Mid-Bore Excitation of Traveling Waves with an Annular Ladder Resonator for 7T Body Imaging with Reduced SAR

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Introduction: The dimensions of the RF shield and the RF frequency for proton imaging at 7T allow the excitation of a propagating TE11 waveguide mode, which has given rise to the concept of traveling wave imaging [1]. RF excitation is typically achieved by using a patch antenna or crossed dipole antenna placed at one end of the bore [1, 2]. A nearly uniform B_1^+ field is produced along the entire length of the bore when it is empty. With a human body in the bore, dielectric boundaries and tissue conductivity give rise to standing wave behavior and attenuation of the B_1^+ field, resulting in a highly non-uniform excitation [3]. The strongest B_1^+ field and maximum SAR occur in the parts of the body closest to the antenna such as the head and shoulders or legs, with very little excitation in the torso. To create a useful excitation in the torso is it necessary to deposit large amounts of energy in the head or legs. Some methods have been proposed for creating structures which guide the traveling wave to deliver the power more efficiently to more distant regions [4]. It would be desirable though to excite the TE11 traveling wave mode at or near the mid section of the bore, close to the imaging volume of the scanner. We propose a novel resonator design, the annular ladder resonator (ALR), which is tailored to couple to the TE11 mode and which can be mounted behind the covers of the 7T scanner in the space normally occupied by the body coil in a conventional scanner. The coil behavior and performance are evaluated through full-wave simulation and the construction of prototype coils.

Methods: FDTD simulations were performed using Microwave Studio (CST, Darmstadt, Germany). The TE11 propagating waveguide mode created by the patch antenna consists of a series of "cells' which propagate down the bore. A vector plot of the H-field of the traveling wave (Fig. 1) shows a typical TE11 cell, where it should be noted that the H-field is only transverse near the center of the bore, and curls into the +/- Z direction near the RF shield. It is possible to couple to the Z-directed B field by placing a loop near the shield lying in an axial plane such that its normal points along Z (the orientation which is normally avoided in RF coil design). The concept behind the ALR coil is to line the bore with such loops, and join them together to create a resonant structure. The simulated ALR coil consists of two large rings of 60 and 66 cm inner diameter with 24 radial rungs joining the two rings (Fig. 2) and 0.8cm wide conductors. This arrangement has the axial loop structure needed to create efficient TE11 excitation as described above. Capacitors were placed in both of the large rings between each of the rungs. Capacitor values were determined to bring the frequency of the appropriate resonant mode to 297.2 MHz. The resonant model was driven with 2 Ports with 90° phase offset for quadrature excitation. Patch antenna excitation was modeled using a resonant coil model driven in quadrature. A body-sized TEM coil was modeled based on one described by Vaughan et.al [5] with a 122cm long RF shield of 62cm diameter centered in the warm bore. 24 rungs of 33cm length and 0.6cm diameter were arranged with their centers on a circle of 58.3cm diameter. The TEM was tuned with capacitors in the model to create a resonant system and driven at four ports with appropriate match circuits. Simulations of the three coil models (patch antenna, TEM and ALR) were used to generate H-field vector maps, B_1^+ and SAR maps both for the empty bore and with the body model (5mm x 5mm resolution). A prototype ALR coil was constructed from 0.62mm thick FR4 circuit board with dimensions that match the model. This was placed in a 680mm RF shield in the bench to evaluate resonant frequency, S parameters and B_1^+ efficiency. In addition, 4 transmit receive loops 10 x 4.5cm in size were constructed which could be placed in the scanner bore for imaging experiments. These were connected to 4 T/R switch and preamp assemblies (Stark Contrast, Erlangen, Germany) and were driven in quadrature.

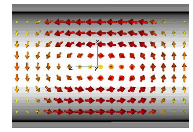

Fig. 1: H vectors in a TE11 "cell:

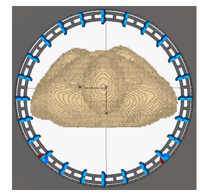

Fig. 2: Annular Ladder Resonator

Results: In order to couple to the TE11 mode the phase of the currents in the loops must vary directly with the azimuthal angle relative to the center of the bore, in analogy to the phase variations in the rungs of a birdcage resonating in the uniform mode. In the ALR coil resonant spectrum the highest frequency mode is an end ring mode, and the next mode lower down in frequency is the desired mode corresponding to the uniform mode of a birdcage. Plots of the H-field vectors (not shown) demonstrate clearly that the TE11 mode is being excited by the ALR coil, with waves propagating out in the + and – Z directions. B_1^+ maps for equal input power for the three coil designs are shown in Figure 3 and SAR maps are shown in Figure 4. A significant feature of the ALR coil is that there is a B_1^+ null through the plane of the coil. This is due to symmetry constraints which require that the B vectors in the plane of the coil have no radial component. Nevertheless many areas just outside the null have equal or higher B_1^+ field compared to patch antenna excitation. SAR in the head is much lower with the ALR coil compared to the patch antenna (0.016W/kg compared to 0.073W/kg). The TEM coil creates the highest B_1^+ field in the torso of all designs, though with significant inhomogeneity. This could be mitigated with B1 shimming or accelerated parallel excitation to redistribute the B_1^+ field [6], something that is not possible with the traveling wave approach using a single excitation structure.

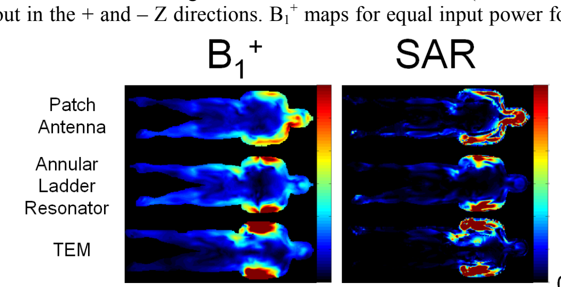

Fig. 3: SAR in the head is greatly reduced with the ALR coil compared to the patch antenna.

If the ALR coil is placed at the edge of the imaging volume (e.g. >25cm from isocenter) the null will not appear in the images but the excitation will still be relatively local compared to placing a patch antenna at the end of the bore. This is demonstrated in Figure 5 where the four loop coils were used to excite the TE11 mode in the scanner. It is also possible that two ALR coils could be placed in the bore either side of isocenter, creating a standing wave between them. Figure 6 shows simulated B_1^+ maps for various separations of a double ALR coil setup with an empty bore. When the two component ALRs are separated by one wavelength, there is no propagation out of the bore. This condition is unlikely to be met when there is a lossy sample in the bore, but this approach may prove useful for tailoring the excitation.

The prototype ALR coil required 6.8pF in the outer ring positions and 6.0pF in the inner ring positions to bring the resonant frequency to 313.4MHz. The coil was driven at two ports, which had S11 of -19 and -23dB. The S21 coupling between the ports was rather high, though, at -7dB. The transverse B field produced by the ALR coil was 10.7dB lower than that produced by the patch antenna, as measured in the empty bore on the bench. This poor performance was not observed in the body-loaded simulations, so it is hoped that further optimization of the tuning, symmetry and geometry of the ALR coil will improve the efficiency.

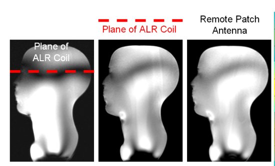

Fig. 4: Phantom images show ALR coil null and effect of moving coil out of FoV

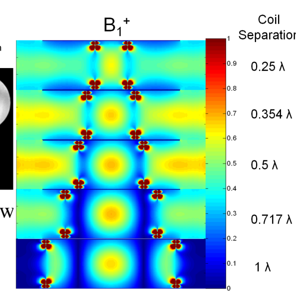

Fig. 5 B1+ maps showing effect of placing two ALR coils in the bore with varying distance between them

Conclusions: Because of the annular structure of the ALR coil, the body can pass through it, and thus it can be placed at any position along the length of the bore. This allows the TE11 traveling wave mode to be excited close to the imaging volume, reducing energy deposition in more distant regions that would normally experience high power deposition with a remotely located patch antenna or crossed dipole antenna. The structure could even be situated between the gradient RF shield and the covers of the magnet, avoiding the obstruction of the bore created by the placement of a large patch antenna.

[1] Brunner D, t. al. Nature 2009; 457:994-999 [2] Zhang B, et.al. Proc ISMRM 2009 p4746 [3] Zhang B, et.al. Proc ISMRM 2009 p498 [4] Andreychenko A, et.al. Proc ISMRM 2009 p500 [5] Vaughan et. al. Magn Reson Med 2004; 52:851-859 [6] Vaughan et. al. Magn Reson Med 2009;61:244-248