A 10-channel TMS-compatible planar RF coil array for human brain MRI at 3T

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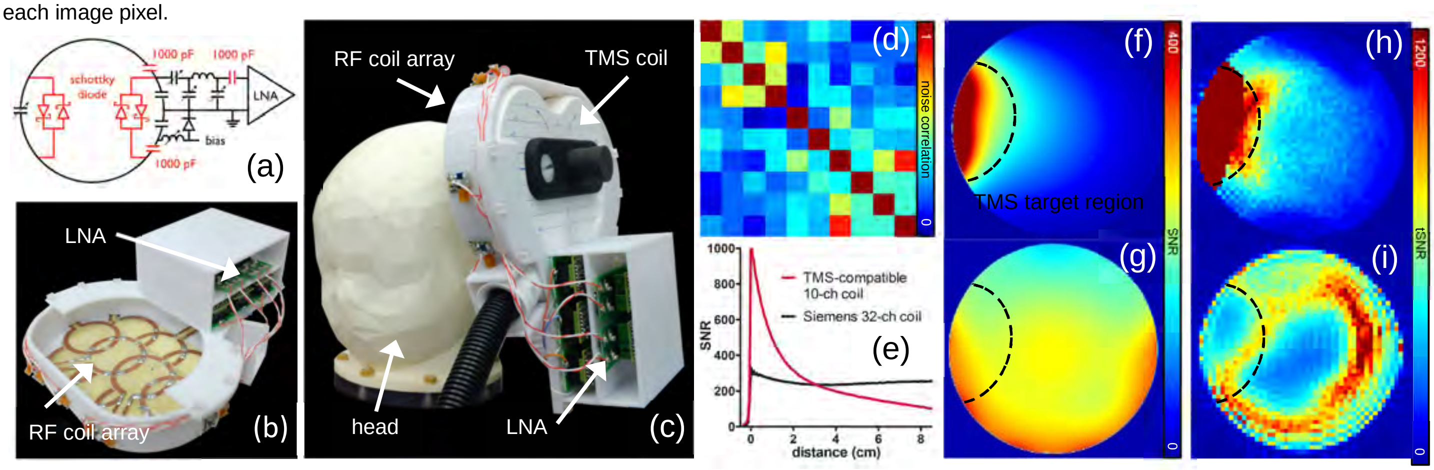
TARGET AUDIENCE: Scientists interested in concurrent transcranial magnetic stimulation (TMS) and MRI.

PURPOSE: Recently, combining TMS, a non-invasive method of stimulating the brain via transient and strong magnetic fields, and fMRI has become a powerful tool to investigate the causal relationships between a target brain region and behavior [1]. However, performing TMS inside MRI typically uses a head volume coil for MRI in order to allow flexible positioning of the TMS coil [2]. This approach leads to relatively poor MRI sensitivity and still limited freedom in TMS coil positioning. Here we developed 10-channel MRI coil array [3] integrated with the TMS coil in order to improve MRI sensitivity and to maximize the freedom in TMS coi positioning for the optimal TMS efficacy. The coil array is placed between the TMS coil and the head with a slim design in order to minimize the distance between the TMS coil and brain to maximize stimulation efficiency. Evidenced by empirical data, our TMS-compatible coil array provides significantly higher sensitivity than conventional head coil at the cost of a smaller FoV coverage.

METHOD: A 10-channel RF coil array was designed for 3T MR system (Skyra, Siemens). Each coil loop with 5 cm diameter was tuned to 123.25 MHz and connected to a low noise pre-amplifier (LNA) integrated with a mixer (Siemens, Erlangen, Germany) through a matching circuit, which had a balanced circuit design and transformed the impedance to 50 Ω in order to obtain the lowest noise figure. An active detuning circuit was formed using a variable inductor and a PIN diode. Fast switching Schottky diodes were in series with high value capacitors to protect the LNA against the potential low-frequency current surge induced by TMS stimulation (red color; Figure (a)). To minimize the coil array thickness for the maximal TMS stimulation efficacy, the coil inductor loops used 0.4 mm copper clad laminates. The matching circuit and LNA were also extended outside the coil array plane through a 20 cm coaxial cable. The 10-channel hexagonally arranged coil array had a housing (Fortus, 400mc, Stratasys, Mn, USA) fitting to the TMS coil (MRI-B91, MagVenture, Denmark) (Figure (b)). To mutually decouple between neighboring coils in the array, coils were critically overlapped to minimize the S_{21} measurement. The matching circuit transforming the LNA's input impedance to a serial high impedance at the coil loop provided further decoupling between coils. The setup of this slim RF coil array (2 mm) with LNAs placed outside the TMS coil was shown in Figure (c).

Data were acquired on a 3T MRI (Skyra, Siemens). Signal-to-noise ratio (SNR) maps were measured with a GRE pulse sequence (FoV: 178x178 mm^2, slice thickness: 5 mm, TR: 462 ms, TE: 10 ms, Flip angle: 25^o). Oversampled data of GRE were used to calculate the noise correlation coefficient matrix between RF coils. Time-domain SNR (tSNR) maps were measured with an EPI pulse sequence (FoV: 224x224 mm^2, slice thickness: 3.5 mm, TR: 2000 ms, TE: 30 ms, Flip angle: 90^o, 120 measurements) by measurnig the ratio between the average and the standard deviation of the time series for each image pixel.



RESULTS: The ratio between the unloaded quality factor (Q) and the loaded Q of a single coil is 147/46 = 3.20. The mutual coupling between adjacent RF coils was below -10 dB for all coils. LNAs brought additional -20 dB coupling between coils. Figure (d) shows the noise correlation matrix: the average of off-diagonal entries was 0.3. Figure (f) and (g) are SNR maps measured by the TMS-compatible 10-channel coil array and the commercial 32-channel coil array, respectively. Comparing between SNR maps demonstrated the relatively high sensitivity of the TMS-compatible coil array at the TMS stimulation target area. Figure (e) shows the SNR profiles through the center of two SNR maps horizontally. Overall, the average SNR of TMS-compatible coil array is 44% better than the commercial 32-channel array within the 5 cm depth. Figure (h) & (i) are tSNR maps measured by the TMS-compatible coil array and the Siemens coil array, respectively. The tSNR of the TMS-compatible coil array also shows a higher sensitivity at the TMS stimulation area, suggesting that the TMS-compatible coil array is suited for recording functional brain activities induced by the TMS stimulation inside an MRI scanner.

DISCUSSION: We designed and constructed a tailored 10-channel RF coil array to allow TMS and fMRI measurements in the same experimental setup. The coil array used small loop coils, each of which had a relatively weak sensitivity in the deep brain region. However, our preliminary data show that, the average SNR of the TMS-compatible coil array is better than that of a commercial 32-channel coil array within 5 cm depth. This depth was considered sufficient for monitoring functional activities elicited by TMS, because TMS mostly excites neurons at superficial cortex. The decoupling between the densely packed coil array elements can to be further optimized in order to increase SNR and to decrease the correlation between array elements. While the preliminary results only show of phantom images, we expect this TMS-compatible RF coil array can also offer both anatomical images and functional MRI signal induced by TMS with high sensitivity.

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