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

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Wadhwa et al.

11

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September 17, 2020

Authors: We would like to thank the reviewer for taking out time to review our manuscript. We welcome the comments made, and hope the response to the questions raised will meet the reviewer's expectations.

Reviewer: Sensitivity is the bane of nuclear magnetic resonance spectroscopy and any improvement in the signal to noise ratio (SNR) is welcome. The paper under review is in that vein; it discusses the design, by computer optimization, of a "distributed metal track"(in the words of the authors) to serve as a Lenz lens. A Lenz lens, called so because it uses Lenz's law of induction and like a lens focusses the magnetic field by a larger coil into a smaller region, when placed between the RF circuit and the sample improves the SNR in MRI and NMR by engineering the distribution of the magnetic field intensity in a region of interest. The paper demonstrates the optimal topology of a Lenz lens, which is then fabricated and its use validated in MR applications at 45 MHz and 500MHz.

The approach adopted is topology optimization, which answers the question "how to place material within a prescribed design region for optimal performance?" Topology optimization is achieved by the use of an adjustable, spatially varying material property. The authors selected the conductivity of the medium to be a function of the spatial coordinates, which they allowed to vary between that of free space, and Cu, a range of10e7. The uniformity of the RF field, which determines the flip angle of the pulse, was the control equation which was minimized subject to a number of constraints. Following the design of two optimal Lenz lenses (one operating at 45 MHz and another at500 MHz) using a commercial finite element software package, in a second simulation stage called post-processing, the magnetic field distribution in the lenses were characterized by replacing the background field with the magnetic field produced by a realistic coil geometry. Finally, the lenses were fabricated and their performance verified with nutation experiments on a water sample at 45 MHz in a 1 T pre-clinical MRI machine and at 500 MHz in a high resolution NMR spectrometer.

They conclude that topology optimization, using a commercial finite element tool, offers a feasible way to find practical Lenz lens arrangements which can be easily fabricated. They were able to find lenses with a B_1 enhancement of about 1.5, a marginal increase in SNR (1.2 and 1.6), a modest decrease in the π/2 pulse duration, and that the topologies are a compromise between signal enhancement and field uniformity.

The improvements demonstrated are modest and restricted to 2D, but the approach shows promise. The mechanics of the paper (the English, punctuations, capitalization, etc.) is, however, in need of some serious repair; errors of this nature are too numerous to even list. The authors are also encouraged to consider some other questions/comments given below.

1. Reviewer: In the introduction, the two sentences on filling factor appear to be in disagreement.

   Author: We apologise for this. What we meant by the statement was that, due to the filling factor (geometrical relation between the coil and the sample volume),

   the maximum usable sample volume is limited by the size of the effective B_1-volume of the coil. But if the sample volume happens to be smaller than the size of the coil, the filling factor can also be improved by reducing the coil's size. We have rephrased the sentences and the changes are indicated between lines 19-25 of the revised manuscript.

2. Reviewer: Chemical elements, such as Cu, are not italicized.

   Author: We thank the reviewer for pointing this out. The chemical elements written in Italic type have been replaced by the suggestion from the Copernicus Publications using LaTeX command `\chem{}`. The changes are indicated in the revised manuscript.

3. Reviewer: The acronym OL is not defined.

   Author: We have now defined the acronym *OL* in the revised manuscript's line 77.

4. Reviewer: What are the limitations of restriction to 2D geometry?

   Author: By reducing the computation to a 2D problem we restricted the material distribution on a plane normal to the B_1 direction. This was done because from Maxwell's equations, it is known that the curl of the current gives the direction of the magnetic field; therefore, to get a unidirectional magnetic field, the material interpolation would have been dominant on this plane. One of the limitations with this approach is that the magnetic field amplification was not along the entire cross-sectional length of the sample, as shown in the graphs in Figure 4 of the manuscript. A 3D design evolution could have improved it. Additionally, 3D topology optimization has the potential to further improve the field homogeneity, since the design will have an extra degree of freedom for material interpolation.

   The inverse material design in 3D space comes with its challenges as discussed in the Conclusion of the manuscript. One major issue is to fabricate the design obtained. Another issue is that the design domain will be restricted to allow for sample placement. Adding additional control equations to overcome these problems over-constrain the optimization problem resulting in a non-converging computation. We still need to work on finding proper conditions, which can provide a useful 3D geometries.

Reviewer: The sample volumes are much smaller than is practically used so any gain in SNR is compromised because of smaller sample volume.

Author: We agree with the reviewer that a smaller sample volume will degrade the *SNR* of the acquired signal. We do not conflict the fact that, in a conventional NMR spectroscopy or imaging, the sample volume used is much higher than the volume used by us for validating the simulation results. Through this paper, we wanted to demonstrate that for special cases for e.g., when performing *MRI* on small living organisms, or for sensitive spectroscopy of small samples, where the coil cannot be placed near the sample, as stated in line 30 of the revised manuscript; it is still possible to enhance the *SNR* of the system by improving the filling factor of the coil. One way to achieve this was by focusing the magnetic field generated by the coil in the sample region. To find the optimum material distribution which could fulfil the requirements *i.e.,* field enhancement (focusing of the magnetic field) and field uniformity, we used topology optimization to obtain the distribution of Cu. Therefore, to compare the performance of the coils with, and without the *OLs*, the sample volume was kept constant to calculate the improvement in the *SNR*.

Reviewer: Besides, when you are off-resonance, the trajectory of magnetization is not 2D anyway. Some discussion on this would be welcome.

Author: To answer the comment made by the reviewer, we have assumed two scenarios:

a)**The coil and Lenz lens arrangement are not tuned to the frequency of operation**

As mentioned by the reviewer "the trajectory of magnetization is not 2D..". The magnetization will have three components in this case. However, only the magnetization component in I_x and I_y direction will contribute to the *NMR* signal, any magnetization along I_z is irrelevant. The *NMR* coils are designed to deliver a unidirectional magnetic field (B_1); therefore, by the reciprocity principle of Maxwell's equations, the coil will only detect the magnitude of the magnetization projected along the B_1 direction. Similarly, the Lenz lens enhances the magnetic field in the direction of B_1; therefore, the Lenz lens will only enhance the signal produced due to the magnetization in the direction of B_1. Though, the signal acquired will be weak if the detector/receiver arrangement is not matched and tuned. This would also be the case when a sufficient volume of the sample is used, but the coil is not matched and tuned at the Larmor frequency.

b)**Lenz lenses are used at frequencies; besides, for the one they have been designed for *i.e.,* 45 MHz, and 500 MHz**

This will not have any effect in the field enhancement, or as a matter of fact on the tuning condition of the coil (as mentioned in line 38 of the revised manuscript); though, the field uniformity may be disturbed. The Lenz lenses are broad-band up to their resonance frequency (as mentioned in line 37 of the revised manuscript). The geometry obtained for low-frequency will also enhance the magnetic field if used at higher frequencies. The field enhancement improves with the increasing frequency (due to stronger inductive coupling) but the uniformity degrades due to the asymmetric material distribution (mentioned in line 247 of the revised manuscript). For the high-frequency geometry, the structure obtained is symmetric, and so is the field distribution with the enhancement. If this geometry is used at lower frequencies the field enhancement will be poor compared to the low-frequency geometry. The characterisation of the lenses at different frequencies was not done, since it was assumed that, if required the operator would design the lens at the frequency of operation to get a better performing device. By better, we mean the lens which produces the magnetic field enhancement, whilst maintaining field uniformity.

Reviewer: Would having two 2D lenses at the two ends of a solenoid be useful? Was it considered?

Author: This is an interesting observation by the reviewer. Ideally, a Lenz lens should also amplify the field in the rings of the solenoid, which should improve its performance, but it's not straightforward. This condition was already explored and reported by Spengler et al. (2017). It does improve the homogeneity further, but only if it forms a kind of a Helmholtz coil pair. Nevertheless, the individual *LL* must also be uniform in order to achieve this condition, and hence, that was why we chose the optimization of a single *LL* as a goal.

5. Reviewer: In Figure 5, what does it mean to have relative length in mm? Would it not be dimensionless?

   Author: We apologise for this confusion. The graph in Figure 5, represents the amplification profile in the x-direction (red), and z-direction (blue), where the horizontal axis represents the relative distance from the centre point of the *OLs*. We have added this information in the caption of Figure 5.

6. Reviewer: It is BRUKER AVANCE not ADVANCE

   Author: We apologise for this typo and have corrected them in the revised manuscript.

7. Reviewer: Figures 6 c) and 6 f) are not nutation spectra; their Fourier transform is.

   Author: Agreeing with the reviewer's comment we have modified the caption of Figure 6 to include that the graphs represent the Fourier transform of the nutation spectra.

Reviewer: Why is there an asymmetry (below and above the maximum) in Figure 6 c) with OL.

Author: As stated in line 310 of the revised manuscript, there was a large magnetic field drift experienced for the ICON system, which was aggravated due to the lack of a frequency locked channel. This causes issue for the long measurements, which was the reason for the asymmetrical nutation spectra.

8. Reviewer: A number of points in the conclusions (3D geometry, Eddy currents, tuning and matching) merit some elaboration in the manuscript.

   Author: We have elaborated the points mentioned by the reviewer in the revised manuscript.

   Reviewer: The statement “It is hardly a surprise that the quest for more signal-to-noise from an existing NMR detector arrangement is matter of numerical optimization.” is questionable.

   Author: We apologise for the confusion that our statement might have created. What we meant was that in an NMR detector, by adding a passive element (in this case a Lenz lens), if all other conditions *i.e.,* the volume, the current applied to the coil, etc. are kept constant, the numerical optimization can help to find an optimum design for such passive elements to enhance the *SNR*. We have rephrased this sentence in the revised manuscript.

   Reviewer: Pardon my ignorance, but I do not know what a “Pareto front” is.

   Author: "Pareto efficiency" is a concept named after "Vilfredo Pareto". It is used to define a situation where an objective cannot be improved further without affecting the other objective or objectives.

   For the explanation, if we have a bi-objective model, where the objective functions are represented on the two orthogonal axes, the line connecting the current objective values forms a front. Improving one objective, generally worsens the other *i.e.,* the "Pareto Front" shows the compromise. One can then choose between different values of the objectives to find the best compromise (Jones,Dylan and Tamiz,Mehrdad (2010)). We have added the reference in the revised manuscript

References

Jones, Dylan and Tamiz, Mehrdad: Practical Goal Programming, in: International Series In Operations Research and Management Science (volume 141), edited by: Hillier, Frederick S., Springer, New York, Dordrecht, Heidelberg, London, 2010, https://doi.org/10.1007/978-1-4419-5771-9.