Four Channel Transceiver Array for Functional Magnetic Resonance Spectroscopy in the Human Visual Cortex at 9.4 T

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Introduction: Functional magnetic resonance spectroscopy (fMRS) at ultra-high field (UHF) strength (≥7T) is a method to investigate the metabolism of the human brain during task induced stimulation [1] or pharmacological challenge [2]. A region of special interest is the visual cortex which undergoes metabolic changes during visual stimulation [1]. The UHF thereby allows for increased spectral and temporal resolution and higher SNR in comparison to lower field strength. However, with increasing field, appropriate coil design becomes much more difficult as not only a high receive SNR, but also a high transmit (B_1^+) efficiency is required for localized spectroscopy experiments and the total SAR is approximately proportional to the square of the Larmor frequency [3] and therefore limits average RF power. Hence an RF coil must be designed with high receive sensitivity, but also high transmit efficiency (B_1^+ / √P) while being optimized to guarantee SAR safety (B_1^+ / √SAR). Receive SNR is usually boosted by the use of multichannel surface coil arrays [4], which can however also be driven in transceiver mode for optimal transmit efficiency [5]. Additionally transceive phased arrays are more flexible than conventional quadrature coils used so far for fMRS [6] because they allow stirring of B_1^+ field by RF shimming. In this work, a four channel transceive phased array for functional spectroscopy in the human visual cortex at 9.4T was designed and optimized with regard to transmit efficiency under SAR constraints.

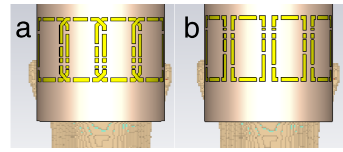

Fig 1: *Four channel transceiver coil with (a) overlapping and (b) non-overlapping loops.*

Fig 2: *Constructed four channel transceiver array with overlapping loops for fMRS in the visual cortex.*

Methods: *Simulation:* As a starting point in the design process, two approaches were examined with numerical EM simulation software (CST microwave studio 2012, Darmstadt, Germany): overlapping loop elements (Fig. 1a) and non-overlapping loop elements (Fig. 1b). In both versions four rectangular loops were lying on a segment of a 3 mm thick fiber glass cylinder with a radius of 8.3 cm and an arc angle of 150°. To reduce radiation losses a copper shield was mounted in 4 cm distance. The time domain solver was used with approx. 37 million mesh cells and the coils were loaded with the “Duke” voxel model from the “Virtual Family” (ITIS, Switzerland). Open boundary conditions were applied in each spatial direction to consider radiation losses.

Non-Overlapped loops: Each element was 85 mm long, 47.75 mm wide and adjacent elements were separated by 8 mm. *Overlapped loops*: To get larger loop elements with a higher penetration depth the loops were overlapped by 15 mm. This resulted in an element size of 85x65 mm². Both setups were simulated with various constant phase shim configurations. To make a fair comparison between the setups the optimal RF shim values for maximum B_1^+ efficiency in a ROI of 23.5x21.6mm² in the visual cortex were calculated (overlapped loops: 0°/24°/59°/129°, non-overlapped loops: 0°/29°/101°/176°).

Measurement: Based on the simulation results the overlapped coil was constructed with equal dimensions as in the simulation (Fig. 2). All coil elements were tuned and matched to a head-and-shoulder phantom with tissue equivalent solution (ε_r = 58.6, electric conductivity = 0.64 S/m). Adjacent elements were decoupled by a resonant inductive decoupling network (RID) [7], to decrease the substantial amount of parasitic resistive coupling. Conventional transformer decoupling was used for non-adjacent elements. With this strategy decoupling was better than -16 dB for all channels. All measurements were done on a 9.4 T Siemens (Erlangen, Germany) Magnetom system with the before mentioned phantom. 2D Turbo Flash sequences (TR/TE =100ms/4ms) were acquired for each individual channel. With the extracted phase maps the optimal RF shimming phases (0°/78°/200°/304°) were calculated in a Matlab (The Mathworks, Natick, USA) script for a 21.25x21.25 mm² ROI in the primary visual cortex. With that driving phases actual flip angle maps (AFI) [8] were acquired in a transversal and sagittal slice and compared to simulation results using identical phase settings.

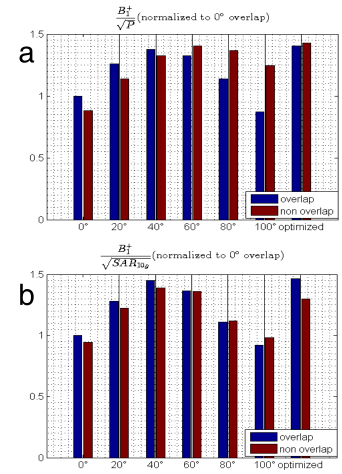

Fig 3: *Simulation results: overlapped vs. non-overlapped coil for (a) normalized B_1^+ efficiency and (b) normalized B_1^+ over √$SAR_{(10g)}$ with constant phase difference between each channel and optimized phase configuration.*

Results: Fig. 3a shows the simulated B_1^+ efficiency (normalized to 0° of the overlapped coil) in the head model for various constant RF shimming phases. Here the specified shim angle has the meaning of a constant phase offset between adjacent channels. In the configuration optimized for the visual cortex both coils had very similar transmit efficiencies (1% difference). However the situation changed if the maximum of $SAR_{(10g)}$ was taken into account: Fig. 3b shows B_1^+ over √$SAR_{(10g)}$ (normalized to 0° of the overlapped coil). Here the overlapped coil excelled the non-overlapped version by 12.5% when both were driven in their corresponding optimized phase configuration. Fig. 4 displays the slice of maximum $SAR_{(10g)}$ (phases 0°/78°/200°/304°) and a total input feed power of 2W. The point of maximum $SAR_{(10g)}$ was located in the visual cortex with 2.99 W/kg. The measured B_1^+ efficiency is shown in Fig. 5a with a comparison to the simulated data (Fig. 5b). With a delivered power of 4.3 kW we were able to achieve an average B_1^+ of 63 µT in the plotted rectangular voxel (12.4x12.4mm²) in the visual cortex region. The penetration depth of the magnetic field produced by this coil along the central line in the transversal plane was evaluated by linear regression and gave a field drop-off of 7.1 nT/(V·mm) corresponding to 3.3 µT/mm when driven with 4.3 kW. So even for spectroscopy in more deeply centered voxels, for example in white matter, this coil provides sufficient B_1^+ field.

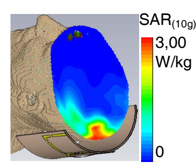

Fig 4: *Simulation results: 2D cut plane through slice of highest $SAR_{(10g)}$ with total input power of 2W and phases 0°/78°/200°/304°*

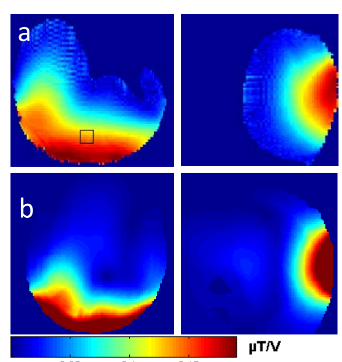

Fig 5: *B_1^+ efficiency (a) as experimentally determined by AFI and (b) as simulated by CST in the “Duke” voxel model (phases: 0°/78°/200°/304°). (left) transversal plane, (right) sagittal plane.*

Conclusion: Based on EM simulation we demonstrated that for this particular setup overlapping individual coil elements has better performance in terms of B_1^+ / √SAR than non-overlapping loops, while the transmit efficiency B_1^+ / √P in the visual cortex is identical. We built a prototype coil and were able to determine RF shims for a ROI in the visual cortex. Experimental and simulated B_1^+ maps are in accordance and show that the coil produces 63 µT in the visual cortex and is therefore suitable for functional spectroscopic imaging experiments in the future.

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