Applications of dielectric pads, novel materials and resonators in 1.5T and 3T MRI

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Abstract. In order to boost the performance of magnetic resonance imaging without increasing the static magnetic field, it is necessary to increase its intrinsic sensitivity. This allows a reduction in the scanning time, increased spatial resolution, and can enable low-field strength systems (which are much cheaper and can be used to scan patients with metallic implants) to have a higher signal-to-noise ratio (SNR) so that they are comparable to more expensive higher field strength systems. In this contribution, we demonstrate radiofrequency field enhancing and shaping devices based on novel materials, such as high permittivity dielectric structures and metamaterials. These materials can substantially enhance SNR, thus potentially increasing image resolution or allowing faster examinations.

1. Introduction

In almost all magnetic resonance experiments, the equipment used to detect the very small signals (radiofrequency (RF) coil) consists of simple structures made of copper conductors [1]. Different approaches have been proposed to enhance MRI characteristics while keeping the static field constant. The main approach is the optimisation of arrays of RF coils used for signal reception. The use of multichannel coil arrays results in a substantial improvement of the SNR and enables a significant increase in the speed of MRI data acquisition (at the cost of SNR) using parallel imaging methods. However, one area that is only beginning to be explored is the use of new materials in MRI that can boost the sensitivity. The field of materials research has produced many new types of material in the past twenty years, and this gives an enormous opportunity to investigate how MR detection can be improved by using and designing new materials.

Here, we demonstrate how to improve clinical MRI systems by using composite materials, such as metamaterials and very high permittivity low loss ceramics. The use of these composite materials enables an unprecedented degree of freedom in the manipulation of RF fields in MRI, and leads to increases in local SNR and reductions in local tissue heating (reduction of specific absorption rate (SAR)).

2. Metasurface for increase in local transmit efficiency

The vast majority of clinical MRI scans use a body coil for transmission. While this allows homogeneous excitation over all body parts at a field strength of 1.5 T, it is naturally quite inefficient for imaging relatively small regions of the body such as the extremities. Although SAR is not typically a limiting factor at 1.5 T, it does become an issue when patients with metallic implants have to be scanned. In this case, the local SAR limits must be reduced significantly, even if the body part being imaged does not correspond spatially to a region of high SAR. Therefore it would be highly advantageous to be able to increase the local transmit efficiency close to the imaging region-of-interest since the overall power, and therefore SAR delivered to the patient can be decreased while maintaining optimum image quality.

We experimentally demonstrated an increase in the local transmit efficiency of a 1.5 T MRI scanner by using a metasurface formed by an array of brass wires embedded in a high permittivity low loss medium [2]. Placement of such a structure inside the scanner results in strong coupling of the RF field produced by the body coil with the lowest frequency electromagnetic eigenmode of the metasurface. This leads to spatial redistribution of the near fields with enhancement of the local magnetic field and an increase in the transmit efficiency per square root maximum specific absorption rate in the region-of-interest. We have investigated this structure in vivo and achieved a factor of 3.3 enhancement in the local radiofrequency transmit efficiency [2]. This metasurface can be considered as a wireless coil that redistributes electromagnetic fields and increases the local transmit efficiency in the area of interest.

3. Annular resonator for 3 T MRI based on artificial-dielectrics

Dielectric resonators have primarily demonstrated at ultra-high field strengths, where the dimensions of the resonators are tractable. However, at clinical field strengths the dimensions, specifically the outer diameter of the resonator, are too large to be practical. Here a novel design of a compact annular volume resonator based on the combination of high permittivity materials and an array of nonmagnetic metallic wires is presented, and we refer to this type of structure as an artificial-dielectric. Composite structures made of metal inclusions were actively investigated after the second world war and were named artificial-dielectrics. These artificial materials were characterized by enhanced values of the effective permittivity and were mainly used as materials for microwave lenses. The development of artificial-dielectrics was an important step toward to the concept of ‘metamaterials’ – novel materials with artificially created electromagnetic properties. Nowadays, the term metamaterial has expanded to include many classes of previously-developed materials such as artificial dielectrics, artificial magnetics, chiral and bi-anisotropic media which exhibit unusual features. Although there have been many previous examples of using “metamaterial” structures for MRI, the vast majority have been surface elements. We demonstrated the first application of an artificial-dielectric in a volume coil design [3]. The artificial-dielectric resonator operates as a passive wireless structure which is electromagnetically coupled with the body transmit coil on a commercial 3 Tesla clinical MRI system. Electromagnetic simulations and phantom verification of the performance of the proposed resonator will be presented, and compared to those of a physically larger conventional dielectric resonator.

4. High permittivity dielectric pads improve the transmit field and receive efficiency

We proposed and evaluated both theoretically and experimentally a ferroelectric material based on BaTiO3 (with ZrO2 and CeO2-additives) with permittivity equal to 4500 for scanning extremities at 1.5 T [4]. High values of relative permittivity and low dielectric losses in barium titanate based ceramics can be achieved by using additives of cerium and zirconium oxides that shift the Curie temperature and blur the phase transition. This material exists in a paraelectric phase, i.e. it is a ferroelectric with a Curie point below room/body (operating) temperature with a spontaneous dielectric polarization below its Curie temperature. Electromagnetic simulations and phantom/in vivo experiments showed an increased in the local transmit efficiency from the body coil of ∼20–30%, resulting in an ∼50% lower transmit power level and a significant reduction in local and global SAR throughout the body [4]. For in vivo wrist experiments, the SNR of a commercial eight-channel receive array, integrated over the entire volume, was improved by ∼45% with the dielectric pads.

5. Conclusions

The local transmit efficiency as well as the SNR can be increased for 1.5 T and 3T MRI by using, metasurfaces [2], resonators [3] and materials with very high permittivity [4]. In general case, these devices can be considered as a new wireless inductively-coupled coil. In the present form, the proposed devices need several improvements in design to increase their practical functionality. Future models might incorporate ceramics with higher permittivity and temperature stability.

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References

[1] Vaughan J and Griffiths J 2012 *RF Coils for MRI* (Wiley, New York).
[2] Shchelokova A V et al. 2018 Experimental investigation of a metasurface resonator for in vivo imaging at 1.5 T, *Journal of Magnetic Resonance* **286**, 78.
[3] Mikhailovskaya A et al. 2018 A new quadrature annular resonator for 3 T MRI based on artificial-dielectrics, *Journal of Magnetic Resonance* **291**, 47.
[4] Zivkovic, I et al. 2019 High permittivity ceramics improve the transmit field and receive efficiency of a commercial extremity coil at 1.5 Tesla, *Journal of Magnetic Resonance* **299**, 59.