nature portfolio

# Peer Review File

## Nonlinear Metamaterials Enhanced Surface Coil Array for Parallel Magnetic Resonance Imaging

**REVIEWER COMMENTS**

**Reviewer #1 (Remarks to the Author):**

The paper concentrates on the design and application of non-linear metamaterials (NLMMs) for Magnetic Resonance Imaging (MRI).

In particular, the authors demonstrate a signal-to-noise ratio (SNR) enhancement in parallel imaging applications.

Simulations combining circuit simulations of nonlinear components are fused with numerical EM simulations using commercial software.

Based on the simulations, experiments are performed in a laboratory setup and MRI scans are performed using a 3T system and an 18-channel coil array.

The results are solid, and the paper is well written and understandable to the common reader, also without an extensive background in the field.

The theoretical and experimental results appear to be of high standards and are correct.

However, I have a few comments:

1) MRI should be called more a medical imaging modality, not an apparatus; see Abstract line 16

2) Claiming that ''this research lays the foundations for practical utilization in clinical settings'' is not true and I cannot support this view (see comments below); see Abstract line 29

3) Check line 41 after Ref. 9

4) Line 57: it is true that metamaterials may have properties that do not occur naturally, but I would not make this a defining property.

5) Line 78: in addition to Refs. 25-27, also Ref. 30 is about non-linear metamaterials which are shown not to influence the transmit field and should be named here as well for completeness.

6) Line 80: It is not true that ''non-linear metamaterials automatically enhance the RF reception field exclusively''.
They can be designed to do so, as demonstrated in Refs. 25-27 and 30, and the present work. However, imagine the design of the inverse NLMM that is proposed in these works. It would only influence the transmitted RF field, but not the reception field.

7) Though the statements from lines 87 - 89 is generally true, it somewhat holds for the present paper as well since also for the MRI applications in the present paper one could choose a better-suited Rx coil of which the size is adapted to the phantom in use; see the general comments below.
Moreover, reading Ref. 30 I have the impression that there are indeed scenarios in which a metamaterial in combination with the body coil (large birdcage coil integrated into the MRI scanner) can yield a better SNR performance than surface coils or arrays. This observation is substantiated in the work ''Volumetric wireless coil for wrist MRI at 1.5 T as a practical alternative to Tx/Rx extremity coil: a comparative study'', doi: 10.1016/j.jmr.2022.107209

8) Line 382: Clinical applications may not be in reach yet as claimed, and there are some open problems which need to be solved. Thus, the way is not yet paved.

General comments:
Firstly, the metamaterial structure presented here appears somewhat bulky and obstructs potentially clinical use.
In total, several centimeters for the meta atoms, the nonlinear varactor-loaded parts, the distance to the coil, and the acrylic holder result in a structure which may not be of use in clinical routine.
In the literature, e.g. in Ref. 30 that is cited, designs seem to be presented that are more than one order of magnitude thinner (at the mm scale) and also allow for similar detuning effects regarding the transmission field interaction.

It seems to me that for experiments and MRI scans only a 2x2 metamaterial array was used, and it is clearly misleading that in Fig. 1 a 4x4 structure is shown.
With regard to this, the comparison in the MRI results part is not justified.

As can be seen in Fig. 1 a, the metamaterial covers a significantly smaller area/volume than the Rx coil. Thus, it is not surprising at all that locally the constellation with the suggested metamaterial yields a larger SNR as would a smaller Rx coil, to which the metamaterial might be compared in terms of SNR increase.
For a 2x2 arrangement, we can barely speak of a metamaterial at all. All unit cells are boundary elements (in a 4x4 or larger realization there are interior elements with a different number of coupled nearest neighbors).

Moreover, the required spacing between the metamaterial and an Rx coil is, of course, utterly important for tuning the entire system and handling the delicate interactions, but there seems to be no other alternative for (fine-)tuning of the metamaterial's resonance frequency for the suggested realization.
Precise spacing may again obstruct the use in a clinical setting and the lack of a tuning capability does not allow to adjust the author's metamaterial to different loading conditions (patients) or MRI scanner types (different vendors with slightly varying static field strengths).

For better performance, have you thought about back-to-back mounted varactor diodes as non-linear elements? What are the advantages of varactor diodes compared to different components with similar functionality?

What is the benefit of having a nonlinear element in every single meta atom? Why does this strategy outperform the available designs in the literature, e.g. in Refs. 25 or 30, in which the entire metamaterial is detuned with just one single nonlinear element?
As every lumped component will decrease the quality factor, it is difficult to follow the author's design decisions.

Some of the results in the present work are not drastically new or unexpected.
i) It was shown before in the literature that metamaterials can outperform local Rx coils; see, e.g. the recent work ''Enhancing the brain MRI at ultra-high field systems using a meta-array structure'', doi: 10.1002/mp.16801 and references therein.

ii) Transmit detuning via non-linear elements is shown in several works that the authors cited (Refs. 25-27 and 30) and the detuning in the present work does not seem to be superior or radically new.

iii) The present works seems to build on the publications cited in Refs. 22 and 25 (note overlapping authors). The metamaterial design is already explored in those works and is adopted in the present work (with the inclusion of nonlinear elements in every single unit cell now).

iv) EM-circuit co-simulations are not new. It is valuable though that the authors performed this analysis and the results for the nonlinear parts are convincing.

I do think the authors produced valuable scientific results and I am convinced that the methods hold up to high standards, but I have some doubts that the present paper represents a sufficiently striking advance to justify publication in Nature Communication. Thus, I recommend publication in a different journal, as the results deserve to be published. However, ultimately this decision has to be made by the editor.
If publication in Nature Communications is appropriate, I suggest that the authors submit a revised version of the manuscript.

**Reviewer #2 (Remarks to the Author):**
The authors proposed a metamaterial-inspired structure with a nonlinear response for improving the signal-to-noise ratio of the multichannel receive arrays in MRI. The task posed in the work is relevant, and the manuscript contains the elements of substantial work. However, several essential details and evidence must be added to the paper to address the posted aim fully. Please find below the specific comments.

Major comments:

1. The novelty of the research needs to be increased. The design of the proposed NLMM is very similar to ones that have been described in the previous works of some of the authors,

e.g., https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201905461, https://www.nature.com/articles/s42005-019-0135-7. So, the key point of the current research is to investigate how the metamaterial-inspired structure affects the sensitivity, signal-to-noise ratio, and detuning of the multichannel receive array. In this sense, it is needed to add more details and sufficient results. In particular,

1.1 Page 5, lines 85-87 The following statement in the Introduction is not evident since these structures still have the resonant response and may affect the coil tuning and matching: 'The property of NLMMs that only interact with the RF reception field renders them compatible with receive-only multichannel surface coil arrays.' I suggest reformulating it or removing this part.

1.2 Page 13, lines 259-261: 'The NLMM was positioned on the top of the coil Body 18, and the gap between the two was mechanically adjusted using an acrylic plate bracket in order to control the coupling effect strength.' Could the authors estimate the coupling effect quantitatively? How exactly was the structure located relative to the coil elements (it is advisable to have a clearer schematic view of the experiment)?

1.3 Page 14, lines 285-286: 'As the gaps between the coil Body 18 and the NLMM increased, the noise decreased (Fig. 3f insets).' - It is unclear what noise and signal levels the coil had in the reference case. Did all antenna elements participate in signal reception, or only several?

1.4 Continuing the previous two comments, the authors found the optimal gap between the coil and coil array for particular cases, i.e., a particular object and coil geometry. What if one takes the human-size object (that is a more clinical case) or the coil with more dense elements? This is one of the key points of the work that should be described in detail. The chosen load – a bottle phantom is too small, while the authors claim that they used a commercial coil optimized for the upper trunk imaging. The receive coil is tuned and matched in the presence of a specific load. It is irrelevant to scan a small object with it. It is necessary to make a comparison with the human-sized objects to convince of the practical functionality of the concept. Of course, it is ideal to perform in vivo studies as was done in several related works already [e.g., https://onlinelibrary.wiley.com/doi/10.1002/adma.202102469 or https://www.nature.com/articles/s41467-020-17598-3]. At a minimum, please use a proper phantom. In addition, please explain how much the quality factor of the proposed NLMM structure will change when placed near a large load in the form of a human body. In this

regard, are there any limitations in the applications of the proposed structure?
2. Fig. 5 from supplementary material: The average angle is not apparent from the presented angle map. I recommend using a jet colormap. Also, please provide graphs of the signal depending on the angle like was done in Ref. https://onlinelibrary.wiley.com/doi/10.1002/adma.202102469 (see Fig. 3c). It is one of the common ways to estimate the effect to transmit field.
3. The results of experimental studies with apple do not look compelling. This small object (besides not biological) has nothing in common with the human body. In addition, we see an increase in the signal in a tiny area; from the images, I can assume that it is about a couple of cms, while the signal in the upper part of the apple is smaller. The image with NLMM looks noisier than in the case of a standard coil. As was mentioned above, I suggest changing the sample and estimating the SNR in the region of interest that may be of clinical interest, e.g., the liver, if we are talking about the abdomen imaging.
4. Page 18, lines 380-382: 'By simply scaling the NMAs, we can readily tune the resonance frequency of the NLMM to match the Larmor frequency in ultra-high MRI.' I cannot fully agree with this judgment. The fact is that when we work in ultra-high-field MRI, using a body coil for transmission becomes irrelevant since the transmission field will be non-uniform due to the reduction in the RF wavelength. So, the common practice is transmitting antenna arrays (dipoles or loops or a combination of both). It is not evident that the approach proposed by the authors will work similarly for such systems. I would suggest adjusting the sentence and leaving it at the level of an idea for future work rather than a statement.

Minor comments:

1. Page 3, lines 38-41: It seems like there is a typo at the end of the sentence, or something is missed: '...,1 among others.'
2. Page 12, lines 255-256: the sentence 'We conducted experiments on a Siemens 3 T Prisma MRI system to assess the effectiveness of the NLMM in enhancing the SNR of MRI with a surface coil array' should be revised as ...the effectiveness of the NLMM in enhancing the SNR of a surface coil array. The SNR is a key characteristic of the receive coil used in MRI. For me, 'SNR of MRI' sounds uncertain.

3. Page 14, line 296: there is a typo in ‘reduces ta the MRI operating frequency’.

**Reviewer #3 (Remarks to the Author):**

The work is technically sound and is a novel contribution to the field.

It would be useful to know how this technique compares to other metameterial/metasurface MRI designs that are in the literature, and to also elaborate on applications where very localised SNR improvements would be advantageous.

Dear reviewers,

We sincerely thank you for the insightful comments and suggestions in evaluating our manuscript entitled "Nonlinear Metamaterials Enhanced Surface Coil Array for Parallel Magnetic Resonance Imaging". We found all the comments and suggestions are constructive and helpful, and we have considered each point raised, implementing revisions accordingly. Notably, we have significantly enhanced our manuscript by incorporating experiments of in-vivo MRI validation and providing details of our metamaterial design. We have endeavored to address the major concerns in the reviews, which include:

Firstly, in response to the strong concerns regarding the absence of demonstrations of our nonlinear metamaterials (NLMMs) on appropriate phantoms and biological materials, we conducted in-vivo human lower leg imaging following the acquisition of ethics approval. We compared the signal-to-noise ratio (SNR) of NLMM-enhanced imaging with that of imaging solely using the surface coil array (SCA). Our findings demonstrated a maximum SNR enhancement of ~2.8 times when utilizing the SCA for acquisition. Especially, we found the consistent enhancement with 3-fold and 4-fold accelerated acquisitions using parallel MRI (pMRI). Intriguingly, our NLMM helped the distinguish of connective tissue between fat lobules, a distinction not discernible with pMRI using SCA alone.

Secondly, in response to the rationality and novelty of our design, we clarified the benefits of integrating nonlinear elements into each meta-atom. The advantages mainly include mitigating the amplification of coupling effects as the size of the VLSRR approaches that of the coil element. This optimization improves the integration of NLMMs with SCA. Additionally, we analyzed the minimal impact of additional loss by lumped elements on the quality factor of NLMMs. Furthermore, we discussed strategies for manufacturing lightweight and user-friendly metamaterials, aiming for further integration design and manufacturing with surface coils.

Thirdly, to address the concerns of the implementation of our NLMM, we supplemented the details of pre-experiments for determining the position of the NLMM on the SCA. Through the experiment, we identified the area where coil elements overlap and positioned the NLMM at this overlap area for pMRI validation. The coil overlap area was also the region with optimal signal baseline, enabling a more conservative estimation of SNR enhancement ratio by the NLMM. Additionally, we conducted quantitative estimations of coupling effects based on the inferred relative positions of NLMM and coil elements within the surface coil array.

Below, we listed the comments (in black text) and our point-by-point responses (in blue text). We have revised the manuscript and supplemental materials accordingly, and have highlighted the revisions. We believe that our current work has been improved by addressing your concerns.

Thank you once again for dedicating your time and attention to our manuscript.

## --------Reviewer Comments--------

### Reviewer #1:

*The paper concentrates on the design and application of non-linear metamaterials (NLMMs) for Magnetic Resonance Imaging (MRI).*
*In particular, the authors demonstrate a signal-to-noise ratio (SNR) enhancement in parallel imaging applications.*
*Simulations combining circuit simulations of nonlinear components are fused with numerical EM simulations using commercial software.*
*Based on the simulations, experiments are performed in a laboratory setup and MRI scans are performed using a 3T system and an 18-channel coil array.*

*The results are solid, and the paper is well written and understandable to the common reader, also without an extensive background in the field.*
*The theoretical and experimental results appear to be of high standards and are correct.*

We express our gratitude to the reviewer for providing valuable comments. The manuscript has been revised to enhance its clarity in accordance with the feedback received.

*However, I have a few comments:*

*1) MRI should be called more a medical imaging modality, not an apparatus; see Abstract line 16*

We thank the reviewer for the comment. We have revised the first sentence of the abstract, and the updated version is as follows:

"Magnetic resonance imaging (MRI) is a crucial medical imaging modality, …"

*2) Claiming that "this research lays the foundations for practical utilization in clinical settings" is not true and I cannot support this view (see comments below); see Abstract line 29*

We appreciate the reviewer's valuable comment. To promote the potential application of our proposed nonlinear metamaterial (NLMM), we have conducted in-vivo human extremity imaging to demonstrate the function of the NLMM, following the acquisition of ethics approval. The results will be discussed in detail below.

We have revised the last sentence of the manuscript abstract, and the updated version is as:

“This research contributes to expanding our comprehension of NLMMs and demonstrates the potential for their practical utilization in MRI and clinical settings, …”

The results of the in-vivo MRI validation are elaborated below and have been added into the revised manuscript and supplementary materials.

In the experiments, as shown in Fig. R1a (Fig. 5a in the revised manuscript), the Body 18 surface coil array (SCA) is employed for the in-vivo human imaging. The NLMM is placed on the SCA with a separation distance of 20mm, which is the optimal distance as proved by the phantom test, and the lower leg is fixed on the NLMM with the help of a leg holder. As the reference, the lower leg contacts the SCA in order to obtain optimal SNR and image quality for the solely SCA imaging.

The MRI signal is enhanced with the presence of NLMM, evidenced by the acquired images within the region of interest (ROI), as shown in Fig. R1b (Fig. 5b in the revised manuscript). We quantitatively evaluated the maximum SNR in images with and without the metamaterial, demonstrating that the NLMM achieved a maximum SNR improvement of approximately 2.8 times. The slight discrepancies in images with and without the NLMM can be attributed to the weight of legs. When the NLMM is applied, the leg holder supports the lower leg, allowing the surrounding tissue to freely drop. This contrasts with the reference case, where the full weight of the leg rests on the contact surface between the leg and the surface coil.

We validate the SNR improvement for the in-vivo pMRI. As shown in Figure R1c and R1d (Fig. 5c and 5d), images of the human lower leg using the parallel imaging algorithm at different acceleration ratios reveal the effect of the NLMM. We zoomed in the surface regions of the lower leg. With the NLMM enhancement, the separation of connective tissue between fat lobules became more prominently visible, a feature that remained evident even with 3-fold and 4-fold accelerated acquisition using the GRAPPA algorithm. On the contrary, in the absence of the NLMM, image details are blurred and difficult to discern due to decreased SNR resulting from accelerated parallel imaging. The pMRI experiment on the human leg, utilizing metamaterial-enhanced surface coils, underscores the potential of the NLMM in improving the SNR and imaging speed of clinical MRI.

Herein, we performed extremity imaging as a proof of concept. In our future work, we will perform imaging experiments on spinal or liver imaging, which is of more interest for clinical applications.

The experiment of the in-vivo imaging is added in the section of “MRI validation of NLMM using in vivo lower leg imaging” on Page 18 of the updated manuscript.

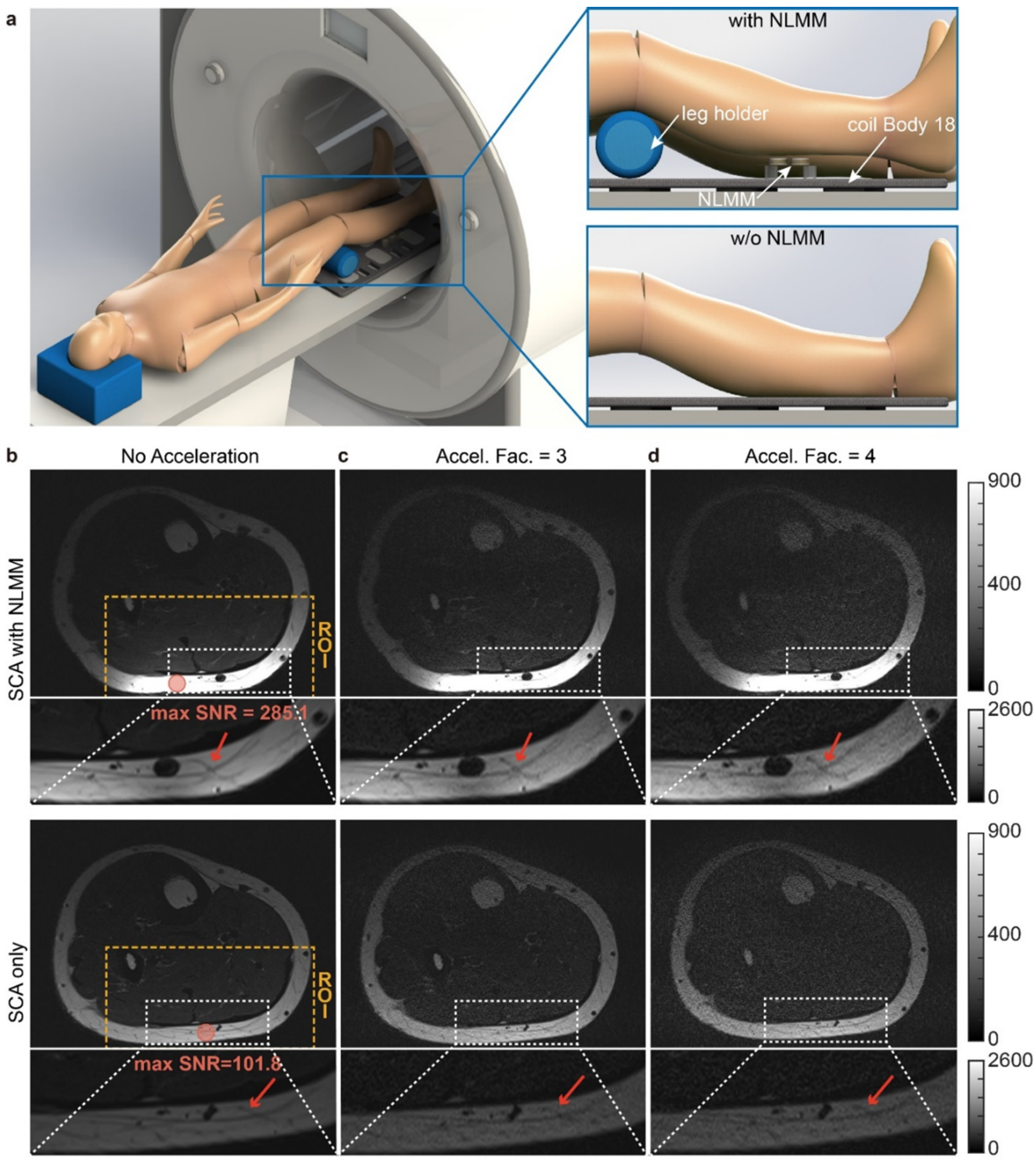


**Fig. R1 | 3T parallel-MRI of the human lower leg using Body 18 surface coil array. a** Illustration of the experimental setup, presenting panoramic and side views to illustrate configuration with and without the NLMM. **b-d** Comparison of the lower leg images acquired with (the top row) or without NLMM (the bottom row) at different acceleration settings. Insets are the enlarged images, which highlight the distinction in tissue details originating from the NLMM enhancement.

*3) Check line 41 after Ref. 9*

We thank the reviewer for the thorough review, and we have corrected the typos in the manuscript.

*4) Line 57: it is true that metamaterials may have properties that do not occur naturally, but I would not make this a defining property.*

We appreciate the reviewer for the comment. Our intention was not to imply that this is the sole defining characteristic. Rather, our aim was to highlight the unique features that distinguish metamaterials from dielectric materials, such as high permittivity ceramics for MRI enhancement.

We have revised Line 57 in the manuscript, and the updated version is as follows:

"Metamaterials are a class of artificially engineered materials characterized by periodic sub-wavelength structures, and demonstrate unique properties that are not inherent in natural substances. The sub-wavelength periodic structures are commonly named by unit cells or meta-atoms."

*5) Line 78: in addition to Refs. 25-27, also Ref. 30 is about non-linear metamaterials which are shown not to influence the transmit field and should be named here as well for completeness.*

We thank the reviewer for the thorough review. We have revised the manuscript to include Ref. 30 in reference to the nonlinear metamaterial.

*6) Line 80: It is not true that "non-linear metamaterials automatically enhance the RF reception field exclusively".*

*They can be designed to do so, as demonstrated in Refs. 25-27 and 30, and the present work. However, imagine the design of the inverse NLMM that is* *proposed in these works. It would only influence the transmitted RF field, but not the reception field.*

We thank the reviewer for the insightful comment. Achieving an inverse NLMM is possible through the design based on a pair of antiparallelly configured diode, back-to-back varactor, and so on. However, we notice that the NLMM based on a single varactor-loaded split resonant ring is specifically designed to enhance the RF reception field exclusively in most published works. This is due to the resonance amplitude decreases as the excitation power increases.

We have revised Line 80 in the manuscript, and the updated version is as follows:

"Consequently, NLMMs can be designed to selectively enhance either the RF transmission or reception field. In most cases, they specifically enhance the RF reception field exclusively,…"

*7) Though the statements from lines 87 - 89 is generally true, it somewhat holds for the present paper as well since also for the MRI applications in the present paper one could choose a better-suited Rx coil of which the size is adapted to the phantom in use; see the general comments below.*

*Moreover, reading Ref. 30 I have the impression that there are indeed scenarios in which a metamaterial in combination with the body coil (large birdcage coil integrated into the MRI scanner) can yield a better SNR performance than surface coils or arrays. This observation is substantiated in the work "Volumetric wireless coil for wrist MRI at 1.5 T as a practical alternative to Tx/Rx extremity coil: a comparative study", doi: 10.1016/j.jmr.2022.107209*

We thank the reviewer for the insightful comment, and we would like to address these concerns for better clarity.

Firstly, we agree that there is size disparity between the phantom and the selected coil in our experiment. We choose the Body 18 coil because it offers a higher coil density than available smaller-sized surface coil array, such as Flex 4. We have roughly calculated the average channel size of Siemens surface coil array, as listed in Table R1. A higher coil density could be beneficial for validating the combination of the metamaterial prototype and the surface coil array, as well as testing parallel imaging. Additionally, in response to the aforementioned comment 4), we have included an experiment of imaging human lower legs, as they present a more appropriate volume load for the Body 18 coil.

Secondly, we investigate the NLMM enhancement on the surface coil array and parallel imaging in this work. The coupling of NLMM with other types of surface coils will be studied in our future work. The ultimate goal of our future research will be generating NLMM enhanced customized surface coil to achieve optimal SNR for practical imaging. Hopefully, we may publish our future work and give the reviewer more appealing results.

**Table R1 | Average channel size in Siemens's surface coil array**

| Siemens's coil type | dimensions[1]: L×W (mm) | channels number | average channel size[2] ($mm^2$) |
|---|---|---|---|
| UltraFlex Small 18 | 190×410 | 18 | 4328 |
| UltraFlex Large 18 | 290×590 | 18 | 9506 |
| **Body 18** | **385×590** | **18** | **12619** |
| BioMatrix Body 18 | 415×619 | 18 | 14271 |
| Flex 4 small | 366×174 | 4 | 15921 |
| Flex 4 large | 516×224 | 4 | 28896 |

[1] data of coil dimensions is from https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/coils

[2] average channel size = dimensions / channels number

Thirdly, it is true that MRI images using metamaterial with a body coil have exhibited a higher SNR compared to a surface coil. Our study aims to emphasize the potential of employing metamaterials with surface coil arrays, since surface coils are gaining significance in clinical practice. We appreciate the reviewer for pointing out this discrepancy, and have revised the original manuscript.

We have revised Line 87-89 in the manuscript with comprehensive consideration of this and following comments, and the updated version is as follows:

Most NLMMs for MRI reported so far were employed in conjunction with the body coil or single-loop surface coil, with limited exploration into metamaterial structures suitable for integration within existing surface coil arrays (ref. [34] in revised manuscript). The augmentation of surface coil arrays through the incorporation of NLMMs holds considerable merit, particularly as surface coils and pMRI are gaining significance in clinical practice..

8) Line 382: Clinical applications may not be in reach yet as claimed, and there are some open problems which need to be solved. Thus, the way is not yet paved.

We appreciate the reviewer's comment. To address some concerns, we have validated our metamaterials through MRI scanning of in-vivo human lower legs, and we are working to employ our NLMM in more clinical inspection areas in future research.

We have made the necessary adjustment to Line 382 in the manuscript, and the updated version now reads as follows:

This study validates the integration and benefits of clinical imaging coils with artificial structured materials, thereby facilitating the development of MRI technology.

*General comments:*

*Firstly, the metamaterial structure presented here appears somewhat bulky and obstructs potentially clinical use.*

*In total, several centimeters for the meta-atoms, the nonlinear varactor-loaded parts, the distance to the coil, and the acrylic holder result in a structure which may not be of use in clinical routine.*

*In the literature, e.g., in Ref. 30 that is cited, designs seem to be presented that are more than one order of magnitude thinner (at the mm scale) and also allow for similar detuning effects regarding the transmission field interaction.*

We express our gratitude to the reviewer for providing insightful comments. While the current experimental setup may present some challenges in ease of use, we highlight our work as an innovative proof of concept for enhancing surface coil arrays, and especially for parallel imaging. The reviewer's valuable feedback aligns with our ongoing engineering methods to improve and offers additional perspectives.

Regarding the distance to the coil and the acrylic holder, as this distance is fixed after calibration, we plan to address this concern by employing 3D printing and other plastic molding techniques to manufacture a customized holder. We intend to package the holder along with the metamaterial component and cover them with flexible sponge materials, to make the NLMM be a more user-friendly surface coil enhancement accessory.

In our future research, we will explore techniques such as flexible printed circuit boards (FPCBs) and laser direct writing to implement thinner metamaterials. By comparing the RF field shaping and enhancement of thinner metamaterials with the presented structures, we will try to achieve compact metamaterials for MRI enhancement in future iterations.

*It seems to me that for experiments and MRI scans only a 2x2 metamaterial array was used, and it is clearly misleading that in Fig. 1 a 4x4 structure is shown.*

*With regard to this, the comparison in the MRI results part is not justified.*

*As can be seen in Fig. 1 a, the metamaterial covers a significantly smaller area/volume than the Rx coil. Thus, it is not surprising at all that locally the constellation with the suggested metamaterial yields a larger SNR as would a smaller Rx coil, to which the metamaterial might be compared in terms of SNR increase.*

*For a 2x2 arrangement, we can barely speak of a metamaterial at all. All unit cells are boundary elements (in a 4x4 or larger realization there are interior elements with a different number of coupled nearest neighbors).*

We appreciate the reviewer's comment and would like to provide further clarification on the mentioned issues.

Firstly, regarding the arrangement matter, the simulations, MRI experiments in the main text, and the VNA tests in the supplementary materials consistently use a 2×2 array. We recognize that the caption in Fig. 1a may have caused confusion, as it was intended to serve as conceptual illustrations of our proposed metamaterial arrangement. We modified the caption in Fig. 1a as "Schematic diagram illustrating the arrangement of meta-atoms to form the NLMM", and clarified the scale of the array in the Materials and Methods section.

To address the concern of the scalability, additional simulation calculations were conducted, comparing the 2×2 array with a 4x4 array. The simulation results are presented in Fig. R2. The findings indicate that: (1) the resonant frequency of the 4x4 array with the same size meta-atoms is slightly higher than that of the 2×2 array, but the frequency matching can be achieved by slight tuning of the meta-atom's radius and period (Fig. R2a); (2) the magnetic field distribution and field enhancement ratio near the central 2x2 sub-array in the 4x4 array are comparable to those in the 2x2 array, as depicted in Fig. R2b and R2c. While the 4x4 array extends the magnetic field enhancement over a larger area, both the 2x2 and 4x4 arrays exhibit similar levels of magnetic field enhancement.

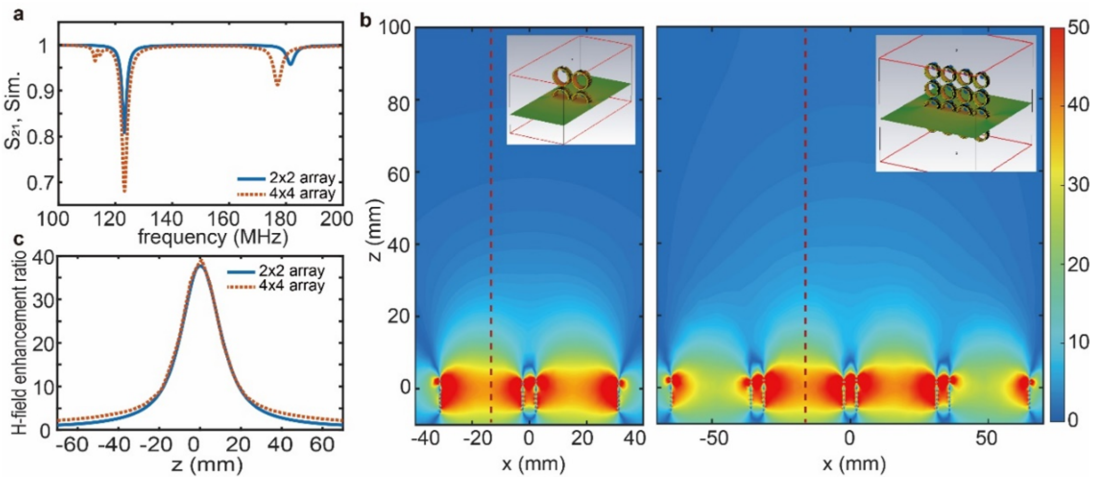


**Fig. R2 | Comparison of simulation results between 2×2 meta-atoms array and 4×4 meta-atoms array. a** Comparison of frequency resonance of 2×2 and 4×4 meta-atoms array. **b** Comparison of magnetic field distribution and enhancement ratio by 2×2 and 4×4 meta-atoms array. **c** Comparison of 1D magnetic field enhancement ratio of 2×2 and 4×4 meta-atoms array along the red line in **(b).**

Secondly, we agree the merit of comparing imaging results using metamaterials with a larger-coil-unit surface coil array to those without metamaterials with a smaller-coil-unit surface coil array. However, currently, we do not have commercially available surface coil arrays with a smaller average channel size, such as UltraFlex 18 in Table R1. Nevertheless, the improved SNR achieved now implies that the NLMM enhanced surface coil array could have the SNR comparable to the sole surface coil array with smaller-coil-unit.

Compared to the approach of integrating more electronic components and cables into limited coil space to increase channel numbers, metamaterials could contribute to enhancing SNR in parallel imaging as a passive and readily deployable method.

Thirdly, despite the fact that all units of the 2x2 metamaterial are boundary units, making it technically ineligible as a metamaterial from an equivalent parameters' perspective, for MRI-enhancing metamaterials, the shaping and enhancement of the RF magnetic field are the most crucial metrics. Therefore, based on simulation results, the 2x2 array and 4x4 array are considered analogous in this context.

*Moreover, the required spacing between the metamaterial and an Rx coil is, of course, utterly important for tuning the entire system and handling the delicate interactions, but there seems to be no other alternative for (fine-)tuning of the metamaterial's resonance frequency for the suggested realization.*
*Precise spacing may again obstruct the use in a clinical setting and the lack of a tuning capability does not allow to adjust the author's metamaterial to different loading conditions (patients) or MRI scanner types (different vendors with slightly varying static field strengths).*

We appreciate the reviewer's insightful comment. We would like to clarify that adjustments to the distance between NLMMs and surface coils are for regulating coupling strength and are only necessary during the calibration process. As demonstrated in Fig. 3f in the manuscript, deviations from the optimal coupling distance may result in a reduction in SNR; however, a certain level of tolerance is maintained.

To adapt to various loading conditions, we modify the resonance frequency of the NLMMs by adjusting the metamaterial period. Using the structure similar in [R1], this adjustment process could be a one-step operation.

*For better performance, have you thought about back-to-back mounted varactor diodes as non-linear elements? What are the advantages of varactor diodes compared to different components with similar functionality?*

We appreciate the reviewer's comment. We noticed there are studies focused on the SRR loaded with back-to-back varactors, such as ref. [36] in revised manuscript. In contrast to back-to-back varactors as nonlinear elements, a single varactor loaded SRR is more straightforward to fabricate. Specifically, it only requires soldering the varactor to the ends of the ring made by copper wire.

The primary advantages of varactor diodes include the absence of additional lumped capacitors required (compared to the antiparallel diode pair method in ref. [30] of the revised manuscript) and the absence of complex logic circuitry needed (compared to the DIP switch method in ref. [28] of the revised manuscript). Furthermore, varactor loaded SRRs have lower production complexity, and varactors are cost-effective as mature commercial components.

In our ongoing research, we are actively exploring additional nonlinear components, such as back-to-back mounted varactor diodes, heterostructure barrier varactor (HBV) and PIN diode. We aim to comprehensively compare the effects of these different nonlinear components in our investigations.

*What is the benefit of having a nonlinear element in every single meta-atom? Why does this strategy outperform the available designs in the literature, e.g. in Refs. 25 or 30, in which the entire metamaterial is detuned with just one single nonlinear element?*

*As every lumped component will decrease the quality factor, it is difficult to follow the author's design decisions.*

We appreciate the reviewer's comment. The benefit of having a nonlinear element in every single meta-atom mainly includes two aspects.

Firstly, integrating a large varactor loaded SRR (VLSRR) with the surface coil may encounter challenges due to the inductive coupling between them, potentially resulting in significant impedance influence on the coil, which can affect tuning and matching. To address this, we simplified the coil element and the VLSRR as two coaxial loops and utilized the Maxwell Formula[R2] to calculate the mutual inductance between them:

$$c = \frac{2\sqrt{Rr}}{\sqrt{(R+r)^2+\Delta^2}}$$

$$M = -\mu_0\sqrt{Rr}\left(\left(c-\frac{2}{c}\right)K(c)+\frac{2}{c}E(c)\right)$$

where *R* and *r* represent the radii of the two loops, *Δ* is the distance between them, and *K(c)* and *E(c)* are elliptic integrals of *c*. We set *R*=60 mm which is similar to the size of conventional RF coils or the VLSRR in previous studies, and calculate the mutual inductance under various *r* and *Δ*. The results are shown in Fig. R3a. We observed a significant intensification of coupling when the size of the VLSRR approaches that of the coil element, which suggests a potential for significant interference with the surface coil. To improve compatibility between the VLSRR and the surface coils, we introduced the VLSRR to each meta-atom, forming the nonlinear meta-atom (NMA).

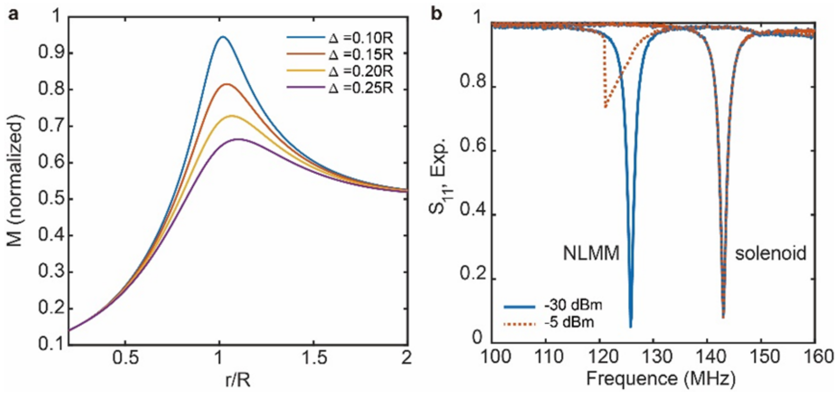


**Fig. R3 | Estimation results to illustrate the design decisions of the nonlinear meta-atom (NMA). a** Calculation results of the mutual inductance between two coaxial loops**. b** Experimental $S_{11}$ measurements of the single solenoid and the NMA.

Secondly, in previous studies, a large VLSRR primarily served as a detector for incident power. However, by incorporating a small VLSRR into each meta-atom, we ensured that all metamaterial units are identical and exhibit independent nonlinear responses, thereby making nonlinearity an intrinsic property of the meta-atoms. This independent nonlinearity feature facilitates the scalability and enables the three-dimensional deformable arrangement of metamaterial arrays. We have improved the clarity regarding these design considerations in the last paragraph of the "Design of Nonlinear Meta-atoms and Metamaterials" section in the updated manuscript, and add detailed analysis including Fig. R4 to the Supplementary Information.

Additionally, we have thoroughly considered and analyzed the losses attributed to lumped elements. Specifically, we employed for a low-resistance varactor (SMV1235-079LF, Skyworks) with an internal resistance of 0.60Ω (measured at 500MHz, 3V bias, as per the datasheet). To assess the ohmic and dielectric losses in the solenoid part of the nonlinear meta-atom (NMA), we employed equations[R3]:

$$R_{ohm} = \sqrt{\frac{\omega_0 \mu_0 \rho}{2}} \frac{l_{w,tot}}{\pi d} = 0.818\ \Omega$$

$$R_{dielec} = \frac{2\varepsilon_{im}}{\omega_0 C(\varepsilon_{re}+1)^2} = \frac{2\varepsilon_{im}\omega_0 L}{(\varepsilon_{re}+1)^2} = 15.8\ \Omega$$

The geometric parameters of the solenoid are detailed in Table 1 of the Supplementary Information, and $\rho$ is the resistivity of copper, $\varepsilon$=2+0.06i is the permittivity of the scaffold's material, and $\omega_0$=143 MHz is the resonant frequency of the single solenoid. The solenoid inductance L is calculated using the Nagaoka formula[R4]:

$$L = \frac{\pi\mu_0 N^2 D^2}{4l} F\left(\frac{D}{l}\right)$$

$$F\left(\frac{D}{l}\right) = \frac{4}{3\pi}\left[\frac{\sqrt{1+u^2}}{u^2}\big(K(k)-E(k)\big) + \sqrt{1+u^2}E(k) - u\right]$$

where $u = D/l$, $k = \sqrt{u^2/(1+u^2)}$, $K(k)$ and $E(k)$ are elliptic integrals of $k$, respectively. It is calculated as $L$=1.315 $\mu H$. The quality factor of the solenoid resonator is:

$$Q = \frac{\omega_0 L}{(R_{ohm} + R_{dielec})} = 70.8$$

Upon theoretical calculation and analysis, we find that the dielectric loss in the NLMM predominantly influences the quality factor. The introduction of the lumped element varactor into each unit results in a relatively modest increase in losses.

Furthermore, we conducted experimental measurements of the $S_{11}$ for both the single solenoid and the NMA (Fig. R3b), subsequently calculating their respective quality factors:

$$Q = \frac{\omega_0}{\omega_H - \omega_L}$$

where $\omega_H - \omega_L$ corresponds to the -3 dB bandwidth of the $S_{11}$ curve. The experimental outcomes indicate a similarity between the single solenoid (Q = 60.2) and NMA (Q = 58.6), with the experimental quality factor of the single solenoid close to the theoretically calculated values (Q = 71.3). We have added the estimation of losses and quality factor to the Supplementary Information.

*Some of the results in the present work are not drastically new or unexpected.*

*i) It was shown before in the literature that metamaterials can outperform local Rx coils; see, e.g. the recent work "Enhancing the brain MRI at ultra-high field systems using a meta-array structure", doi: 10.1002/mp.16801 and references therein.*

*ii) Transmit detuning via non-linear elements is shown in several works that the authors cited (Refs. 25-27 and 30) and the detuning in the present work does not seem to be superior or radically new.*

*iii) The present works seems to build on the publications cited in Refs. 22 and 25 (note overlapping authors). The metamaterial design is already explored in those works and is adopted in the present work (with the inclusion of nonlinear elements in every single unit cell now).*

*iv) EM-circuit co-simulations are not new. It is valuable though that the authors performed this analysis and the results for the nonlinear parts are convincing.*

We appreciate the insightful comments provided by the reviewer, and we would like to clarify the novelty of our manuscript as follows:

For comment i), we thank the reviewer for providing the latest research on metamaterials for MRI enhancement, which we have referenced in our revised manuscript. This previous work designed metamaterials utilizing broadside-coupled split-ring resonators and high-permittivity materials, which worked with a standard one-channel transmit and 32-channel receive head coil. The study demonstrated improvements in transmit efficiency and signal sensitivity. However, our study differs in two main aspects from this prior work.

Firstly, due to the shorter RF wavelength in the 7T MRI, the RF architecture of 7T MRI scanners differs from that of 1.5T/3T MRI scanners. 7T scanners lack a body coil for whole-body excitation and instead utilize transmit-receive birdcage head coils. These birdcage coils produce an outside-in uniform RF field similar to body coils. In contrast, torso coil arrays and spine coil arrays used in 3T scanners generate inside-out unilateral fields, making further SNR enhancement more challenging. Our study explores the combination of metamaterials with unilateral torso coil arrays, thus potentially expanding the application of metamaterials.

Secondly, in 7T MRI settings, where transmit field inhomogeneity is a concern, previous research has aimed at enhancing transmit efficiency. Consequently, metamaterials used in 7T MRI combined with birdcage coils have predominantly exhibited linear responses. However, in 3T settings, ensuring transmit field homogeneity with nonlinear metamaterials becomes critical. Our study validates the effectiveness of NLMM-enhanced surface coils for achieving this objective.

In response to comments (ii) and (iv), we agree that the common practice of using varactors for nonlinear, tunable, or programmable metamaterials. However, our primary objective is to employ computational electromagnetic methods to directly model the power-controlled response of metamaterials, which has not been fully investigated. Additionally, this simulation method will provide better guidance for the integrated design of surface coils and NLMM in future work.

Metamaterials utilizing varactors for control can be broadly categorized into two types: DC voltage-controlled (ref. [40,41] in revised manuscript) and AC incident power-controlled (ref. [27,42,43] in revised manuscript). Conventional simulation models the varactor as a constant capacitor and then conducts a parameter sweep of the capacitance value. Advancements have enabled the direct simulation of voltage-controlled metamaterials, with importing varactor S-parameters obtained from circuit simulations into lumped elements of electromagnetic simulations (ref. [44,45] in revised manuscript). However, the approaches for directly modeling the power-controlled response of metamaterials have not been fully investigated.

In this study, we propose an EM field-circuit joint simulation process for our NLMM with varactors to improve the understanding on the nonlinear response of metamaterials in temporal and frequency domain. Our nonlinear simulation allows us to observe the establishment of bias voltage across the varactor and the electric field distribution around the split ends, which is shown in Fig. R4. The joint simulation method effectively integrates the field and lumped element parameters.

We have revised the first paragraph of the "Numerical modeling of the nonlinear response and field distribution" section in the manuscript for clarity, and added additional simulations results including Fig. R4 to the Supplementary Information.

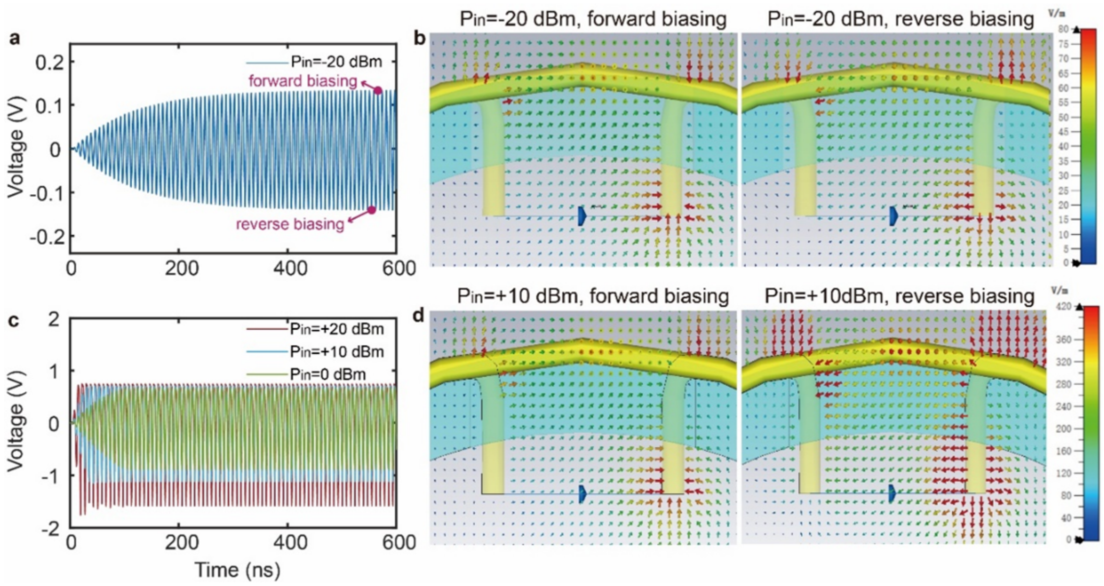


**Fig. R4 | Simulation of bias voltage establishment and electric field distribution across the varactor. a, c** Temporal domain process of bias voltage establishment across the varactor under varying incident power. **b, d** Comparison of the electric field distribution around the split ends during the peak of forward and reverse biasing occurrences.

In response to comment (iii), we have made significant progress compared to previous works. Firstly, we optimized the structure of the NLMM for surface coil application by integrating a small VLSRR into each metamaterial unit. Previous designs utilized a single large VLSRR equivalent in size to the metamaterial array for incident power detection, which posed challenges in coupling due to the large VLSRR matching the size of the surface coil element. In contrast, by introducing small VLSRRs to each meta-atom, the NMAs become identical and independently exhibit nonlinear responses, enhancing compatibility with the surface coils. More details have been provided in response to the previous comments for concerning "the benefit of having a nonlinear element in every single meta-atom".

Secondly, we introduce a novel method for enhancing the surface coil array, particularly in the context of receive-only surface coil 3T MRI systems. This study expands the application of metamaterials by integrating them with torso coil arrays. The integration of NLMM with the surface coil array represents a novel aspect of our research, and we have verified the feasibility of metamaterials in in-vivo imaging applications, particularly in parallel imaging.

*I do think the authors produced valuable scientific results and I am convinced that the methods hold up to high standards, but I have some doubts that the present paper represents a sufficiently striking advance to justify publication in Nature Communication.*

*Thus, I recommend publication in a different journal, as the results deserve to be published.*

*However, ultimately this decision has to be made by the editor.*

*If publication in Nature Communications is appropriate, I suggest that the authors submit a revised version of the manuscript.*

We express our gratitude once again to the reviewer for providing valuable comments. The manuscript has been revised to enhance its clarity.

**Reviewer #2:**

*The authors proposed a metamaterial-inspired structure with a nonlinear response for improving the signal-to-noise ratio of the multichannel receive arrays in MRI. The task posed in the work is relevant, and the manuscript contains the elements of substantial work. However, several essential details and evidence must be added to the paper to address the posted aim fully. Please find below the specific comments.*

We appreciate the valuable comments from the reviewer. The manuscript has been revised to address the concerns from the reviewer.

*Major comments:*

*1. The novelty of the research needs to be increased. The design of the proposed NLMM is very similar to ones that have been described in the previous works of some of the authors, e.g., https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201905461, https://www.nature.com/articles/s42005-019-0135-7. So, the key point of the current research is to investigate how the metamaterial-inspired structure affects the sensitivity, signal-to-noise ratio, and detuning of the multichannel receive array. In this sense, it is needed to add more details and sufficient results. In particular,*

*1.1 Page 5, lines 85-87 The following statement in the Introduction is not evident since these structures still have the resonant response and may affect the coil tuning and matching: 'The property of NLMMs that only interact with the RF reception field renders them compatible with receive-only multichannel surface coil arrays.' I suggest reformulating it or removing this part.*

We are grateful to the reviewer for providing valuable comments. While metamaterials may indeed impact coil tuning and matching, the impedance matching circuit of the coil, coupled with the subsequent amplifier, provides the coil with a certain level of tolerance in its performance. Our main strategy is to optimize the coupling strength by adjusting the coupling distance. This allows metamaterials to exploit RF magnetic field enhancement without disrupting the normal operation of the coil.

In response to this suggestion, we have removed lines 85-87 and revised lines 90-91 as follows:

"It is possible to achieve enhanced SNR in surface coil imaging without causing the coil to deviate excessively from its normal operational state."

*1.2 Page 13, lines 259-261: 'The NLMM was positioned on the top of the coil Body 18, and the gap between the two was mechanically adjusted using an acrylic plate bracket in order to control the coupling effect strength.' Could the authors estimate the coupling effect quantitatively? How exactly was the structure located relative to the coil elements (it is advisable to have a clearer schematic view of the experiment)?*

We appreciate the insightful comment from the reviewer. We shall first address the second question about the position of the metamaterial relative to the coil.

Firstly, we conducted MRI scanning of a large phantom that covered approximately 1/3 of the coil Body 18 coil we used. The imaging results of the phantom placed at different positions on the surface coil array are illustrated in Fig. R5a. In this figure, the signal intensity near the green dotted line appears higher, indicating the area where the coil elements overlap (similar to Fig.7 in doi: 10.1088/1361-6560/aab691). Additionally, in Fig. R5a, BO1, BO2, and BO3 on the left side represent the coil positioning illustrated in the MRI scanner software. Combined with the description provided on the official website, Body

18 comprises 3×6 channels, and the distribution of coil channels can be roughly estimated as depicted in Fig. R5b.

Secondly, experimental tests found that regardless of the NLMM's position on the surface coil array, the SNR after NLMM enhancement was almost consistent (Fig. R5c and R5d). In the experiments, we chose to place the metamaterial and phantom at the position along the green line on the surface coil (Fig. 5a), with a more optimal baseline and more conservative estimation for SNR enhancement ratio. Furthermore, since the SNR after NLMM enhancement remained almost consistent regardless of the NLMM's position on the surface coil array, it is advantageous for the subsequent engineering integration of large-array NLMMs with surface coils.

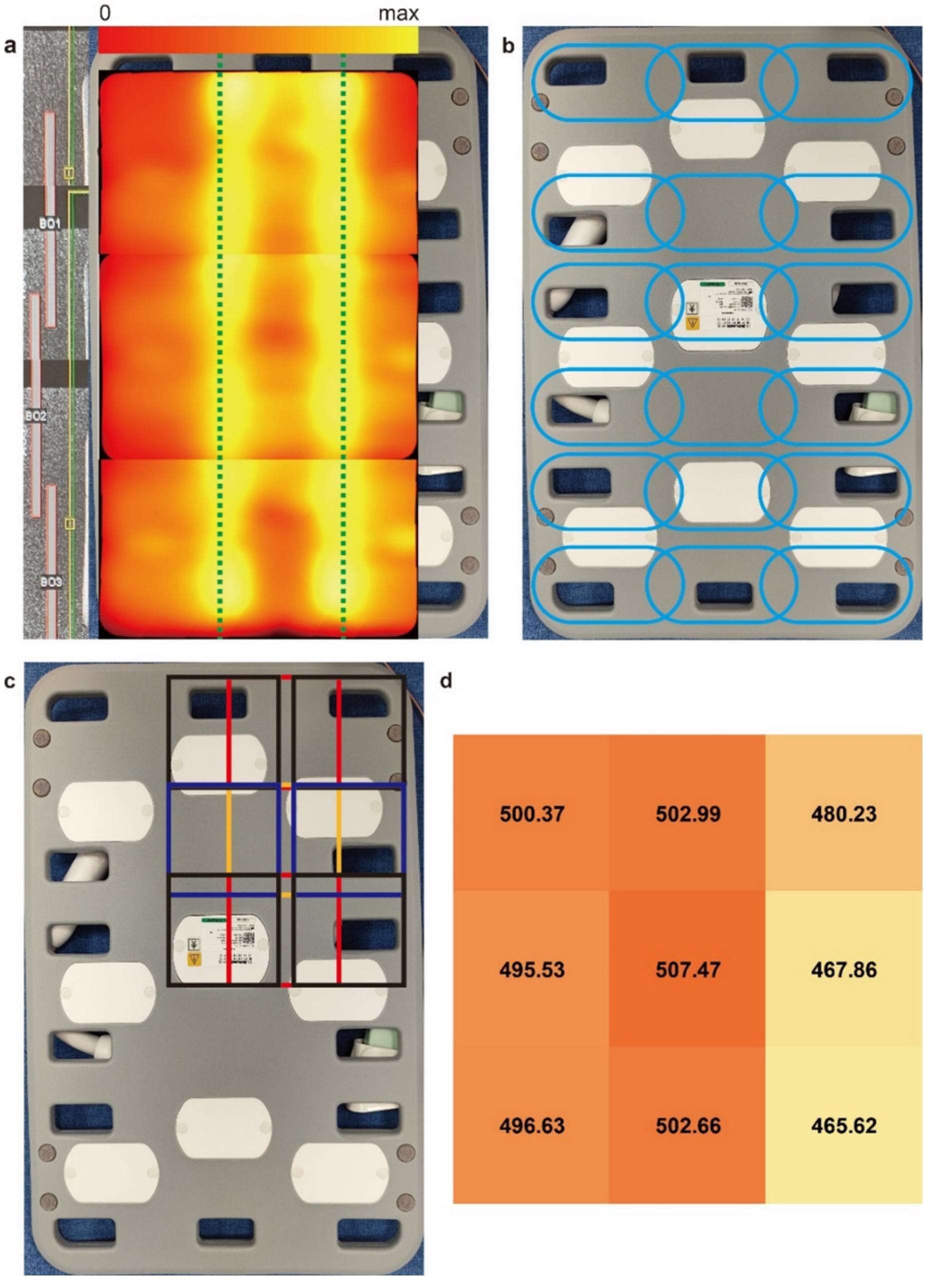


**Fig. R5 | Preliminary experiment to determine the position of the metamaterial relative to the coil. a** Images of a large phantom positioned at three different locations on the surface coil array, including the coil positioning illustrated in the MRI scanner software (BO1, BO2 and BO3 on the left). **b** Rough estimation of coil element distribution. **c** Placement of the metamaterial and the phantom at nine different positions (represented by different colored boxes) on the surface coil, with corresponding calculation of SNR (**d**).

After determining the location, we quantitatively estimate the coupling effect according to the following simplified method.

Due to the inductive coupling effect (magnetic flux coupling) between the metamaterial and the coil, we calculated the mutual inductance between the metamaterial unit and the coil element to assess the coupling strength. In our calculation, the metamaterial unit is simplified as a solenoid, while the coil element is simplified as a ring. However, it's important to note that obtaining an accurate estimation requires information on the size and arrangement of the surface coil array, which is currently unavailable due to commercial confidentiality constraints. Below, we provide an overview of our estimation method.

Firstly, we calculate the mutual inductance using the Neumann Formula[R5] between the RF coil and the unit cell in the metamaterial:

$$M = \frac{\mu_0}{4\pi} \oint \oint \frac{\overrightarrow{dl_1} \cdot \overrightarrow{dl_2}}{\Delta}$$

Where $\overrightarrow{dl_1}$ and $\overrightarrow{dl_2}$ are two elementary filaments separated by the distance $\Delta$.

Secondly, we calculate the self-inductance of the unit cell in the metamaterial. The self-inductance of unit cell is calculated using the Nagaoka formula[R4] mentioned above. The self-inductance of the coil loop is calculated as[R6]:

$$k = \frac{D}{D - \frac{d}{2}} \sqrt{1 - \frac{d}{D}}$$

$$L_{coil} = \frac{\pi}{5} D \sqrt{1 - \frac{d}{D}} \left[ \left( \frac{2}{k} - k \right) K(k) - \frac{2}{k} E(k) \right]$$

Thirdly, the coupling coefficient is given by:

$$\kappa_i = \frac{M_i}{\sqrt{L_i L_{coil}}}$$

$$\kappa_{tot} = \Sigma_i \kappa_i$$

We estimated the coupling coefficient between the two overlapping coil elements and the 2×2 metamaterial array at different coupling distances, as shown in the Fig. R6. The results show that the overall coupling strength between the metamaterial and the surface coil decreases with the increase of coupling distance. Therefore, we can decrease the coupling strength by increase the coupling distance, avoiding the surface coil to deviate excessively from its normal operational state.

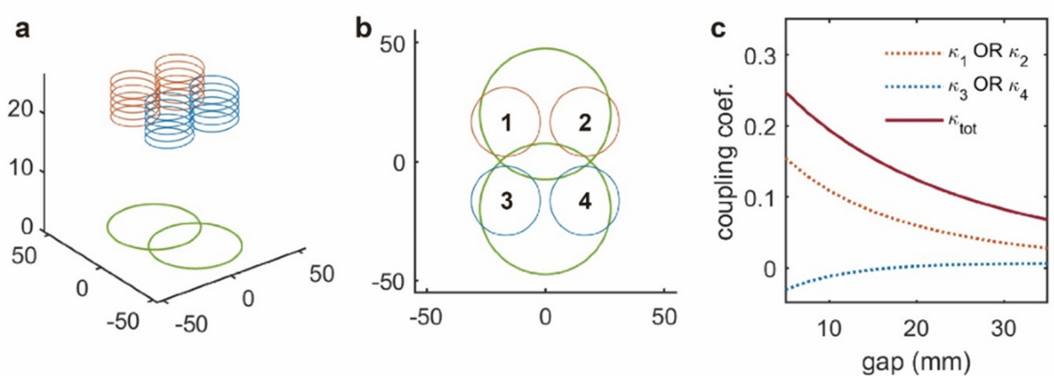


**Fig. R6 | Estimation of quantitative coupling effect. a** and **b** Schematic diagrams of simplified models used to calculate the mutual inductance between metamaterial units and coil elements. **c** Quantitative calculation results of the coupling coefficient.

*1.3 Page 14, lines 285-286: 'As the gaps between the coil Body 18 and the NLMM increased, the noise decreased (Fig. 3f insets).' - It is unclear what noise and signal levels the coil had in the reference case. Did all antenna elements participate in signal reception, or only several?*

We appreciate the reviewer's thoughtful comments. In response, we have added the value of noise levels in Fig.3b of revised manuscript. The standard deviation of noise ($\sigma_{noise}$) in the reference case is 2.36. Referring to the blue line in Fig. 3f of revised manuscript, readers can ascertain that the maximum signal level equals $\sigma_{noise} \times \max\{SNR\} = 2.36 \times 248 = 585$.

During the MRI experimental validation, we turned on all the coil element to participate in the signal reception following the default configuration, which has been added in the "Method" section of revised manuscript.

*1.4 Continuing the previous two comments, the authors found the optimal gap between the coil and coil array for particular cases, i.e., a particular object and coil geometry. What if one takes the human-size object (that is a more clinical case) or the coil with more dense elements? This is one of the key points of the work that should be described in detail. The chosen load – a bottle phantom is too small, while the authors claim that they used a commercial coil optimized for the upper trunk imaging. The receive coil is tuned and matched in the presence of a specific load. It is irrelevant to scan a small object with it. It is necessary to make a comparison with the human-sized objects to convince of the practical functionality of the concept. Of course, it is ideal to perform in vivo studies as was done in several related works already [e.g., https://onlinelibrary.wiley.com/doi/10.1002/adma.202102469 or https://www.nature.com/articles/s41467-020-17598-3]. At a minimum, please use a proper phantom. In addition, please explain how much the quality factor of the proposed NLMM structure will change when placed near a large load in the form of a human body. In this regard, are there any limitations in the applications of the proposed structure?*

We thank the reviewer for the insightful comment. While there are some mismatching of load and coil, we highlight our work as a prototype to demonstrate the concept that metamaterials can enhance MRI imaging with a surface coil array. A small phantom has been selected for experimentation due to the small-scale the metamaterial array we made.

We had concentrated on examining the response of metamaterials in larger in-vivo samples after the acquisition of ethics approval. The results of the in-vivo MRI validation are elaborated below and have been added into the updated manuscript and supplementary materials.

In the experiments, as shown in Fig. R7a (Fig. 5a in the revised manuscript), the Body 18 surface coil array (SCA) is employed for the in-vivo human imaging. The NLMM is placed on the SCA with a separation distance of 20mm, which is the optimal distance as proved by the phantom test, and the lower leg is fixed on the NLMM with the help of a leg holder. As the reference, the lower leg contacts the SCA in order to obtain optimal SNR and image quality for the solely SCA imaging.

The MRI signal is enhanced with the presence of NLMM, evidenced by the acquired images within the region of interest (ROI), as shown in Fig. R7b (Fig. 5b in revised manuscript). We quantitatively evaluated the maximum SNR in images with and without the metamaterial, demonstrating that the NLMM achieved a maximum SNR improvement of approximately 2.8 times. The slight discrepancies in images with and without the NLMM can be attributed to the weight of legs. When the NLMM is applied, the leg holder supports the lower leg, allowing the surrounding tissue to freely drop. This contrasts with the reference case, where the full weight of the leg rests on the contact surface between the leg and the surface coil.

We validate the SNR improvement for the in-vivo pMRI. As shown in Figure R7c and R7d (Fig. 5c and 5d in revised manuscript), images of the human lower leg using the parallel imaging algorithm at different acceleration ratios reveal the effect of the NLMM. We zoomed in the surface regions of the lower leg. With the NLMM enhancement, the separation of connective tissue between fat lobules became more prominently visible, a feature that remained evident even with 3-fold and 4-fold accelerated acquisition using the GRAPPA algorithm. On the contrary, in the absence of the NLMM, image details are blurred and difficult to discern due to decreased SNR resulting from accelerated parallel imaging. The pMRI experiment on the human leg, utilizing metamaterial-enhanced surface coils, underscores the potential of the NLMM in improving the SNR and imaging speed of clinical MRI.

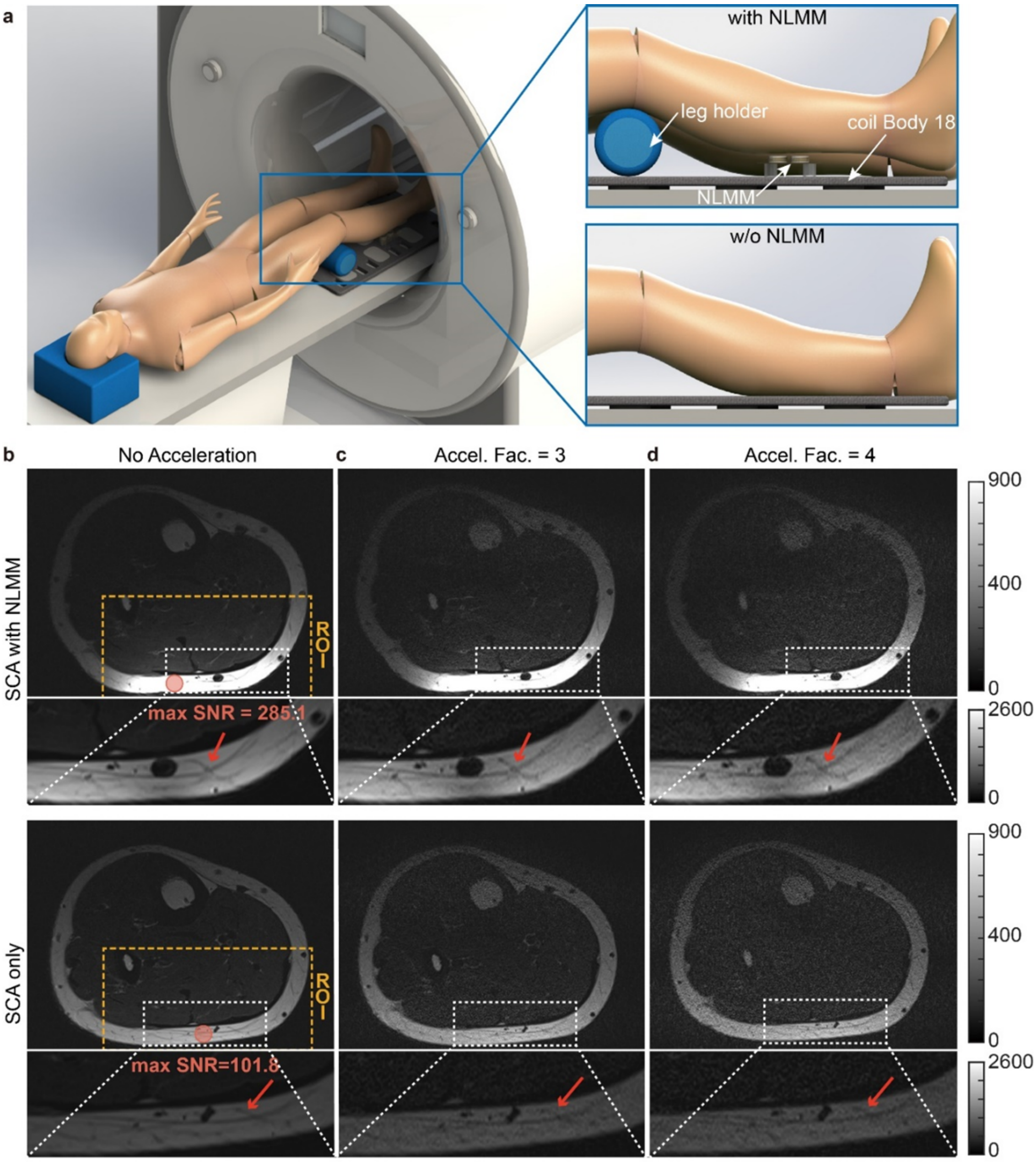


**Fig. R7 | 3T parallel-MRI of the human lower leg using Body 18 surface coil array. a** Illustration of the experimental setup, presenting panoramic and side views to illustrate configuration with and without the NLMM. **b-d** Comparison of the lower leg images acquired with (the top row) or without NLMM (the bottom row) at different acceleration settings. Insets are the enlarged images, which highlight the distinction in tissue details originating from the NLMM enhancement.

Additionally, we measured the quality factor of the proposed NLMM unloaded and loaded with the human lower leg. We utilized an S-parameter set and the network analyzer to measure the -3 dB points of the S11-parameter (Fig. R8), which provided well-defined values for the Q factor:

$$R_Q = \frac{Q_{unloaed}}{Q_{loaded}} = \frac{55.3}{43.0} = 1.3$$

$$\frac{Q_{unloaed}}{Q_{loaded}} = \frac{R_{MMs} + R_{sample}}{R_{MMs}} = 1.3 \Rightarrow R_{sample} = 0.3R_{MMs}$$

The Q value does not change much during both load and unload, indicating that the load has minimal effect on the performance of the metamaterial. However, from the perspective of the Q value, it is evident that the loss of the metamaterial is greater than that of the sample. The loss of metamaterial loss is primarily attributed to dielectric loss (as analyzed in the response to the comment of reviewer #1). Therefore, it is imperative to study scaffolds material with low loss. We appreciate the reviewer for providing this perspective.

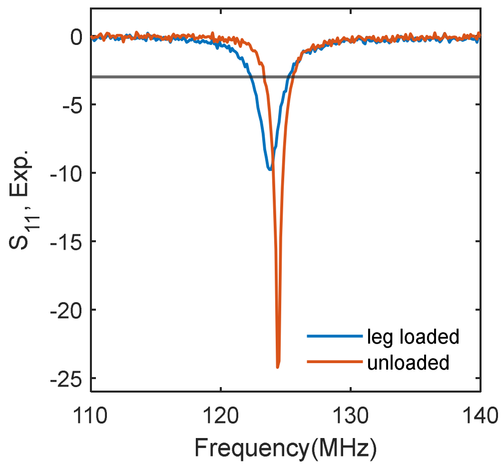


**Fig. R8 | S11 measurements of the NLMM when loaded and unloaded.**

*2. Fig. 5 from supplementary material: The average angle is not apparent from the presented angle map. I recommend using a jet colormap. Also, please provide graphs of the signal depending on the angle like was done in Ref. https://onlinelibrary.wiley.com/doi/10.1002/adma.202102469 (see Fig. 3c). It is one of the common ways to estimate the effect to transmit field.*

We appreciate the reviewer's professional comment. We have made adjustments to Fig.R9 (same figure in the supplementary material) by using a jet colormap, and the modified figure is presented below, replacing the original figure.

Regarding Fig. R9a, we noticed a small area near the bottom of the phantom where the FA was measured at 41° using the dual-angle method. Upon calculation of

$$\frac{\sin 41° \times 2}{\sin 35° \times 2} = 1.054 = 105.4\%$$

we determined that our NLMM has somewhat impact on the RF transmission field, but the primary improvement in SNR still results from enhancing the RF reception field. We appreciate the reviewer for bringing this to our attention.

Additionally, we have incorporated graphs illustrating the signal's dependence on the FA (Fig. R9b). The variations in signal and FA observed both with and without the NLMM exhibit similar trends, confirming the nonlinearity of the metamaterial. We have added Fig. R9b to the supplementary material.

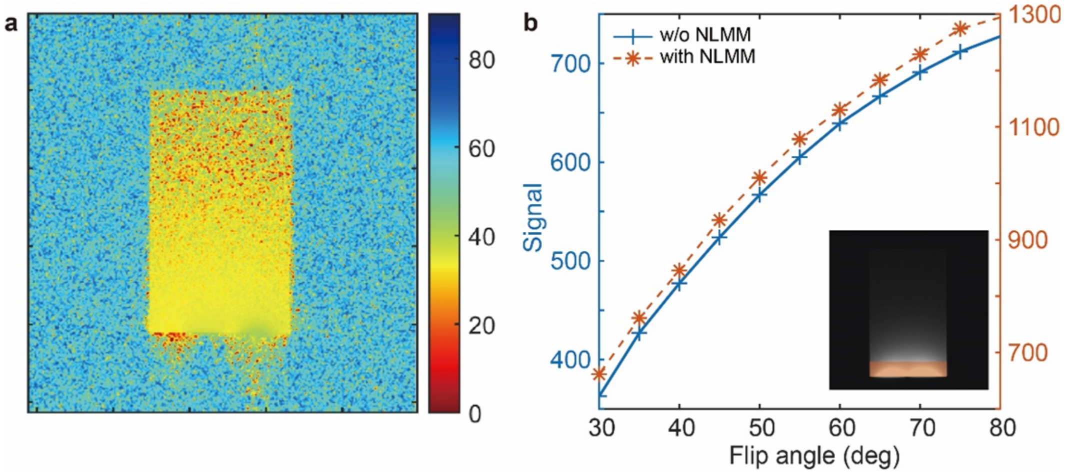


**Fig. R9 | Validation of the nonlinearity of the NLMM through MRI experiments. a** Measurement results of flip angle (FA) during imaging using the surface coil with the NLMM, obtained through the double-angle method with FAs of 35° and 70°, with a TR of 500 ms. **b** Mean signal intensity variations corresponding to different FAs, comparing cases with and without the NLMM. The orange region at the lower right corner in (b) is to calculate mean signal.

*3. The results of experimental studies with apple do not look compelling. This small object (besides not biological) has nothing in common with the human body. In addition, we see an increase in the signal in a tiny area; from the images, I can assume that it is about a couple of cms, while the signal in the upper part of the apple is smaller. The image with NLMM looks noisier than in the case of a standard coil. As was mentioned above, I suggest changing the sample and estimating the SNR in the region of interest that may be of clinical interest, e.g., the liver, if we are talking about the abdomen imaging.*

We appreciate the insightful comment from the reviewer. Recognizing the mismatch between the apple as a load and the large-size surface coil array, we have addressed this concern by including imaging of the human leg.

Following the application of metamaterials, a reduction in signal in the upper part of the image object may be expected. This phenomenon occurs because the metamaterial elevates the position of the object on the surface coil, and given the similarity between the metamaterial and the surface coil, enhancement is concentrated within a specific range of the surface.

Moving forward, our focus will be directed towards continuous efforts to improve the performance of the metamaterial. Additionally, we plan to extend its application to abdominal imaging and explore opportunities for enhancing the imaging of structures such as carotid arteries and temporomandibular joints.

*4. Page 18, lines 380-382: 'By simply scaling the NMAs, we can readily tune the resonance frequency of the NLMM to match the Larmor frequency in ultra-high MRI.' I cannot fully agree with this judgment. The fact is that when we work in ultra-high-field MRI, using a body coil for transmission becomes irrelevant* *since the transmission field will be non-uniform due to the reduction in the RF wavelength. So, the common practice is transmitting antenna arrays (dipoles or loops or a combination of both). It is not evident that the approach proposed by the authors will work similarly for such systems. I would suggest adjusting the sentence and leaving it at the level of an idea for future work rather than a statement.*

We thank the reviewer for the valuable suggestion. We agree the RF architecture of the MRI scanner is different in ultra-high field (UHF) MRI. And we further learned that the coils under UHF are mostly transmit-receive coils, which may not be compatible with the NLMM, because the NLMM's detuning during the RF emission phase may lead to the detuning of the transmit-receive coils. We have revised the "Discussion" sections in the manuscript, and the updated version now is follows:

"Parallel imaging using surface coil arrays has significantly influenced clinical imaging, aligning with the demands for improved sensitivity and reduced scan time in clinical MRI. The construction of parallel MRI surface coil arrays with increased channel numbers has been demonstrated to enhance SNR and optimize the g-factor60. Compared to the approach of integrating more electronic components and cables into limited coil space to increase channel numbers, metamaterials also potentially contribute to enhancing SNR in parallel imaging as a passive and readily deployable method. Metamaterials hold promise for facilitating high-sensitivity, rapidly acquired MRI in the future. This study validates the integration and benefits of clinical imaging coils with artificial structured materials, thereby facilitating the development of MRI technology."

*Minor comments:*

*1. Page 3, lines 38-41: It seems like there is a typo at the end of the sentence, or something is missed: '...,1 among others.'*

*2. Page 12, lines 255-256: the sentence 'We conducted experiments on a Siemens 3 T Prisma MRI system to assess the effectiveness of the NLMM in enhancing the SNR of MRI with a surface coil array' should be revised as ...the effectiveness of the NLMM in enhancing the SNR of a surface coil array. The SNR is a key characteristic of the receive coil used in MRI. For me, 'SNR of MRI' sounds uncertain.*

*3. Page 14, line 296: there is a typo in 'reduces ta the MRI operating frequency'.*

We thank the reviewer's valuable suggestions, and we have incorporated the following updates into the manuscript:

1. Removed the redundant "1" in "1 among others."

2. Revised the sentence to read, "the effectiveness of the NLMM in enhancing the SNR of imaging using a surface coil array."

3. Corrected the typo "ta" to "at."

## Reviewer #3:

*The work is technically sound and is a novel contribution to the field.*

*It would be useful to know how this technique compares to other metameterial/metasurface MRI designs that are in the literature, and to also elaborate on applications where very localised SNR improvements would be advantageous.*

We are grateful to the reviewer for offering valuable comments.

We have made some comparisons between our nonlinear metamaterials and previous works in the manuscript and in the response to comments above, and we would list some typical or latest works in the Table R2 (reference numbers in the following list correspond to those in the revised manuscripts).

**Table R2 | comparisons of some typical or latest works with our work**

| | Static field strength | Response (Linear/Non-L) | Cooperat-ing coil | SNR enhance-ment ratio | pMRI utilization |
|---|---|---|---|---|---|
| **ref. 20** | 1.5 T | linear | single loop coil | non-quantified | Not |
| **ref. 21** | 1.5 T | linear | multi-channel coil array* | ~ 2.7 | Not |
| **ref. 22** | 1.5 T | linear | body coil | ~ 4.2 | Not |
| **ref. 23** | 7 T | linear | multi-channel coil array | ~ 1.4 | Not |
| **ref. 27** | 3 T | nonlinear | body coil | ~ 16 | Not |
| **ref. 30** | 1.5 T | nonlinear | body coil | 2 to 4** | Not |
| **ref. 32** | 1.5 T | linear | 2-channel coil array | non-quantified*** | Conducted |
| **our work** | 3 T | nonlinear | multi-channel coil array | ~3 | Conducted |

* The coil located relevant far from the metamaterial and the sample.

** 2 to 4 times compared with the conventional multi-channel coil array.

*** The enhancement of MRI by metamaterials is characterized by the comparison of g-factor maps, showing an approximately 2-fold improvement in the g-factor.

Therefore, our work investigates and achieves the integration of nonlinear metamaterials with multi-channel surface coil arrays for pMRI, expanding the application of metamaterials in enhancing the SNR of MRI.

While our NLMM currently exhibits limited penetration depth of the SNR enhancement (55 mm penetration depth in phantom imaging and ~40 mm in human imaging), the achieved localized SNR improvement has potential applications for superficial anatomical regions. The applicable regions include the thyroid, carotid artery, temporo-mandibular joint, and cerebral cortex, among others (ref. [55-58] in revised manuscript). We have added the discussion of potential applications in the last paragraph of the "MRI validation of NLMM using in-vivo lower leg imaging" section in revised manuscript.

**Reference:**


R1. Wu, K., Zhao, X., Bifano, T. G., Anderson, S. W. & Zhang, X. Auxetics-Inspired Tunable Metamaterials for Magnetic Resonance Imaging. *Adv. Mater.* **34**, 2109032 (2022).

R2. Maxwell, J. C. *A Treatise On Electricity and Magnetism (Vol. 2)*. vol. 2 (Dover Publications Inc, Mineola, New York, 1954).

R3. Duan, G., Zhao, X., Anderson, S. W. & Zhang, X. Boosting magnetic resonance imaging signal-to-noise ratio using magnetic metamaterials. *Commun. Phys.* **2**, 35 (2019).

R4. Nagaoka, H. The Inductance Coefficients of Solenoids. *Journal of the College of Science, Imperial University, Tokyo* **27**, 33 (1909).

R5. Zhang, X., Meng, H., Wei, B., Wang, S. & Yang, Q. Mutual inductance calculation for coils with misalignment in wireless power transfer. *J. eng.* **2019**, 1041–1044 (2019).

R6. Snyder, J. N. & Grover, F. C. Inductance Calculations Working Formulas and Tables. *Mathematics of Computation* **18**, 164 (1964).

**REVIEWER COMMENTS**

**Reviewer #1 (Remarks to the Author):**

Dear authors, dear editor,

I have checked the comments, replies, and changes in the manuscript according to my first review report.

As I gave a summary in the first report, I will not do so again now.

I apologize for the longer time it took to check and verify. I agree with the changes made and I recommend the paper for publications now.

The concerns I still have may be regarded a matter of taste and personal viewpoint on the topic but they shall not hamper publication.

The paper improved substantially in the present version and is a valuable scientific piece of work, given also the supplemental material.

**Reviewer #2 (Remarks to the Author):**

I thank the authors for addressing all my comments. I still have a few questions and suggestions that should be clarified before the publication. Please see below.

1. Fig. R6 | Estimation of quantitative coupling effect: Please explain why, in the symmetric system, we observe different coupling coefficients in similar unit cells. I expected to see a similar k3-k4 as k1-k2, while the authors demonstrate that the trend is very different with the distance. Were all the unit cells similar in terms of dimensions and resonant frequency?

2. Fig.5, in vivo lower leg imaging: I commend the authors for their effort to perform imaging of a volunteer. However, I believe that more comprehensive SNR data would significantly enhance the clarity of your findings. In Fig.5, the authors indicated the ROI, and I would appreciate if the authors could calculate and add to the main text the results of SNR in this area as well as the SNR values for different acceleration factors. The SNR values are currently demonstrated in fat tissue, which may not be of much clinical interest. It seems

that the penetration depth of the metamaterial effect is around 5 mm, while for clinical output, larger distances are required, at least several centimeters. Also, amplifying the signal from adipose tissue could spoil the contrast-to-noise ratio. Please describe and discuss this limitation of your solution.

3. Fig. R9 | Validation of the nonlinearity of the NLMM through MRI experiments: What was the T1 of the considered phantom? The dependence of the signal on the flip angle does not allow one to conclude the angle at which the maximum signal is achieved (so-called Ernst angle) and, accordingly, about the influence of the metamaterial on the transmitting field. More points need to be measured. Also, in my understanding, since the average flip angle increased by 6 degrees, your reference voltage should be higher with metamaterial, although not significantly. What was the reference voltage (input power) in the experiment without and with the metamaterial? Please note that the impact on the transmitting process is closely related to RF safety (SAR). If the reference voltage was increased when using the proposed structure, the authors should carefully evaluate the safety of using this metamaterial.

In this regard, the following statement from the Discussion is unjustified and must be corrected: (lines 410-411) 'without interfering with the strength and homogeneity of the RF transmission field.'

4. Discussion, lines 413-415: 'We have achieved a maximum 3-fold SNR enhancement, leading to improved image quality in pMRI across various acceleration factors.' This statement is not entirely correct. The authors should detail which penetration depth in the body this increase was demonstrated and correctly discuss the results for different acceleration factors. As was mentioned above, the results for SNR in the ROI should be evaluated. This will allow an honest conclusion about the impact of the metamaterial on pMRI.

**Reviewer #3 (Remarks to the Author):**

The authors have addressed all the comments fully and I support publication

Dear Reviewers,

We sincerely thank you for considering our manuscript entitled “Nonlinear Metamaterials Enhanced Surface Coil Array for Parallel Magnetic Resonance Imaging”. We updated the manuscript and prepared point-by-point responses.

Firstly, regarding the RF safety of our nonlinear metamaterial (NLMM), we conducted detailed discussions and further simulations. The results of flip angle (FA) mapping showed that the increase in FA was localized to a small region. Within a 20×12 mm area, the average FA only increased from 35° to 37.1°, which would not cause a significant temperature rise given the thermal conductivity of tissues. Furthermore, our simulations indicated that the maximum and average specific absorption rate (SAR) values increased by a factor of 1.12 but remained within safety standards.

Secondly, we calculated the signal-to-noise ratio (SNR) at different acceleration factors and positions within the region of interest (ROI) in in-vivo imaging. The NLMM achieved a maximum 3-fold SNR improvement within a 40 mm range. For parallel MRI, the SNR enhancement remained comparable to non-parallel imaging. We also addressed some limitations of our solution and provided a detailed discussion in response to your comments.

Please find our point-to-point response below. Our response is in blue font and our revision of the manuscript and supporting information is highlighted.

Thank you again for your constructive suggestions and kind consideration of our work.

## Response to referees:

**Reviewer #2:**

I thank the authors for addressing all my comments. I still have a few questions and suggestions that should be clarified before the publication. Please see below.

We extend our sincere appreciation to the reviewer for providing further valuable comments. The manuscript and accompanying materials have been revised to improve their clarity.

1. Fig. R6 | Estimation of quantitative coupling effect: Please explain why, in the symmetric system, we observe different coupling coefficients in similar unit cells. I expected to see a similar k3-k4 as k1-k2, while the authors demonstrate that the trend is very different with the distance. Were all the unit cells similar in terms of dimensions and resonant frequency?

We appreciate the reviewer for the comments regarding the unclear description in Fig. R6. In this figure, we calculate the coupling coefficient of each metamaterial unit to each coil element. Specifically, $\kappa_{i1}$ in Fig. R6c refers to the coupling coefficient between the *i*-th metamaterial unit and coil 1 (the numbering of the coils is added in Fig. R6b). Therefore, $\kappa_{11}$ and $\kappa_{21}$ are different from $\kappa_{31}$ and $\kappa_{41}$. The revised Fig. R6 is as follows.

Additionally, all the unit cells are with similar dimensions and resonant frequency.

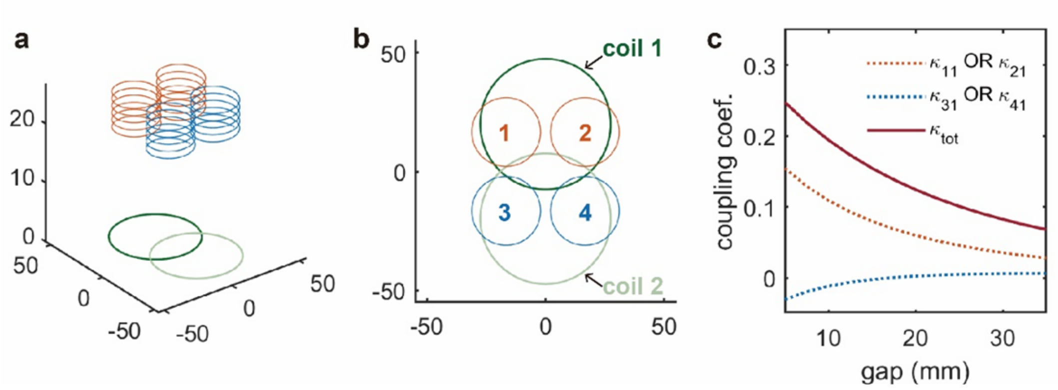


**Fig. R6 | Estimation of quantitative coupling effect. a** and **b** Schematic diagrams of simplified models used to calculate the mutual inductance between metamaterial units and coil elements. **c** Quantitative calculation results of the coupling coefficient $\kappa_{i1}$ (coupling coef.) between *i*-th metamaterial unit and coil 1.

2. Fig.5, in vivo lower leg imaging: I commend the authors for their effort to perform imaging of a volunteer. However, I believe that more comprehensive SNR data would significantly enhance the clarity of your findings. In Fig.5, the authors indicated the ROI, and I would appreciate if the authors could calculate and add to the main text the results of SNR in this area as well as the SNR values for different acceleration factors. The SNR values are currently demonstrated in fat tissue, which may not be of much clinical interest. It seems that the penetration depth of the metamaterial effect is around 5 mm, while for clinical output, larger distances are required, at least several centimeters. Also, amplifying the signal from adipose tissue could spoil the contrast-to-noise ratio. Please describe and discuss this limitation of your solution.

Firstly, we appreciate the reviewer's suggestion to provide more comprehensive SNR data. We calculated SNR results for regions at different distances and for different acceleration factors. The comprehensive SNR data have been added to the manuscript and are also presented in Fig. 5e-g.

The manuscript and Fig. 5 have been revised as follows:

In the second paragraph on Page 18 of the updated manuscript, we added the following discussion:

The presence of the NLMM enhances MRI signals, as evidenced by images acquired within the region of interest (ROI) shown in Fig. 5b. We compared the SNR quantitatively at different distances within the ROI. The results, as shown in Fig. 5e, demonstrate that the NLMM achieved a maximum SNR improvement of 3.3 times, and the SNR enhancement effect was observable within a 40 mm range.

In the third paragraph on Page 18 of the updated manuscript, we added the following discussion:

Furthermore, we validated the SNR improvement in the in-vivo pMRI. Fig. 5c and 5d illustrate images obtained using the GRAPPA algorithm with 3-fold and 4-fold acceleration. We zoomed in on images of the superficial regions of the lower leg. These images showed that the NLMM enhanced the visibility of the separation of connective tissue between fat lobules. This visibility was maintained even with 3-fold and 4-fold acceleration factors. Conversely, without the NLMM, image details appeared blurred and indistinct due to the accelerated acquisition. Quantitative SNR results are presented in Fig. 5f and 5g. While SNR values were lower in parallel imaging, the SNR enhancement ratio attributed to the NLMM remained comparable to that observed in non-parallel imaging. At the 4-fold acceleration, the enhancement depth slightly decreased to 35 mm due to increased aliasing noise. This pMRI study on the human leg, employing metamaterial-enhanced surface coils, underscores the potential of the NLMM in enhancing SNR and imaging speed in clinical MRI.

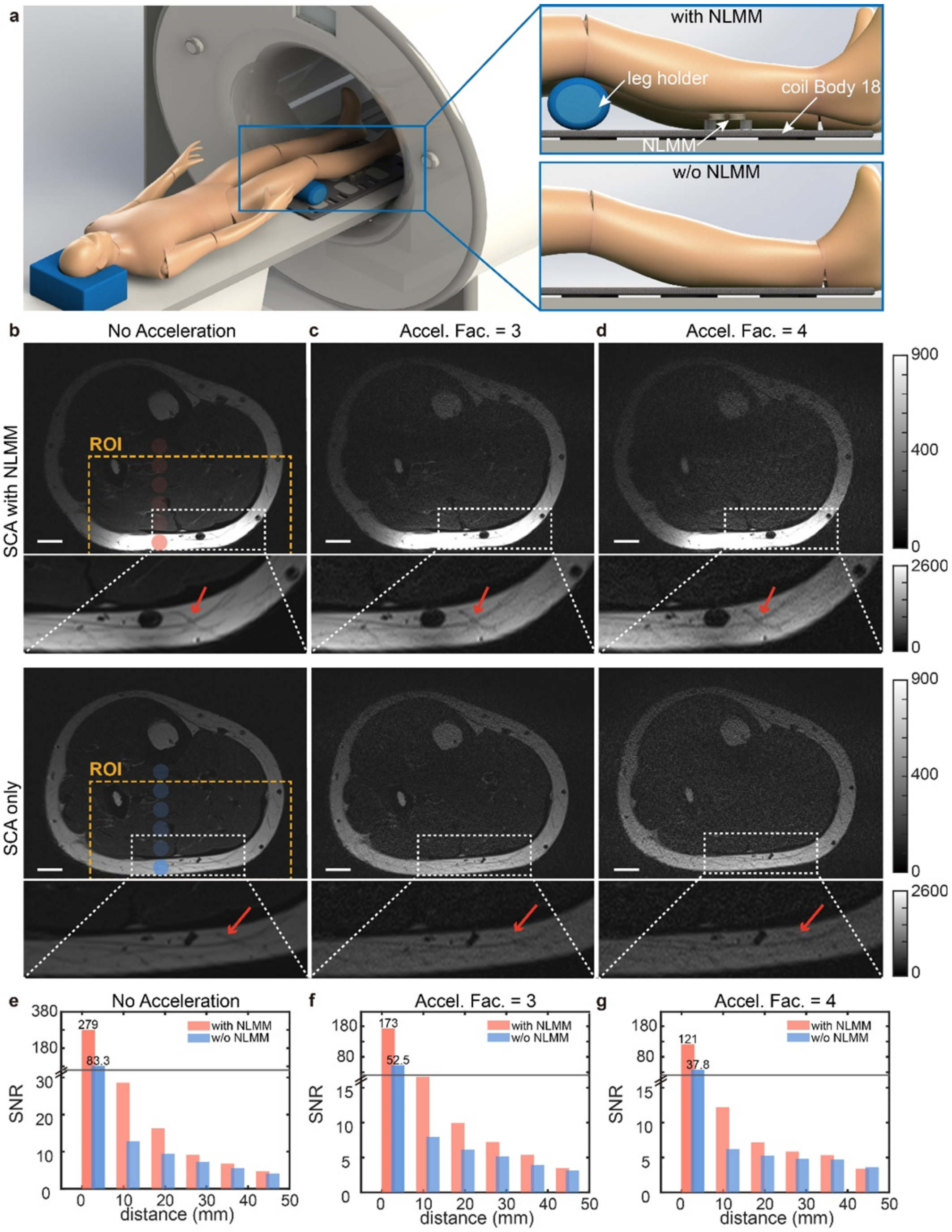


**Fig. 5 | 3T parallel-MRI of the human lower leg using NLMM-enhanced surface coil array. a** Experimental setup illustrations and side views with and without NLMM. **b-d** Comparisons of images acquired with NLMM and without NLMM at different acceleration factors. Scale bars are 1 cm. Insets show enlarged images highlighting tissue detail distinctions improved by NLMM. **e-g** SNR quantification for different acceleration factors at varying discrete distances, as labeled in (b).

Secondly, we thank the reviewer for the suggestion to raise the concerns about the penetration depth. based on the updated Fig. 5, the penetration depth of the SNR enhancement effect is approximately 40 mm. If metamaterials are placed simultaneously on both the upper and lower parts of the leg, better imaging results could be achieved. Moreover, we agree that increasing the enhancement depth is crucial for further clinical applications. Potentially effective measures include using low-loss substrate materials, designing metamaterial structures tailored for specific surface coil configurations, and developing conformal structures that wrap around the imaging region. These approaches will be the focus of our future research.

Thirdly, we noticed the issue of metamaterials affecting the contrast-to-noise ratio (CNR). In our study, metamaterials can amplify signals of all tissues, including both adipose and muscle tissue. While this can improve the overall SNR, the amplification is more pronounced in regions near the metamaterial. Since adipose tissue is located on the body surface, the signal enhancement is more significant in these areas, which may affect the CNR. Several strategies can be employed to address this limitation, such as the fat suppression sequence and advanced image post-processing.

We have incorporated a discussion of the CNR limitation into the revised manuscript in the second paragraph on Page 18. The update is:

It should be noted that our NLMM currently exhibits limited penetration depth for SNR enhancement, with a depth of 55 mm in phantom imaging and approximately 40 mm in the in-vivo imaging. This limitation can potentially affect the contrast-to-noise ratio (CNR). Since metamaterials enhance SNR locally and adipose tissue is often located near the body surface, the signal amplification is more pronounced in these regions, which may spoil the CNR in certain situations. However, the CNR variation may be compensated for by developing customized image post-processing algorithms. Despite the localized SNR improvement, our results still demonstrate the practical significance of the NLMM, particularly for the medical imaging and diagnosis of superficial anatomical regions such as the thyroid[ref 56], carotid artery[ref 57], temporo-mandibular joint[ref 58], and cerebral cortex[ref 59], among others.

3. Fig. R9 | Validation of the nonlinearity of the NLMM through MRI experiments: What was the T1 of the considered phantom? The dependence of the signal on the flip angle does not allow one to conclude the angle at which the maximum signal is achieved (so-called Ernst angle) and, accordingly, about the influence of the metamaterial on the transmitting field. More points need to be measured. Also, in my understanding, since the average flip angle increased by 6 degrees, your reference voltage should be higher with metamaterial, although not significantly. What was the reference voltage (input power) in the experiment without and with the metamaterial? Please note that the impact on the transmitting process is closely related to RF safety (SAR). If the reference voltage was increased when using the proposed structure, the authors should carefully evaluate the safety of using this metamaterial.

In this regard, the following statement from the Discussion is unjustified and must be corrected: (lines 410-411) 'without interfering with the strength and homogeneity of the RF transmission field.'

We appreciate the reviewer's insightful comment. Firstly, we remeasured more points to derive the dependence of the signal on the flip angle. In our previous measurements, we set the TR to 500 ms, which is consistent with the TR used in our dual-angle B1 mapping. This setting resulted in an Ernst angle close to 90°, and our Siemens MRI system cannot set the GRE sequence flip angle beyond 90°. We then set the TR to 100 ms, which matches the TR used in our phantom imaging, and obtained the curves shown in the revised Fig. R9a and S8a. The Ernst angle is about 67° both with and without the metamaterials. According to the definition of Ernst angle: which is:

$$\theta_E = \arccos\left(e^{-TR/T1}\right)$$

we obtained the T1 of the oil phantom to be approximately 110 ms. This confirms that a TR of 500 ms is sufficiently long in the dual-angle B1 mapping to eliminate T1 effects.

We have updated the discussion about the Ernst angle measurement and T1 evaluation on Page 15 in the Supplementary Information Section S8, “Verification of the nonlinearity on MRI and SAR simulation”. The revised text is as follows:

We verified the nonlinearity of the NLMM on the MRI platform. We conducted phantom imaging with different flip angle (FA) settings, while other imaging parameters remained consistent with those in Table 1 and Section S7. When evaluating the mean signal in the region at the bottom of the phantom, the variations in the signal and nominal FA with and without the NLMM exhibited the same trend, as shown in Fig. R9a and S8a. The Ernst angle is about 67° both with and without the metamaterials, indicating that the T1 of the oil phantom is approximately 110 ms.

Secondly, we did not receive specific reference voltage/ input power values from our engineer for the experiments. We used the standard pulse sequence settings and did not modify any sequence parameters between the experiments with and without metamaterials. We fully agree with the reviewer's concerns about RF safety. We have added SAR-related results in Fig. R9 and S8 and discussed this issue on Pages 16-17 of the supplementary information, as follows:

Then we used the dual-angle method to measure the FA map. Ideally, we expect the NLMM not to enhance the RF transmission field, as indicated by the measured FA being equal to the set value in the presence of the NLMM.

…

The measurement results are shown in Fig. R9b and S8b. We observed a local increase in the FA near the lower right surface of the phantom, with a maximum increase of 6.3°, indicating that the NLMM has some effect on the transmission field. However, this impact is not significant. When calculating the average FA within a 20×12 mm region, it increased by 2.1° to reach 37.1°. Therefore, we concluded that while our NLMM does have some impact on the

RF transmission field, the primary improvement in SNR still results from enhancing the RF reception field.

On the other hand, due to the NLMM's impact on the RF transmission field, we further evaluated its effect on RF safety. Generally, although the maximum FA increased by 6.3°, indicating a rise in specific absorption rate (SAR) values, the increase in FA is not significant on average and the heating effect caused by the NLMM will be minimal due to tissue thermal conductivity.

We evaluated the SAR by simulation when employing the NLMM. The simulation model is shown in Fig. R9c and S8c, adapted from the MRI System routine in the CST Studio Suite (provided by Biometrics and Medical Informatics, Otto von Guericke University Magdeburg, Germany). We tuned the birdcage coil to operate at the 3 T Larmor frequency, and used the provided lossy phantom filled with tissue-simulating fluid ($\varepsilon_r$=20, Electric conductivity = 1 S/m). Then, we imported the NLMM model detailed in Section S4. We set the $B_1^+{}_{rms}$ produced by the birdcage coil to 1 $\mu$T[R1], and the simulated SAR results with and without the NLMM are shown in Fig. R9d and S8d. We observed that with the presence of the NLMM, the maximum SAR value increased by a factor of 1.12 (0.753/0.674), and the local average value increased by a factor of 1.12 (0.632/0.565). These results indicate that the SAR increase remains within safety standard[R2]. Additionally, simulations revealed that with the NLMM, RF power deposition occurs on one side, which is related to the polarization direction of the circularly polarized field generated by the birdcage coil. Changing the polarization direction alters the side of RF power deposition.

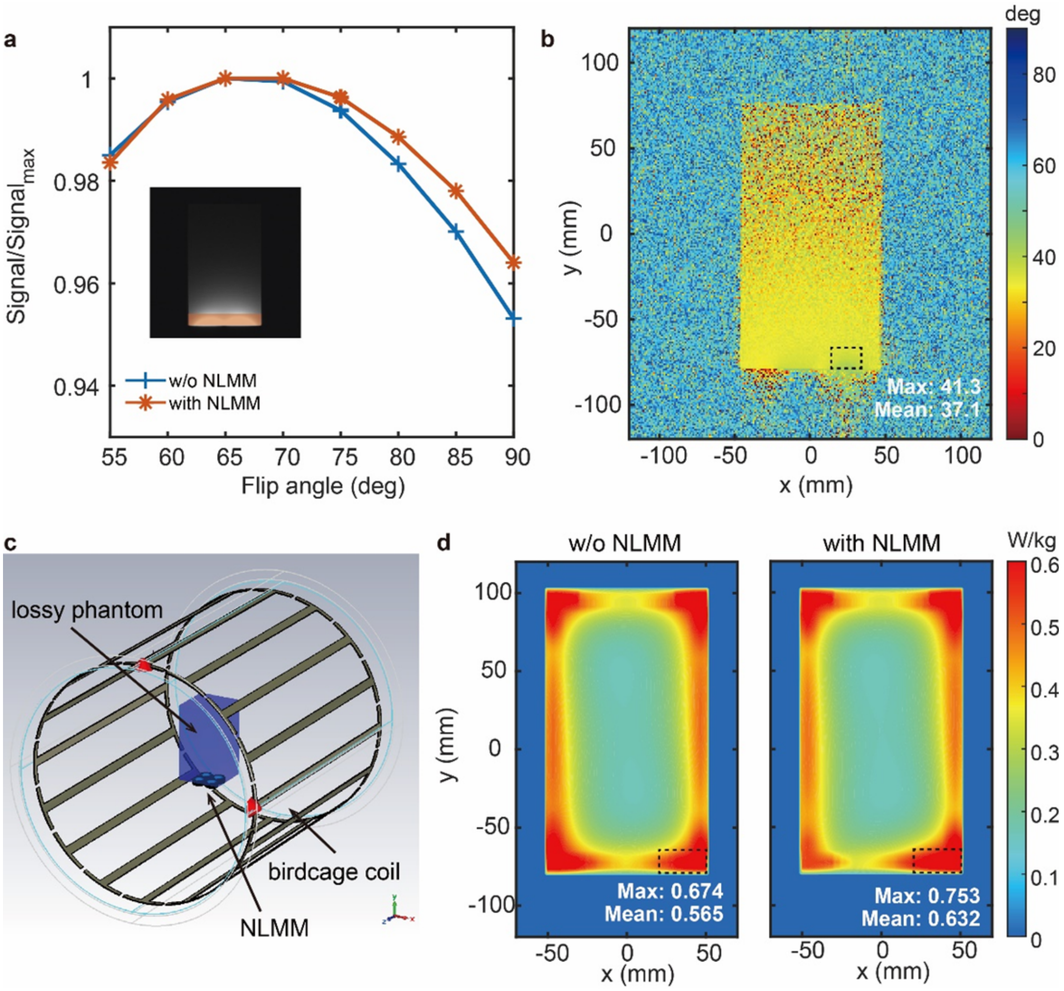


**Fig. R9 and S8 | Validation of the nonlinearity of the NLMM through MRI experiments and SAR simulation. a** Mean signal intensity variation corresponding to different flip angles (FAs) with a TR of 100 ms, comparing cases with and without the NLMM. The orange region at the lower left corner in (a) is employed in the calculation of the mean signal. **b** Measured results of FA during imaging using the surface coil with the NLMM, obtained through the double-angle method with FAs of 35° and 70°, with a TR of 500 ms. **c** Simulation model to evaluate SAR. **d** Simulated SAR maps of the phantom without (left) and with the NLMM (right).

## References:

[R1] Yao, A., Li, Z. & Ma, M. Impact of MRI RF coil design on the RF-induced heating of medical implants: fixed B 1 + rms exposure versus normal operating mode. Phys. Med. Biol. 69, 055021 (2024). doi: 10.1088/1361-6560/ad2714

[R2] McRobbie, D. W., Moore, E. A. & Graves, M. J. MRI from Picture to Proton. (Cambridge University Press, West Nyack, 2017). p348, ISBN 978-1-107-70695-8.

Thirdly, to enhance clarity, we have revised lines 410-411 of the original manuscript. This update is at the end of the first paragraph on Page 20:

In this study, we propose and validate a NLMM composed of an array of solenoidal NMAs, with the aim of enhancing the SNR of MRI when using a surface coil array and in pMRI. Significantly, the NLMM exhibit a little impact on the RF transmission field, with an average local FA increase of 2.1°, while the primary SNR improvement stems from enhancing the RF reception field.

And we have revised the text on Page 15-16 of the manuscript to discuss the results of validating the nonlinearity of the NLMM through MRI experiments and SAR simulation, as follows:

To further demonstrate that the NLMM's minimal impact on the $B_1^+$ field, we measure the relationship between the image signal and the flip angle (FA), and the FA map using the dual-angle method [ref 52]. The FA is a parameter represent the intensity and duration of the RF transmission pulse. The measurement results demonstrated the variation trend of the signal value with flip angle stayed the same after NLMM applied and an average local FA increase of 2.1°, which confirming that NLMM has minimal effect on the $B_1^+$ field and improves SNR by enhancing $B_1^-$ field.

Based on the EM field-circuit joint simulation we proposed, we further evaluated SAR values and the safety of the NLMM. Simulation results indicated that the local average SAR value increased by a factor of 1.12, suggesting that the SAR increase remains within safety standards [ref 53]. Details of the measurement and simulation method and results is in Supplementary Section 8 and Supplementary Fig. 9.

4. Discussion, lines 413-415: 'We have achieved a maximum 3-fold SNR enhancement, leading to improved image quality in pMRI across various acceleration factors.' This statement is not entirely correct. The authors should detail which penetration depth in the body this increase was demonstrated and

correctly discuss the results for different acceleration factors. As was mentioned above, the results for SNR in the ROI should be evaluated. This will allow an honest conclusion about the impact of the metamaterial on pMRI.

We appreciate the reviewer's suggestions on improving the accuracy of expression. We have updated the related discussion at the end of the first paragraph on Page 20. The revised manuscript text is as follows:

We have achieved a maximum SNR enhancement of 3-fold in the phantom and in-vivo imaging, for non-accelerated and 2- to 4-fold accelerated pMRI. The NLMM provided an SNR enhancement effect with a penetration depth of 55 mm in phantom imaging. In the in-vivo imaging, the penetration depth decreases to 40 mm, primarily due to dielectric loss.

**REVIEWERS' COMMENTS**

**Reviewer #2 (Remarks to the Author):**

The authors have taken into account all my recommendations. I recommend accepting this manuscript for publication.