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Interactive comment on “Topologically Optimized Magnetic Lens for MR Applications” *by* Sagar Wadhwa et al.

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Authors: We would like to thank the reviewer for the time and patience for the detailed review of our manuscript. We hope that our comments and the revised manuscript will meet the reviewer's expectations.

Reviewer: The manuscript describes the design and implementation of a technique to increase the amount of RF power delivered to the sample region in magnetic resonance experiments. The B1 coils in MR experiment do a two fold job: a) Creating a homogeneous magnetic field pulse along a direction perpendicular to the main magnetic field direction (taken to be the z-direction in general), b) Detecting the flux induced by the larmor precession of sample magnetisation, the main signal in a MR experiment. The signal to noise measured in any MR experiment thus critically depends on the efficiency of this coil to do both its jobs. In this manuscript a magnetic lens design is computationally optimised such that it focuses more of the rf power from the B1 coil into the sample volume. The optimal design is also fabricated and tested to check for power enhancement at the sample.

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Discussion paper

Improving signal to noise(S/N) and resolution are a constant objective of new techniques introduced in MR. This manuscript provides a way to augment the hardware in exciting MR set-ups to increase S/N by about a factor of two. The technique derives its working principle from the Lenz lens used to enhance the effective filling factor of sample in receiver coils in MR. The manuscript shows a way to computational optimise the lens design to get the most out of the system. Though the enhancement achieved in the end is not very different from the standard Lenz lens design, given the constrains of construction, it demonstrates the possibility to use such a software optimisation for building coils with specific deliverables. They use commercial finite element analysis software for the task. The method can be modified to design coils with other specification such as broad tunability or homogeneity over a specified region of interest etc. Thus the manuscript demonstrates the possibility to use this technique for hardware improvements in MR receiver coil design.

The article starts by introducing the need for S/N improvements in MR and describes some of the hardware techniques that have been used in literature for enhancing sample filling factor and rf power at the sample. **It would be nice to also talk about typical homogeneity in rf fields of the various coils current in use**.

Authors: We have added the information about the magnetic field homogeneity of the coils that were used for the post processing of the Optimized Lens in lines 242 and 270 of the revised manuscript.

Reviewer: The Lenz lens(LL) is introduced and the need to optimising the LL lens to achieve specific goals is mentioned. The background of topology optimisation for inverse material design is also introduced with relevant references.

The main aspects of the new design concern the electromagnetic wave propagation through medium and the electrodynamics involved in magnetic induction and wave propagation through interface. The relevant electromagnetic equation: Maxwell equations and its modifications for the problem are properly introduced. The boundary conditions under which the equations are solved for also explained. **The parameter called penetration factor p needs to explained.**

Authors: To answer the reviewer's request we assume that, the penalization factor *p* was referred to as the penetration factor in Equation 13. If our assumption is correct, the penalization factor was used in the conductivity function to assign a conductivity value for different values of γ_p, as shown in Figure 2 (b) of the manuscript. By changing the value of *p*, the range of conductivity values corresponding to the range of γ_p can be altered, as shown in Figure 1 of this document, where the shaded regions correspond to $\gamma_p \in$ [4.5,5.5]. For lower values of *p* the design obtained will contain grayscale conductivity values that will not have any physical meaning. To reduce the grayscale it was necessary to increase *p*. However, for higher values of *p*, the material would be assigned as *Cu* even for values of γ_p close to zero (i.e. $\gamma_p \approx 0$). The maximum value up to which *p* could be increased was based on trial and error method, and was found to be optimal for *p* = 3. We have added this information in the revised manuscript between lines 134-139 and line 140. Figure 1 is added to the Supplementary of the manuscript.

Reviewer: They provide a comprehensive list of constrains and conditions under which they solve for the optimisation. **It would be nice to know if these conditions are sufficient in themselves, may be with some representative examples from literature**.

Authors: The control equations were defined such that the *Cu* distribution obtained tries to satisfy two conditions, i.e. the field enhancement, and its homogeneity in the sample region. During the numerical experiments, we did not find other conditions that might have helped to improve these goals, without over-constraining the optimization computation. The results obtained are an indication that the control equations were sufficient to produce the desired results, though the uniformity was not as good as the coil itself, as these two conditions were in conflict with each other as mentioned in line 52 of the revised manuscript. When this reply was written, even after a thorough investigation we could not find any supporting literature where topology optimization was used for the scenario presented in the manuscript i.e. optimization of RF devices for field enhancement while maintaining homogeneity.

Reviewer: The optimisation protocol basically creates a region of metal (Cu) and air and finds the profile of Cu that would give rise to the required field strength and uniformity at the sample region. A design variable γ is used to define free space or Cu [0 or 1]. They use a hyperbolic tangent function, defined by a parameter β, to define the material contrast between the Cu and air regions such that construction of the coil would be practical without region defined in multiple grayscale. The numerical algorithm is set up in a commercial software - COMSOL. The various steps for calculating the optimal lens (OL) by iterating over γ and β is explained starting from a initial shape with uniform γ and linearly boundaries (β=1). **The β values are course grained as each increment of β doubles its value. Would a 'slower' increment give better optimisation or the boundary shape change is still sufficiently slow with this step size?**

Authors: The reviewer's observation is correct in assuming that, with the slower increment of β the hyperbolic tangent function's shape change was slow. The β value used in Equation 12 of the manuscript was used to transform this equation from a linear (for lower values of β) to a unit step function (for higher values of β) as shown in Figure 2(a) of the manuscript. This was done to produce a high contrast material distribution, as γ_p is forced to be either air or *Cu* for higher values of β. The reason for not choosing a smaller step size was that the filtered design variable, γ_f would have been projected by a similar function and this would have increased the iteration steps without improving the optimization process (We have added this information between lines 179-182 of the revised manuscript).

Reviewer: The details of the procedure for obtained a OL lens at 45MHz and 500 MHz are explained. Post processing simulations to check the field enhancements given the OL are also performed and the results are explained well. The enhancement obtained are compared to standard receiver colis in their MR instruments for OL and LL and the results are well tabulated in Table 2. The inhomogeneity in the magnetic field are also simulated and compared. They also justify the fact that the amplification achieved was not very different between OL and LL due to practical constrains.

They go ahead and fabricate the LL and perform NMR nutation experiments to demonstrate the rf field enhancement and the results are well tabulated in Table 3.

The paper successfully demonstrates that commercial finite element software can be used to find practical, optimal LL lens with set goals even if the OL does not show much difference from LL.

The theory, the numerical algorithm, simulation and the NMR experiments are all explained well and figures and tables are well presented. The language of the text though requires to be improved. There are many grammatical and typographical errors in the article that need to be taken care of. I will attempt to list a few below......

Authors: We apologise for these mistakes and have corrected them. With all due respect to the reviewer's suggestions, correction #2 was not made. The choice between "a" or "an" was based on the vowel sound of the word 'RF' as suggested in Merriam-Webster: https://www.merriam-webster.com/words-at-play/is-it-a-or-an, last access: 03 September 2020. All changes made are indicated in blue in the revised manuscript.

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Fig. 1. Response of the conductivity function for different values of the penalization factor. The shade regions corresponds to the conductivity values for $\gamma_p \in$ [4.5,5.5]. [FIGURE IS SEPARATELY UPLOADED]

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