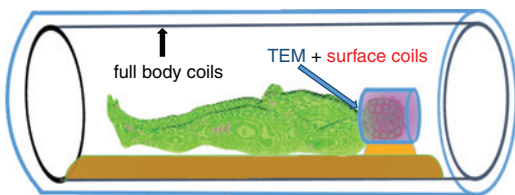


# Combined RF coils for brain imaging at 7 T with receive and transmit resonators

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MRI has the potential to produce clear anatomic, as well as functional, images of the human body. However, the ability to diagnose is limited by signal-to-noise ratio (SNR) and the resolution of current medical systems. To remove the challenges prevalent due to the use of high-field scanners, dedicated RF coils are used. Transverse electromagnetic (TEM) coils have the advantage of providing a homogeneous magnetic field throughout the region, but with a low SNR, while surface coils have the advantage of providing a higher SNR, but with low homogeneity. The research discussed combines both advantages into one by utilising transmit-only TEM RF coils (8-channel) along with receive-only surface coils (varying in number) to obtain good homogeneity, as well as significant SNR improvements, from MRI throughout the human brain.

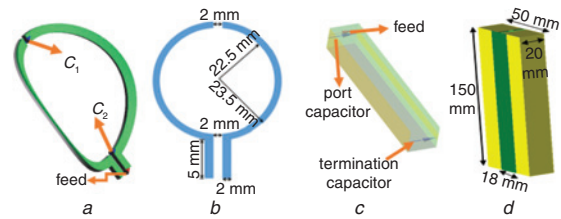
**Introduction:** High-field MRI is becoming increasingly popular for diagnosing brain disease, especially in an ageing society. With a higher external magnetic field ( $B_0$ ), the signal-to-noise ratio (SNR) increases, whereas homogeneity of the RF magnetic field ( $B_1$ ) decreases due to the shorter wavelength. Thus, for ultra-high fields, an RF coil distribution, and arrangement of the coils around the region of interest (ROI) is important in order to obtain an optimum SNR to alleviate the homogeneity problem. For this purpose, RF coils are used in different arrangements (such as transmit-only coils, receive-only coils, and transmit–receive coils) for imaging different parts of the body. Recently, for 7 T and above MRI, transmit–receive multi-channel RF transverse electromagnetic (TEM) coils [1] have been widely used, since they have a large field of view (FOV) and produce relatively homogeneous  $B_1$  fields. However, TEM coils have a relatively low SNR, compared with a surface coil placed closest to the body, and have the ability to improve SNR, but they have a small FOV. A large number of surface coils can be arranged as an array to produce a high SNR and cover a larger FOV. The benefit of using parallel receive-array RF coils has been shown, with up to 32 channels, for the brain, spinal cord, and heart [2–4]. In those conventional studies, receive-only coils were combined with full-body coils, which helped to increase SNR while the transmit magnetic field ( $B_1$ ) is not strong enough in the body. Instead, replacing the body coils with TEM coils can increase the SNR and control the input power excitation, as shown in Fig. 1. In this Letter, phased-array RF coils (in varying numbers of 8, 16, 32, and 44 channels) arranged in a helmet-shaped fashion were placed along with 8-channel transmit-only TEM coils at 7 T to increase the SNR and provide better  $B_1$  homogenisation.



**Fig. 1** Conventional full-body and proposed TEM coils with surface-coil arrangement around human head model

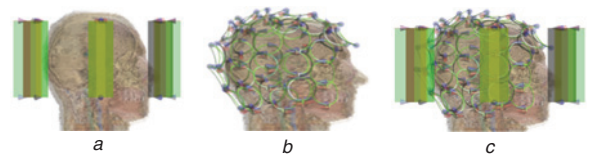
**Method:** When designing a surface-coil resonator, its geometry is usually chosen according to the desired location of the imaging around the human body where an optimum SNR is desired. If the resonator radius is very large, it will collect excessive noise from the surrounding area, but if the radius chosen is small, it will acquire less of the signal from the desired area. Both these situations will ultimately lead to degradation of the SNR. For a desired depth ( $d$ ) within the tissue, the radius of the surface-coil resonator should be  $d/\sqrt{5}$  [5]. In this research, a new model of curved surface RF coil resonator was constructed, and the resonator optimised to increase SNR throughout the ROI and to improve parallel imaging performance (up to 44 channels) while preserving the homogeneity of the magnetic field. A 3D model and detailed dimensions of a single-channel receive-only surface coil are shown in Figs. 2a and b. Each resonator consists of two capacitors ( $C_1$  and  $C_2$ ) for tuning and matching the coils at a Larmor frequency of 298 MHz. The substrate used in this work for all the surface coils

is Rogers 4003 (dielectric constant of 3.38). The thickness and width of the substrate are 0.7 and 3 mm, respectively. The substrate is covered with a copper layer that also has a thickness of 0.7 mm and a width of 3 mm. The coils are arranged at equidistant positions (varying from 8, 16, 32, and 44 channels) around the head model to improve the SNR homogeneously throughout the ROI. Each surface-coil resonator is curved so it can be placed closer to the head, and the acquired signal can be stronger.



**Fig. 2** 3D model and dimensions of surface-coil and TEM-coil resonators  
a 3D model of single-channel receive-only surface-coil resonator  
b Dimensions of single-channel receive-only surface-coil resonator  
c 3D model of single-channel transmit-only TEM coil resonator  
d Dimensions of single-channel transmit-only TEM coil resonator

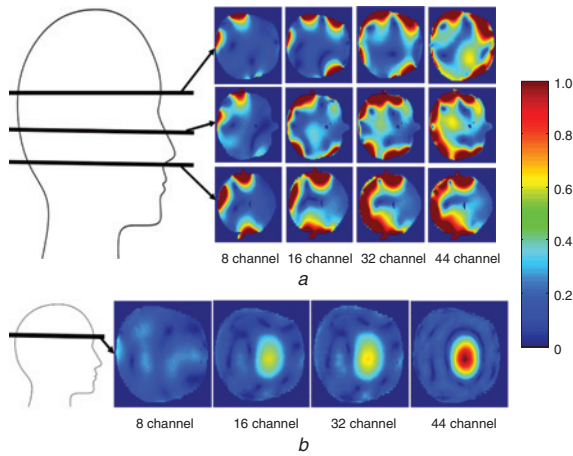
Although a surface coil can generate a higher SNR, it generates inhomogeneous magnetic fields around the phantom, which is why transmit-only TEM coils are utilised along with receive-only surface coils for homogeneous field distributions. A transmit-only TEM coil resonator was designed, as shown in Fig. 2c. Two trimmer capacitors (a port capacitor and a termination capacitor) were used for tuning and matching each channel. Usually, a TEM coil requires a transmit–receive switch for changing between transmit and receive modes, but this arrangement does not need it, as the TEM coil presented in this Letter is designed to work only in transmit mode. As shown in Fig. 2d, a single-channel TEM coil resonator consists of a microstrip transmission line and a finite ground plane. Teflon having a dielectric constant of 2.08 was used as a substrate for all TEM coils [1]. This research utilised the phased-array concept by varying the number of receive-only coils to obtain an optimum number of coils for high-SNR images of the head. The curved surface coils (8, 16, 32, and 44 channels) are combined with TEM coils, and the receive coils were placed close to the head in a helmet-shaped fashion around the TEM coils, arranged as shown in Fig. 3. Electromagnetic simulations were performed using a discretised model of the human body and a finite-difference time-domain method (SEMCAD X, SPEAG, Zurich, Switzerland) at 298 MHz. SEMCAD X was used in this research to estimate SNR by utilising Hoult’s principle of reciprocity, which illustrates that SNR is directly proportional to  $B_1$  field:  $SNR \propto B_1 / \sqrt{P_{dis}}$  [6]. Convex optimisation is utilised to localise transmit ( $B_1^+$ ) and receive ( $B_1^-$ ) magnetic fields. A localisation technique was used for receive-only coils, where the RF power of transmit coils was localised at the centre of the human head, and the receive coils were used to obtain better SNR at the ROIs.



**Fig. 3** Coil arrangement around human head model  
a Arrangement of transmit-only TEM coils  
b Arrangement of receive-only surface coils  
c Effective arrangement of transmit-only TEM coils and receive-only surface coils

**Results and discussion:** To determine the performance of the different configurations, it is necessary to evaluate  $B_1$  field performance of the various coil arrangements. Table 1 shows comparisons between  $B_1^+$  field (transmit) distributions of body coils and TEM coils. It is clear that a TEM coil provides a higher  $B_1^+$  field around a human head phantom. Table 2 shows the  $B_1^-$  field (receive) distribution of different receive channels around the human head phantom, and using 44 channels provides a higher  $B_1^-$  field, in comparison with other configurations.

It is clear from Fig. 4a that 44-channel coils provide overall good performance along all slices, in comparison with other combinations of 8, 16, and 32 channels. Fig. 4b shows that  $B_1^-$  field localisation is better from 44 channels, leading to a higher SNR from 44 channels.  $B_1^+$  and  $B_1^-$  shimming was done with the utilisation of convex optimisation for transmit–receive coils.



**Fig. 4**  $B_1^-$  map for receive-only surface coils

a Without optimisation  
b With optimisation

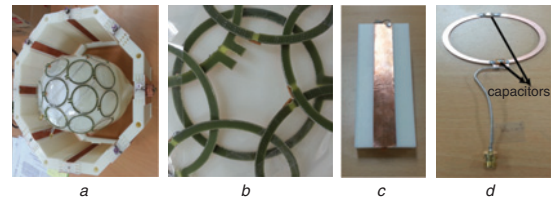
**Table 1:** Comparison of  $B_1^+$  field distribution between conventional body coils and TEM coils

	Body coils	TEM coils
$\Sigma B_1^+$ on head (mT)	0.515	8.763
Mean value (nT)	8.54	145.35
Standard deviation (nT)	12.05	178.53

**Table 2:** Comparison of  $B_1^-$  field distribution between different receive coils

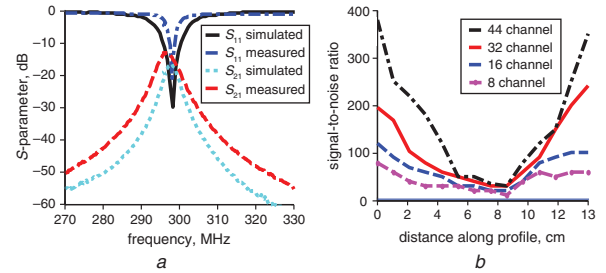
	8 channel	16 channel	32 channel	44 channel
$\Sigma B_1^-$ on head (T)	3.52	5.04	7.52	9.18
Mean value ( $\mu$ T)	0.58	0.83	1.24	1.52
Standard deviation ( $\mu$ T)	0.58	1.77	2.43	2.62

Fig. 5 shows the measurement setup as well as a prototype of the implemented design. For simplicity, Fig. 6a shows the simulated as well as measured reflection coefficient ( $S_{11}$ ) of single-channel receive-only coils. It also shows the  $S_{21}$  parameter between the closest coils that are placed around the phantom. The  $S$ -parameter response is sensitive to the load and position of the coil with respect to the human body, so initial adjustments were performed with the coils positioned close to the human head.  $S_{11}$  was found to be smaller than  $-15$  dB at 298 MHz for both simulation and measured scenarios, proving that the coil matches  $50 \Omega$  at this frequency.  $S_{21}$  represents coupling between the closest pairs of coils, and all values are smaller than  $-12$  dB. The simulation was done with 55 channels in the surface coils, but it showed no significant improvements in  $B_1^-$  field, compared with 44 channels. Fig. 6b shows the relative SNR against distance along the human head. The SNR is directly proportional to the  $B_1^-$  field and found its highest values along the surface, decreasing as it goes farther away from the coil. In this Letter, 44-channel receive-only surface coils along with 8-channel transmit-only TEM coils were selected, as they provided the overall increase in SNR while preserving  $B_1$  homogeneity, in comparison with the other coil combinations.



**Fig. 5** Implemented design with human head phantom

a Prototype  
b Measurement setup  
c Single-channel transmit-only TEM coil resonator  
d Single-channel receive-only surface-coil resonator



**Fig. 6** Reflection coefficient and SNR of receive-only surface coils

a  $S$ -parameters of receive-only coils  
b SNR against distance along profile

**Conclusion:** This Letter suggests that it is possible to achieve substantial improvements in homogeneity and SNR by using a large number of relatively small receive coil elements in a close-fitting helmet design, along with transmit-only multi-channel TEM coils at 7 T. Although sensitivity was found to be highest at the cortex, significant improvements were observed throughout the ROIs. The 44-channel receive-only RF coils in combination with 8-channel transmit-only TEM coils provided optimum performance by preserving a homogeneous magnetic field while increasing the SNR.

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One or more of the Figures in this Letter are available in colour online.

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