil arrays have been designed to image almost every part of the human anatomy [2]. The aim of this study was to assess the feasibility of parallel MRI for the human torso using array coils. In theory, volume array coils offer increased SNR over standard body coils. However, there are many technical problems that remain to be addressed. To help the design of some novel array coil structures, we theoretically investigate the RF field of an 8-element torso coil loaded with an anatomically accurate model of a human torso. In the literature, the quasistatic approach based on Biot-Savart's law is widely used to verify the coil design [2,7]. However, this method fails when used with arrays because it does not properly allow for mutual coupling. Also the quasi-static approach assumes a current distribution on the coils and thus fails when coils are used in high-field imaging where the current distribution is less likely to be well characterized [8]. This paper presents a full-wave analysis method, that is, the combination of the finite difference time domain (FDTD) method with method of moment (MoM), to determine the currents of the coil and RF fields inside the body generated by array coils [9]. The simulation explored several imaging related parameters such as $B_1$ distribution, signal intensity (SI), wave polarization, and energy absorption rate (SAR) inside the biological body. The preliminary results are reported and demonstrate the feasibility of the design concept of array imaging of the human torso.

## 2. Methods

In order to model the field/object interactions, a voxel-based human torso model has been incorporated into the numerical simulations. The model data was obtained from the U.S. Air Force Research Laboratory (http://www.brooks.af.mil/AFRL/HED/hedr/), which represents a large male. Frequency dependent dielectric properties were obtained using a volume-averaging method and the proton density of body tissues were adapted from low-field image data.

The evaluated array geometry is shown in Fig.1. It is an array of 8 similar sized rectangular coils wrapped laterally around the chest. Recognising that the patient's size and torso geometry could vary significantly, the simulated general array does not conform too closely to the torso model. The coil elements are located about 2-4 cm from the human torso model. The capacitors were distributed at equal intervals in each single coil element to maintain uniform current and reduce dielectric interaction and losses from loading effects [10]. The coils were tuned to 85 MHz and matched to 50 ? . Eight sinusoidal sources were used to excite the coils with quadrature phasing to achieve a circularly polarized field. This proposed model could be applied for coils as either transmitters or receivers according to reciprocity theory.

In designing array coils, one of the most important things is to minimize the mutual inductance between the coils [2]. The cancellation of the coupling could be achieved by overlapping neighbouring coils. However, for a flexible torso array, overlapping is not such an attractive choice. Overlapping can only cancel coupling between adjacent coils and the coupling between these coils will vary as the structure flexes. Especially for SENSE imaging, adjacent coil elements should not overlap [11]. Therefore, we use a capacitor network to achieve coil decoupling. In theory, this method has no constraint in geometric arrangement of the coils thereby allowing placement of coils that could optimize parallel spatial encoding without concern for coupling between the coils.

The numerical analysis of the RF field produced by the array was based on a full-wave solution of Maxwell's equations. The MoM was applied to evaluate the current density distribution on the coils and the FDTD method was employed to find the steady-state electromagnetic fields (EMFs) inside the torso, which were then used to calculate the $B_1$ field, SI, and SAR map, etc.

For the current density calculation, quadrature voltage sources were applied, and current **J** was induced on the coils to satisfy the boundary condition of zero tangential electrical field. In the MoM discretization, all the coils were divided into small segments, and then the current on each segment was decomposed into a linear combination of basis functions and formulated into a matrix equation in which the unknowns are the currents, obtained by multiplying the inversed impedance matrix by the voltage vector using iteration techniques. Once the currents of the coil were obtained, FDTD was employed to investigate the RF fields in the presence of the inhomogeneous torso model excited by the calculated currents. To allow for RF radiation a three dimensional perfectly matched layer (PML) was applied as an absorbing boundary condition. The FDTD outputs were the magnitudes and phases of the steady-state EMFs, which were combined using a peak detection method.

The parameters, such as SI and SAR were derived on the basis of the FDTD results. The strategy of assessing NMR signal strength was based on the principle of reciprocity and the formulation [12] was

$$SI = iwM_0 \sin^n\left(kgt\left|\hat{B}_{1t}^{+}\right|\right)\left|\hat{B}_{1r}^{-*}\right| \qquad (1)$$

where, $w$ is the operating frequency, $M_o$ is the initial magnetization, $g$ is the gyromagnetic ratio, $t$ is the RF pulse duration of the transmission field, $k$ is a dimensionless constant to adjust the flip angle. $\hat{B}_{1t}^{+} = (\hat{B}_x + i\hat{B}_y)/2$ is the positive circularly-polarized component of the transmission $B_1$ field, and $\hat{B}_{1r}^{-} = (\hat{B}_x - i\hat{B}_y)^*/2$ is the negative circularly-polarized component of reception $B_1$ field. The integer $n$ is sequence-dependent, and is equal to 3 for a SE sequence and 1 for a GE sequence respectively. It is assumed that the magnetization is constant over each FDTD cell and the effect of relaxation times and other factors similar factors have been neglected. In order to evaluate the potential safety problem, the SAR value is evaluated as $SAR = s\left|E\right|^2/2r$ , where **E** was the electric field and $r$ was the local mass density. The simulated image is constructed by combining the images of individual coils using the sum of the squares method.

## 3. Simulation and Results

To implement the FDTD calculation, the cell size was 4 mm and the entire computational domain was divided into a $x \times y \times z = 139 \times 119 \times 143 \approx 2.4 \times 10^6$ box region and the torso model was embedded within this (see Figure 1). The 8 array coil elements were placed around the torso centred at the position of the heart. Twelve PML layers with a parabolic conductivity profile were located on the six open sides which effectively absorbed any radiated EMF energy. The results of the FDTD calculation show that the array of coils can achieve higher SNR than standard volume coils. With decoupling the coils in the array provide distinct, high SNR images of the regions adjacent to each coil. These distinct images can be combined to produce an image of a complete section such as would be produced by a volume coil but with higher SNR. Fig.2 shows the magnitude of transverse magnetic field component $B_1$ and it can be seen that the array coils perform much better than a single surface coil. It can also be seen that the predicted RF field behaviour is very dependent on the geometry of the sample and the array coils.

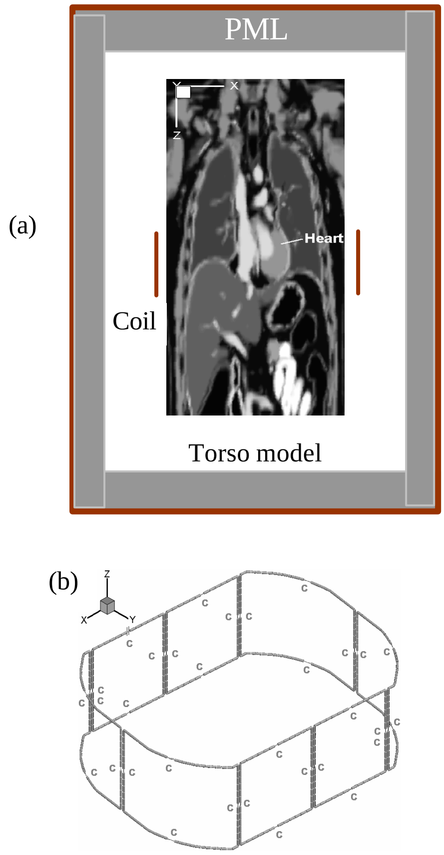


**Figure 1. The 8-element array and its FDTD model loaded with human torso (shown the xz section)**

The simulation also showed that the homogeneity of the $B_1$ field could be improved by optimizing the phase of the currents in the coils. Different combinations of phase were simulated and one was selected which best approximated a circularly polarized field, which has a theoretical advantage of $\sqrt{2}$ in SNR over linearly polarized coils [11]. Introduction of a non-homogeneous load disturbs the uniformity of the field as shown in Fig.2 (c,d). As the non-uniform load causes the flip angle to vary over the region of interest (see Figure 2(b)), an RF power level was chosen that resulted in an averaged $90^0$ flip for the imaging zone with a 3-ms rectangular pulse. Two modes of operation were simulated, one where the transmit field is produced by a body coil which is assumed to produce a uniform $B_1$ field and a second where the array of surface coils is used to both transmit and receive. Figure 3 shows the high local signal intensity adjacent to each coil that decreases toward the centre of the region and Figure 4 shows the simulated images that result. Although the signal intensity is low in each individual image the combined images of Figure 5 show that a reasonably uniform image of the whole region can be achieved. These preliminary simulated results on human torso model are encouraging. Some small bright and dark artifacts can be seen close to the coil conductors due to the rapid changes in $B_1$ and hence SI and flip angle in these regions.

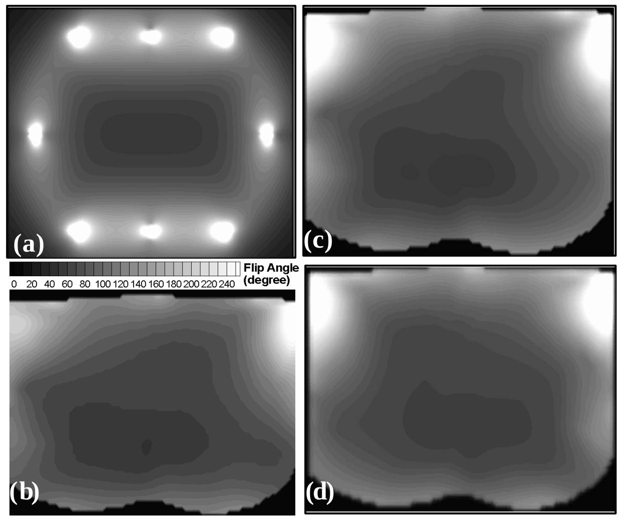


**Figure 2. (a) The simulated field in the plane z=0(a) $|B_1|$ map without load; (b) The flip angle map with load; (c) Transmit $|B_1|$ map with load; (d) receive $|B_1|$ map with load**

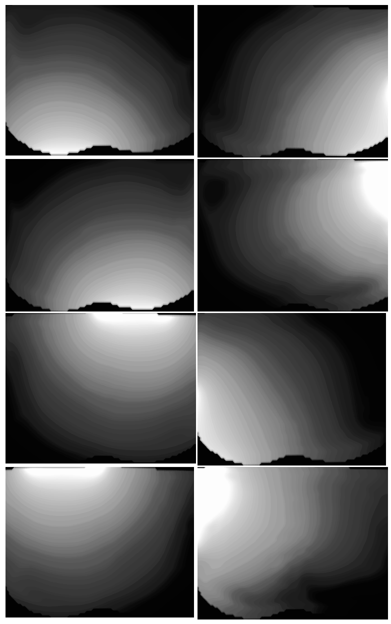

**Figure 3. The signal intensity (SI) of each coil in the phased array**

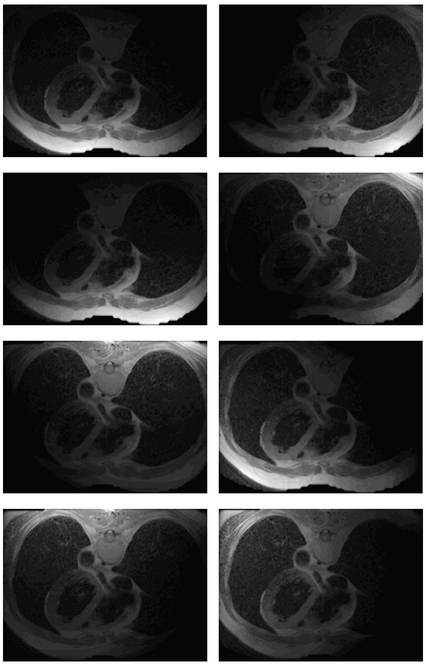

**Figure 4. The simulated GE image of each coil in the phased array**

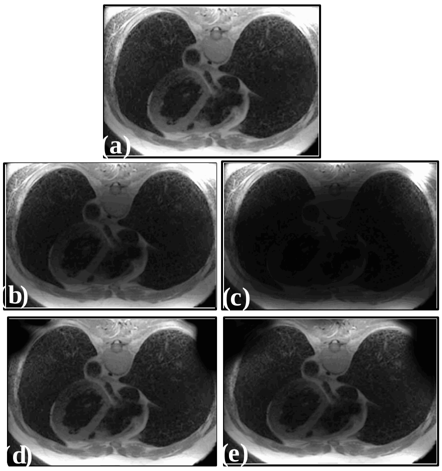


**Figure 5. The combined GE image (a)Receive Only; (b,d) Tranceive GE sequence; (c,e) Tranceive SE sequence. Plane Averaged flip angle: (b,c) 45$^o$(a,d,e) 90$^o$**

Figure 6 shows the variation of SAR across the imaging plane and shows that relatively larger values of SAR are located in the skin/muscle near the torso surface due to the large strength of the RF field in the skin and the high conductivity of the muscle.

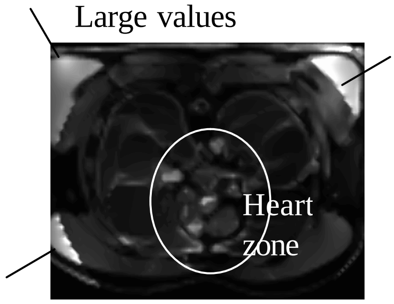


**Figure 6. SAR map in the z=0 plane**

## 4. Discussion

Single surface coils can be used to image surface tissues but to acquire images of regions in the interior of the torso requires a combination of sensitivity and magnetic field homogeneity over a larger field of view (FOV). This cannot be realised with a single surface coil because if the size of the coil is increased to improve the magnetic field homogeneity then the sensitivity is reduced. Similarly, small coils achieve high sensitivity at the expense of reduced magnetic field homogeneity. As shown by these simulations, an array of surface coils can achieve a combination of sensitivity and homogeneity that will allow imaging of complete torso sections.

This study investigated the RF field of volume-array coils by numerical evaluation of the Maxwell's wave equations at 2T (85 MHz). The basic limitation of the FDTD method was recognized and hybrid approaches were developed to overcome this. The coil currents were calculated by MoM and the RF field inside the body were evaluated by the full wave approach based on the finite difference approximation of the Maxwell's Equations. This approach should generate much more realistic information of the RF behaviour inside the body than the conventional quasi-static assumption for the current distribution and also the B1 field in the tissues. The problem of EMF interaction with the biological object in high field MRI has been studied for over a decade. Accurate assessment of the field-sample interaction phenomenon will help to find the optimal coil structure. Circuit theory and other quasi-static approaches do not handle interactions between coils in an array and do not even give accurate results for single coils in high frequency cases where the coil elements represent significant fractions of a wavelength. The high frequency case has to be addressed using full-wave approaches such as FDTD. Future work will extend this approach to higher field strengths and frequencies with the aim of overcoming the problems of volume coils in these situations.

From these simulated results it is seen that the RF field is disturbed by the sample even at 2T (85 MHz) and it is known that this effect becomes worse at higher field strengths and frequencies. This is because the wavelength is reduced by both the increased frequency and the dielectric properties of the body to a scale where the interactions become much more complex. Although the array interactions are complicated they hold the promise of overcoming some of the problems associated with imaging with volume coils at high field strengths [5-7,10]. Aside from image quality concerns there are safety concerns that non-uniform fields can cause localised hotspots where SAR limits are exceeded. This is a concern with volume coil imaging at high fields but these simulations show that the distance from surface coils to the body need to be monitored to avoid the high fields that exist in close proximity to the conductors. SAR limits will be more of a concern with fast imaging sequences and care needs to be taken that guidelines are not exceeded. Compared with volume coil the array of surface coils still has the advantage of lower global SAR and higher SNR [6,10].

Arrays of surface coils can be used to yield a circular polarized field, giving a theoretical advantage of $\sqrt{2}$ in SNR versus linear polarized coils[11]. At higher frequencies, the stronger interaction between the field and sample could compromise circular polarization and may decrease potential SNR gains.

Although the MoM simulations did not show a large effect of the sample on the currents in the coils at 2T, this effect will increase at higher frequencies. The method employed here should properly account for the more complex interactions and this will be investigated as this project progresses

In this theoretical study a specific array was simulated and seems to be an effective method for torso imaging. It is a promising RF coil structure for torso imaging at high field with or without a body coil. Cardiac imaging is a specific area in the torso to be explored using a volumetric transceiver phased array. This could also be applied to other parts of the body.

## 5. Conclusion

Accurate modelling of the interactions between coils and the body is needed to design arrays of surface coils for acquiring images of specific regions of interest in MRI at high frequencies. In this work, we present a hybrid MOM/FDTD computational model that was used to investigate the RF characteristics of an array of 8 surface coils loaded with an anatomically-accurate multi-tissue model of the human torso. The numerical studies showed that the array can provide a field of view similar to a body coil but allows for the possibility of using parallel imaging techniques. Using this kind of torso array will allow a large field of view for high resolution imaging with reduced scan times. The next step is to determine the optimum configuration of an array of coils for human torso/cardiac applications. It is also anticipated that these kinds of concepts and implementations will help to design of MR RF coil at higher field strengths.

## Acknowledgement

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