A Four Channel Transmit Receive "Loopole" Array for Spine Imaging at 7.0 Tesla

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Introduction: A loop element with a non-uniform current distribution behaves as both a loop antenna and an electric dipole antenna[1]. At 7 Tesla in a body sized phantom this "loopole" element can achieve either higher central B_1^+ or higher SNR as compared to a traditional balanced current loop depending on the orientation of the excitation port[2,3]. With increasing current imbalance the loopole performs more like an electric dipole antenna, which has been shown to be favorable for central SNR in body sized objects at 7T[4]. Nevertheless the loopole coils can still be fabricated like conventional surface coil loops, i.e. tuned with trimmer capacitors, decoupled through overlapping and tiled to make dense transceiver arrays. A loopole coil also exhibits reduced loading sensitivity compared to an electric dipole, where proximity to the conductive object results in significant tune and match variation[5]. These properties make the loopole a desirable building block in practical transceiver coil arrays to image centrally located body regions.

Achieving adequate flip angle in the spine at 7T has been a challenge due to its central location, limited available RF power and SAR constraints. In this work we designed a four element loopole array consisting of an anterior and posterior shell with two overlapped loopole elements in each half for human spine imaging at 7T. In each pair of elements one is used to transmit and both are used to receive. We performed bench measurements, simulations and MR experiments comparing the proposed design with a variety of previously described 7T spine arrays [6,7].

Methods: Full wave electromagnetic simulations were performed with the FDTD method (CST Microwave Studio). An elliptical phantom was modeled with $\varepsilon_r = 40.5$, $\sigma = 0.58$ S/m, 50 cm long, 29 cm wide and 19 cm high. Four loopole array elements 15 cm along z and 10 cm wide with 10 capacitors each were modeled on a curved surface (Fig.1). Each element had three 18pF capacitors in the long feed leg, three 3pF capacitors in the opposite leg and two 15pF capacitors in each of the short legs. For comparison an offset loop array design previously implemented for spine imaging[6,8] and a recently published dipole spine array design[7] were modeled and simulated. The offset loop array consisted of three overlapped 15 × 10 cm rectangular loops in which the center loop and one side loop were used for transmit with a 90 degree transmit phase. The dipole spine array consisted of two dipoles 37 cm along z separated by 6cm driven with optimal phase for a central excitation. To ensure that the loopole design could provide an adequate z field of view, a two element loopole array with elements overlapped in z direction (Fig.2) was also simulated. All elements were excited with 50Ω ports in simulation.

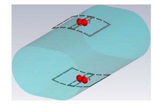

Fig.1 Loopole Array

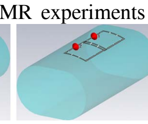

Fig.2 Extended z Loopole Array

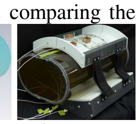

Fig.3 Constructed Array

For experimental verification a four element loopole array was constructed to match the simulated model (Fig.3). An in-house custom built interface was used to excite the loopole array on a 7T scanner (Siemens, Erlangen Germany). The loopole array was compared against an in-house custom built spine array based on offset loop design[8]. Transmit phases were chosen to align all phases at the center of the phantom. A series of GRE images with TR=2000 ms, and different RF pulse voltages were acquired. A sine curve was fitted to the pixel intensities to obtain B_1^+ maps. SNR was calculated using the Kellmann method[9] from GRE acquisitions both with and without RF excitation with flip angle calibrated in the spinal cord (TR/TE/Flip/BW = 200ms/4.07ms/20°/300Hz per pixel, Matrix =256*256, FoV = 320mm, Slice = 3mm). In-vivo turbo spin echo (TSE) images were acquired in axial (TR/TE/BW/Slice= 5410ms/71ms/238Hz per pixel/2mm, Matrix = 512*512, FoV = 200mm, TF =8 , 130° Refocusing, TA = 6.36 mins) and coronal planes (TR/TE/BW/Slice= 6100ms/70ms/238Hz per pixel/2mm, Matrix = 512*512, FoV = 256 mm, TF =8 , 130° Refocusing, TA = 9:17 mins). In vivo studies were approved by our IRB and were performed with written informed consent of all volunteers prior to the examination.

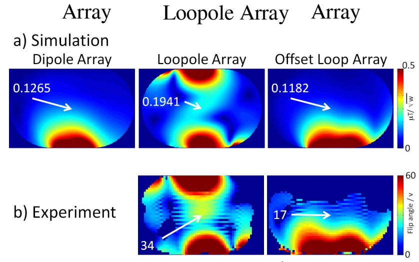

Fig.4 a) Simulated Axial B_1^+ /√Peak 10g. SAR b) Experimental B_1^+ maps

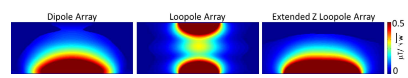

Fig.5 Sagittal B_1^+ /√Peak 10g. SAR - Simulations

Results: ***Simulations:*** Better than -20dB match was achieved for all elements in the designs compared. Simulations achieved critical decoupling ($S_{12} < -25$dB) for the overlapped loopole (Fig.1) elements. S_{12} coupling between overlapped elements in offset loop array was less than -20dB. S_{12} coupling for the two elements of the dipole array was –12 dB. Taking SAR as the limiting factor, we first generate B_1^+ maps normalized by SQRT(peak 10g SAR) (Fig.4a). The loopole array achieved at least 35% improvement over compared designs for central B_1^+, in part because it exhibited lower peak SAR. The loopole array also achieved at least 25% improvement in central B_1^+ when normalized to square root of absorbed power (results not shown). The loopole elements tiled along z (Fig.2) achieved critical decoupling ($S_{12} < -28$dB). Sagittal B_1^+ maps (Fig.5) indicate that although a single loopole element has a shorter z field of view than the 37 cm dipole, with additional power, extended z loopole array could achieve similar or better coverage than the dipole array.

Experiments: The Unloaded & Loaded Q values for the loopole elements were 80 & 8 respectively. All elements were matched better than -20 dB with isolation better than -18dB. Experimental phantom B_1^+ maps normalized to excitation voltage (Fig. 4b) indicate that the loopole array achieved two-fold improvement in central B_1^+ efficiency over the offset loop array. In-vivo SNR maps (Fig 6) indicate that the loopole array achieved on average 15% SNR improvement in spinal cord and more than 50% improvement in the disc compared to the offset loop array within the 15cm FoV of the loopole. It was only possible to achieve a 65 degree flip angle in the spinal cord with the available power and standard RF pulses, but this was sufficient to generate axial and coronal T2 weighted images (fig. 7). The in-vivo images demonstrate exquisite anatomical detail for the caudal equina nerve roots in the mid-lumbar spine. These images could significantly improve in-vivo characterization of foraminal and facet joint anatomy prior to spine interventions for pain.

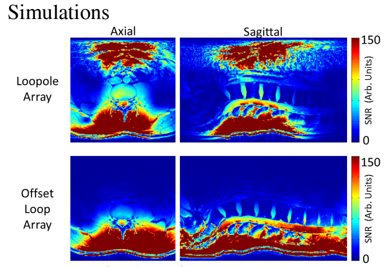

Fig.6 In-vivo SNR maps

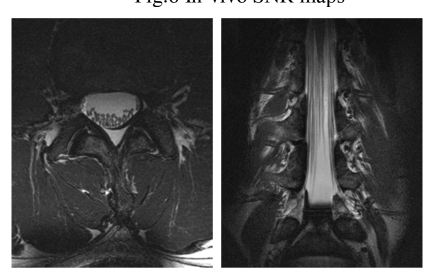

Fig.7 In-vivo Axial and Coronal TSE Images

Discussion and Conclusions: Substantial B_1^+ and SNR improvements in the spinal region were achieved by using anterior and posterior loopole elements. Simulations show that loopoles can be overlapped in the z direction for improved coverage. In principle dense coil arrays can be engineered by overlapped and tiled loopoles, providing the convenience of loop coil design with the performance of electric dipoles.

References: [1] Horner F. Properties of Loop Aerials, The Wireless Engineer, Vol. 25, Aug. 1948 p254-259 [2] Lakshmanan K. ISMRM 2014 p0397 [3] Lakshmanan K. ISMRM 2014 p0315 [4] Wiggins G. ISMRM 2013 p2737 [5] Lee W. ISMRM 2013 p4367 [6] Duan Q. ISMRM 2010 p51 [7] Duan Q. ISMRM 2014 p0316 [8] Wiggins G ISMRM 2009 p2951. [9] Kellman P. MRM 54:1439–1447 (2005)