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Gradient power reducing using pulsed selection-field sequences

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Abstract

Large selection-field power is required to generate a sufficient gradient strength in Magnetic Particle Imaging (MPI). Without cooling, the subsequent heat generation can limit the maximum experiment time. For commercially available MPI scanners a lot of effort was put into active cooling requiring space and infrastructure to dissipate heat. In this abstract, a promising power handling for the selection-field generation is presented. Using a pulsed instead of a continuous selection-field the gradient strength can be increased and no active cooling is required.

I Introduction

Magnetic Particle Imaging (MPI) uses static and dynamic magnetic fields to measure the spatial distribution of superparamagnetic iron oxide nanoparticles [1]. Recently, a human-sized MPI brain imager was presented, generating a moving field-free-point (FFP) in a large field-of-view (FOV) with a sufficient gradient strength [2]. For this MPI scanner, the generation of the selection-fields is the most power consuming part. In MPI, the spatial resolution is proportional to the gradient strength [1]. The gradient strength in turn is proportional to the currents in the selection-field coils. In operation with high current densities and without active cooling, over time the selection-field coils can reach a critical limiting temperature. However, for some applications, it is not mandatory to operate the selection-fields continuously, but instead several repetitive periods would be sufficient. Since MPI has proven to generate perfusion maps for the detection of ischemic stroke [2,3], one targeting application would be recurring monitoring after stroke treatment in an intensive care unit (ICU). In this particular scenario, short repetitive measurements over long monitoring times would be required. To be accommodated in the ICU a compact bed-sized MPI-scanner without requirements on the building infrastructure would be needed. Previously, a pulsed excitation field was proposed [4], which aims at sharpening the point-spread function (PSF) and thus should not be confused with the present work that targets the selection field. We propose a variable pulsed current sequence for selection-field generation. By sequently switching of the selection-field the heat generation is reduced which opens up a multitude of measurement scenarios and operating locations. In the experiments, all measurements were done with the human-sized MPI brain imager [2].

II Material and methods

II.I Dynamic selection-field

The electromagnetic generation of the selection field inside the MPI scanner is performed by a coil setup in Maxwell configuration consisting of two coils wounded around a soft iron yoke. Beside amplifying the magnetic field the soft iron yoke serves as structural support and provides a thermal capacitance. Each selection-field coil

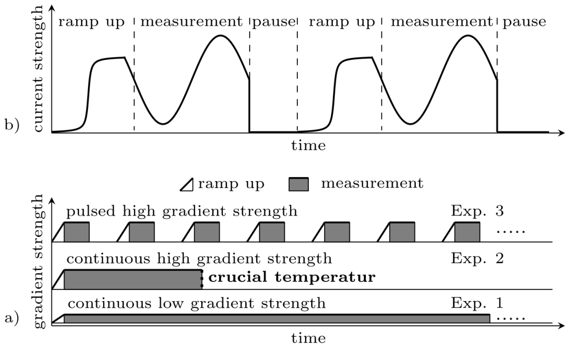

Figure 1: The schematic drawings of the three experiments with two different gradient strengths are depicted in a). The design of the applied pulsed measurement sequence for the selection-field generation is shown in b). Depending on gradient strength, a pause time to decrease the heat generation is inserted. To prevent overshooting of selection-field currents, a ramp-up function prior to each measurement is used.

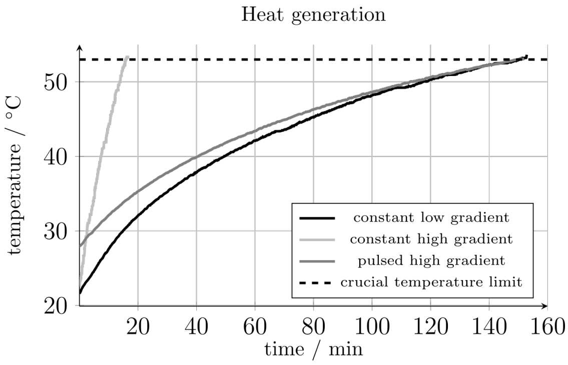

Figure 2: Heat generation during 2D measurements over time with a crucial temperature limit of 53 °C. The measured selection-field coil temperature depending on a continuous low gradient strength of 0.1365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ is marked in black. The temperature behavior by an increased continuous gradient strength of 0.2365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ is marked in light gray. Using the same gradient strength but with a pulsed sequence, a temperature behavior similar to the low gradient strength can be observed in gray.

consists of 648 turns of copper band fixed with epoxy resin resulting in an inductance of 200 mH. In order not to stress the epoxy resin too much, a critical temperature limit of 53 °C is defined for the scanner. Each coil features a serial resistance of 1.8 Ω and is fed by a programmable current source (SM-1500, Delta Electronica). Static currents in the coils generate a gradient strength of 0.0236 $\mathrm{Tm}^{-1}\mu_0^{-1}$ per Ampere. DC currents of 5.8 A generate the low gradient strength of 0.1365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ while the high gradient strength of 0.2365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ is generated by static currents of 10 A. In addition, the selection-field coils are also used to generate a slowly shifting focus-field. Applying sinusoidal shaped currents with a phase difference of π between each selection-field coil, the FFP is moved towards the coil carrying the lower currents. The applied sinusoidal currents feature an amplitude of 3.7 A for the high gradient strength and an amplitude of 2.15 A for the low gradient strength. The currents oscillate with a frequency of 2 Hz. Together with an orthogonal drive-field a 2D slice is sampled by the trajectory of the FFP [5]. This measurement sequence is applied for all experiments.

II.II Experiments

Several temperature measurements were carried out to assess the heat generation. The temperature was measured with PT100 probes placed in the epoxy resin layer between the soft iron yoke and each coil. In a first experiment, the sinusoidal shaped 2D sequence with a low gradient strength of 0.1365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ was set in a continuous mode and the temperature behavior was observed (see Fig. 1, a). To achieve a higher spatial resolution the gradient strength was increased to 0.2365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ in a second experiment. For some applications, it is not mandatory to measure continuously. To take advantage of measurement interruptions, a pulsed procedure was developed (see Fig. 1, b). It switches off the selection field after a selectable number of measurement periods and adds a selectable pause time. Due to the reactance of the selection-field coils, the coil currents show a limited slew rate. To suppress overshoots by the control unit of the current source, the sequence starts with a smooth ramp-up function. The end of the measurement sequence is appended to the end of the ramp-up function and enables the currents to be stabilized before the actual measurement period begins (see Fig. 1, b). Using the pulsed sequence a period length of 5.9 s was set, consisting of 3 s pause time, the ramp-up function and the measurement time for one 2D slice.

III Results and discussion

In Fig. 2, the selection-field coil temperature in dependence of the experiment time is shown. The first experiment used a continuous 2D measurement sequence with the low gradient strength. The applied lower currents allowed a measurement for 152.8 minutes until the critical temperature limit was reached. With the applied measurement sequence, image frames are measured with 2 Hz. Thus 18331 image frames where measured during that experiment. Increasing the gradient strength to 0.2365 $\mathrm{Tm}^{-1}\mu_0^{-1}$ led to a much steeper temperature rise, limiting the experiment time to 17 minutes (see Fig. 2).

The shortened experiment time decreased the number of measured image frames to 2035. Compared to the continuous measurement, the results of the pulsed experiment showed a duty cycle of 8.57 %. The course of the temperature curve in Fig. 2 is similar to the continuous measurement with a low gradient strength. The crucial temperature limit was reached after 152 minutes resulting in 1554 measured image frames. Since there was no active temperature control, the three experiments started with different temperatures of 21.6 °C, 22.6 °C and 28.1 °C in the order of the experiments. The slew rate of the temperature in the pulsed experiment was lower compared to the slew rate applying a constant low gradient. If, in addition, the temperature offset of 6.5 °C between the two experiments is considered the experiment time further increases. For a 24 h monitoring scenario after stroke treatment, one could consider measuring perfusion maps every 30 minutes. With 120 continuously measured image frames required to create perfusion maps, the duty cycle decreases to 3.33 %. The resulting lower heat generation enables the required long monitoring times. The application of pulsed sequences with certain duty cycles limits the number of measured image frames over time. In the experiments, the number of continuously measured image frames with the high gradient strength was larger than the number of pulsed measured image frames, even though the experiment time was longer. However, for system calibration measurements with a sufficiently dense sampling [2], the pure robot movement time exceeds the maximum experiment time of 17 minutes of the second experiment. By smart using of pause times during robot movement, the total measurement time for system matrices minimally increases.

IV Conclusions

Within this work, we presented a pulsed sequence for the electromagnetic generation of the selection fields to create variability for different measurement scenarios. We could generate higher gradient strengths for longer experiment times before reaching a crucial limiting temperature. Since no active cooling is required, the MPI scanner can be used spatially flexible, e.g. in an ICU. Furthermore, the presented approach can also be applied to other magnetic field generation processes such as drive-field generation.

Author's Statement

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