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Using 3D printing to implement a hyperthermia insert for a preclinical MPI scanner

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Abstract: Magnetic particle imaging (MPI) is a rapidly developing imaging modality, which determines the spatial distribution of magnetic nanoparticles. Magnetic fluid hyperthermia (MFH) is a promising therapeutic approach where magnetic nanoparticles are used to transform electromagnetic energy into heat. The similarities of MPI and MFH give rise to the potential of integration of MFH and MPI. 3D printing is used for the manufacture of an oil-cooled MFH insert. The design and the implementation of a MFH insert for a preclinical MPI scanner is presented in this paper.

I. Introduction

Magnetic fluid hyperthermia is a method for heating nanoparticles by exciting them with an alternating magnetic field. The magnetic nanoparticles (MNPs) are used to couple magnetic energy into the body to heat tissue via hysteresis power loss. MPI is a new imaging modality that makes use of the nonlinear magnetization of the MNPs [1]. The physical principles of MFH and MPI are similar, and similar magnetic nanoparticles are used for both. Furthermore, in MPI, the gradient fields saturate the nanoparticles everywhere except in the vicinity of a field-free region (FFR). In the saturated regions, the particle magnetization is effectively locked in value and only the MNPs in the FFR can respond to an AC excitation field and generate heat, which makes the spatially selective MFH possible. MPI and MFH may be integrated together in a single device for simultaneous MPI-MFH to allow for seamless switching between imaging and therapeutic modes [2]. The challenge of integrating the MFH insert into the MPI scanner lies in the minimization of its effect on the MPI receive chain. The voltage induced in the receive coil of the MPI system caused by the insert can damage the low noise amplifier (LNA). Therefore, a compensation coil is needed. A modified DEPSO (Differential Evolution Particle Swarm Optimization) algorithm is proposed and used to optimize the structure of the compensation coil [3].

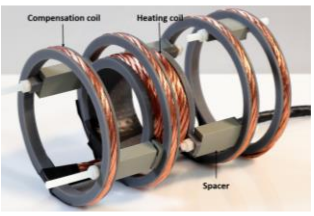

Figure 1: Prototype of the MFH insert.

The specific topology of the coil is difficult to achieve with conventional manufacturing and a high level of integration is mandatory to make good use of the finite space inside the MPI scanner. Addictive manufacturing techniques allow manufacturing of customized parts with complex shape [4,5], which have been successfully used for MPI applications in the past. In this work, the insert is implemented using additive manufacturing and tested under high power.

II. Material and methods

The MFH insert is composed of a heating coil and a compensating coil. The heating coil is a solenoid coil positioned at the center of the scanner bore; while the compensation coil is in series with the heating coil but wound in the opposite direction.

II.I Design of the prototype and cooling unit

A prototype is manufactured to validate the effectiveness of the compensation (Fig. 1). According to the coil configuration given by DEPSO, the compensation coil can be made of 4 windings, which should be positioned at -58 mm, -9 mm, 60 mm, and 91 mm to the FFP along the bore axis. The prototype is composed of 3D printed parts to support the litz wire and spacers in between of each winding to keep the windings in the designed positions (Form2, Formlabs, Massachusetts, USA and Ultimaker B.V., Utrecht, Netherlands). The compensation could be fine-tuned by iteratively adjusting the position of the windings by the use of spacers of different heights, which reduced the time of optimization.

According to simulations, a current of 170 A is needed to generate a magnetic flux density of 10 mT in the center of the coil. Therefore, the insert needs to be liquid cooled. The design of the cooling unit is shown in Fig. 2, the coil topology is identical to the prototype. The components of the cooling unit has to carry mechanical load, sustain thermal stress in high frequency magnetic field and oil surrounding environment. While the heating coil is wound directly on a PMMA tube, the compensation coil is wound on 3D-printed coil supports (Grey Resin, Formlabs,

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Massachusetts, USA) with cutouts to maximize the contacting surface to the coolant while maintaining the shape of the windings. As the Grey Resin shows no deflection up to 100 °C under experiment conditions, it can be safely used to support the litz wire. 3D printing helped to lower production times and costs significantly compared to subtractive machining of the parts. A tube shaped separator is printed from Clear Resin (Formlabs, Massachusetts, USA) and is placed between the heating coil and the compensation coil to guide the coolant flow. The printed parts are light-weighted and with a thickness of only 1.5 mm while providing all required topologic details. Thus, 3D printing allowed saving a significant amount of space. Building the main parts of the cooling unit (Fig. 2) from transparent materials (PMMA and Clear Resin) allows to assure the correct fit of all parts including the litz wire during the assembly process and enables visual inspection of the system for air bubbles in the coolant.

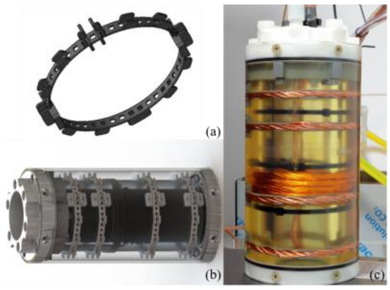

Figure 2: (a) The printed part to hold the compensation coil with cutout. (b)Design of the cooling unit. (c)Assembled insert filled with oil.

II.I High power test of the MFH insert

To test the MFH insert with high power, a power amplifier AG 1012 (T&C Power Conversion, Inc., New York, USA) is used to generate a sinusoidal 700 kHz signal. The impedance is matched to 50 Ω for optimal power transmission. To monitor the coils temperature, a PT100 temperature sensor (C220, Heraeus Nexensos GmbH, Kleinostheim, Germany) is attached to the coil through a 3D printed mount. The feedthrough signal from the coil to the PT100 is eliminated by a low pass filter (LPF). Fig. 3 shows a block diagram of the entire system.

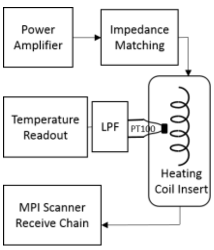

Figure 3: Block diagram of the MFH insert with the temperature sensor.

III. Results and discussion

The transmission coefficient from the insert to the LNA output was measured by a network analyzer (LF-RF E5061B, Keysight Technologies, California, USA) to evaluate the effectiveness of the compensating coil. Taking into account the amplifying effect of the LNA, the dampening of the insert at 700 kHz is 101 dB, 88 dB and 54 dB for x, y and z channel respectively. Due to the good compensation result, the power level of the induced signal in the receive chain of the MPI scanner is below the maximum input power of the LNAs in all three channels when the send power of the MFH insert is below 1 kW. The magnetic field generated by the MFH insert in a volume of 22.5 mm × 18 mm × 12 mm around the center of the heating coil is measured in steps of 1.5 mm in each direction. The covered volume is chosen to imitate the size of a rat brain, which is the target for MFH therapy in this project. The average magnetic flux density was determined to 11.2 mT, with a standard deviation of 4×10^{-4} mT. The working frequency of the setup is tuned to 700.8 kHz at room temperature. With 650 W output power the current in the coil reaches 150 A_{rms}. The temperature sensor indicates that the cooling system of the coil is effective.

The printed parts showed high precision and stability. The cooling unit is filled with oil over a time span up to months and tested with high power under pressure up to two bars for several times, no deformation of the printed parts is observed. The material could be used to print parts for the integration of the insert into the MPI scanner and phantoms for future measurements.

IV. Conclusions

Within the scope of this work, a hyperthermia insert for a preclinical MPI scanner was implemented, which allows for the generation of a high frequency magnetic field suitable for MFH. Additive manufacturing offered the crucial ability to build parts with complex geometry from different materials. This made it possible to integrate the optimized coil system and a suitable cooling unit. Due to the high level of integration, the limited volume inside the MPI scanner is used effectively which allows for a wider range of experiments within the insert.

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Author's statement

Conflict of interest: Authors state no conflict of interest. The authors would like to thank the German Federal Ministry of Education and Research (BMBF) in the framework Health Research (Gesundheits-forschung), contract number 13GW0230B, 13GW0071D and 13GW0069A for financial support.

References

[1] B. Gleich and J. Weizenecker. Tomographic imaging using the nonlinear response of magnetic particles. *Nature*, 435(7046):1217-1217, 2005. doi: 10.1038/nature03808.

[2] D. Hensley, Z. W. Tay, et al. Combining magnetic particle imaging and magnetic fluid hyperthermia in a theranostic platform. *Physics in Medicine & Biology*, 62(9), 3483, 2017. doi:10.1088/1361-6560/aa56 01

[3] H. Wei, A. Behrends, et al. Implementation of a heating coil insert for a preclinical MPI Scanner designed using DEPSO. *International Workshop on Magnetic Particle Imaging*, 209, 2019.

[4] S. Dutz, A. Stang, L. Wöckel, D. Zahn, C. Grüttner, N. Löwa, O. Kosch, F. Wiekhorst, 3D printed measurement phantoms for evaluation of magnetic particle imaging scanner, Transactions on Additive Manufacturing Meets Medicine, Vol 1 No 1 (2019): Trans. AMMM, DOI: 10.18416/AMMM.2019.1909S03P12.

[5] A. C. Bakenecker, I. Topolniak, K. Lüdtke-Buzug, B. R. Pauw, T. M. Buzug, Additive manufacturing of superparamagnetic micro-devices for magnetic actuation, Transactions on Additive Manufacturing Meets Medicine, Vol 1 No 1 (2019): Trans. AMMM, DOI: 10.18416/AMMM.2019.1909S09T06