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Radiofrequency safety of high permittivity pads in MRI—Impact of insulation material

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Purpose: High permittivity dielectric pads are known to be effective for tailoring the RF field and improving image quality in high field MRI. Despite a number of studies reporting benign specific absorption rate (SAR) effects, their “universal” safety remains an open concern. In this work, we evaluate the impact of the insulation material in between the pad and the body, using both RF simulations as well as phantom experiments.

Methods: A 3T configuration with high permittivity material was simulated and characterized experimentally in terms of B_1^+ fields and RF power absorption, both with and without electrical insulation in between the high permittivity material and the sample. Different insulation conditions were compared, and electromagnetic analyses on the induced current density were performed to elucidate the effect.

Results: Increases in RF heating of up to 49% were observed experimentally in a tissue-mimicking phantom after removing the material insulation. The B_1^+ magnitude and RF transceive phase were not affected. Simulations indicated that an insulation thickness of 0.5–2 mm should be accounted for in numerical models in order to ensure reliable results.

Conclusion: A reliable RF safety assessment of high permittivity dielectric pads requires accounting for the insulating properties of the plastic encasing. Ignoring the electrical insulation can lead to erroneous results with substantial increases in local SAR at the interface. Conversely, the material insulation does not need to be modeled to predict the B_1^+ effects during the design of the pad geometry.

KEYWORDS

dielectric pads, electromagnetic simulations, insulation, radiofrequency fields, safety

1 | INTRODUCTION

Performing MRI at higher static magnetic field strengths (B_0) has been an ongoing trend in MR technology, where the increased intrinsic SNR can be leveraged to increase

spatial resolution or shorten acquisition time. Obtaining high quality MR images at higher fields can be challenging, however, in particular when the wavelength of the RF fields becomes similar or smaller than the dimensions of the body part that is being imaged. This is the case

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for body imaging at $B_0 \geq 3\text{T}$ where the RF wavelength is around 30 cm in muscle tissue, and neuroimaging at $B_0 \geq 7\text{T}$ where the RF wavelength reduces to approximately 13 cm in brain tissue.¹ Under these conditions, a pronounced reduction in the uniformity of the RF magnetic transmit field (B_1^+) is observed, leading to undesirable spatial variations in image contrast.² Additionally, the increased levels of RF power deposition in tissue, for which safety limits are issued in terms of the specific absorption rate (SAR), can impose restrictive constraints on the sequence parameters, which can compromise the image quality gains when moving to higher fields.

Various RF technologies have emerged to address these challenges, both in the active form of parallel RF transmission using multiple independent RF transmitters, as well as in the form of passive materials such as high permittivity materials or “dielectric pads.”³ These flexible materials typically have a relative permittivity (ϵ_r) of approximately 100–500 and are positioned in between the volume RF coil and the human body. Various degrees of freedom in shaping the RF field can be addressed by modifying the material properties or the geometrical distribution using specialized software tools.⁴ The passive approach offers a straightforward and practical solution, requiring no additional hardware or software changes nor pulse sequence modifications, and has therefore gained considerable attention from the MR community. Parallel RF transmission, on the other hand, introduces considerable additional hardware requirements as well as software overhead in terms of RF management, B_1^+ calibration sequences, and advanced SAR models.⁵

As with the development of customized RF transmit coils, the application of passive materials to manipulate the RF field warrants dedicated RF safety assessment, typically involving numerical simulations and validation experiments such as B_1^+ mapping and thermometry.⁶ Despite the large body of literature reporting benign SAR effects of high permittivity materials,^{7–21} their “universal” safety remains difficult to establish as their design may vary considerably. When the materials enhance the B_1^+ efficiency in the region of interest, reductions in SAR can be anticipated by virtue of the reduced RF power required by the system. Although the 10 g-averaged SAR ($\text{SAR}_{10\text{g}}$) distribution can be affected with local increases close to the material, the dominant peak $\text{SAR}_{10\text{g}}$ value is generally not increased even when considering similar RF input power levels.^{10–12,16,18,19,21} Some reports have raised safety concerns, however, indicating potential increases in peak $\text{SAR}_{10\text{g}}$ of up to 160% depending not only on design parameters such as permittivity and pad geometry but also on RF field polarization, which are difficult to generalize.^{22,23} At this point, it is not clear which conditions ensure safety

compliance when using dielectric pads, nor have these effects been demonstrated or validated experimentally.

In light of these concerns, we hypothesized that the insulating materials in between the human body and the high permittivity material may explain at least some of the disparities in these findings, as this thin layer can be challenging to model in numerical simulation tools. In practice, such insulation would always be present, both in the form of the plastic container that is used to seal the materials, as well as in the form of the patient gown that is used during scanning. The most realistic approach would be to account for this insulating layer explicitly in the simulation model, however this requires a highly refined spatial discretization grid at the interface between the body model and the dielectric pad, which can be computationally demanding.^{13,14,19} Some groups have recommended implementing a deliberate separation of 10 mm to reduce these computational demands, however such countermeasures can also reduce the B_1^+ enhancement and hamper the placement of pads in close-fitting receive arrays.²³ Further insights into the relevance of this insulation layer could also provide a handle into what numerical modeling strategy should be considered for obtaining a realistic RF safety assessment of high permittivity pads in MRI.

In this work, we aim to evaluate the effect of material insulation in the RF safety assessment of high permittivity materials employed in MRI. Electromagnetic (EM) simulations in a numerical body model are performed to evaluate the effect of material insulation on the B_1^+ field and SAR distribution. The observed effects are validated via B_1^+ mapping and MR thermometry in a rectangular phantom at 3T. The effects of different insulation conditions are then evaluated in a rectangular phantom through EM simulations. Finally, an EM analysis is performed on the induced current density to disentangle the role of conduction and displacement current densities on the observed results.

2 | METHODS

2.1 | Configuration

The study was guided by a 3T body imaging scenario where a single high permittivity pad was positioned at the anterior side of the male body model “Duke.”²⁴ The effects of the high permittivity pad were evaluated when the material was either electrically insulated from, or in direct contact with, the human body (it should be noted that the latter configuration represents a “worst case scenario” in the sense both that the material would clearly never be placed in direct contact with the skin, and also that there is in practice always a scanning

gown present on the patient). Further experimental and numerical studies were performed in an open rectangular phantom of size $32 \times 24 \times 11$ cm, filled with an aqueous gel of polyvinylpyrrolidone (PVP-10) to establish dielectric properties similar to the human body ($\epsilon_r = 48$ and $\sigma = 0.50$ S/m).²⁵ The material was gelled using 1% agarose to reduce thermal convection and allow for a dielectric pad to be positioned directly on top of the phantom material. A dielectric pad of size $18 \times 18 \times 1.5$ cm was constructed using a 5:1 (weight ratio) suspension of BaTiO₃ powder in demineralized water, which resulted in dielectric properties of $\epsilon_r = 307$ and $\sigma = 0.16$ S/m at 128 MHz.⁸ The material was finally heat-sealed in polypropylene ($\epsilon_r = 2.5$, $\rho = 10^8$ Ω cm) of approximately 500 μ m thickness.

2.2 | EM simulations

Simulations of the transmit B_1^+ efficiency, RF transeive phase (ϕ^\pm), dissipated power density (P_d), SAR_{10g} distribution and induced current density (\mathbf{J}) were obtained in a high pass quadrature birdcage body coil model (61 cm diameter, 50 cm length) using the finite difference time domain method (XFDTD 7.4, Remcom inc., State College, PA). The simulation grid was set to a uniform spatial resolution of 2 mm within the RF coil and simulations were performed using graphics processing unit (GPU) acceleration (Tesla K40c, NVIDIA, Santa Clara, CA). The SAR averaging procedure was set to exclude the high permittivity pad, in order not to bias local SAR effects close to the dielectric material due to density weighting (i.e., assuming that the material is thermally isolated from the body). All simulation data were normalized to the RF input power, unless specified otherwise.

A rectangular phantom model was used to evaluate the effect of different insulation conditions by varying insulation thickness and electrical resistivity, as well as the effect of different pad permittivities. All model perturbations were performed around a baseline dielectric pad with a relative permittivity of $\epsilon_r = 300$, $\sigma = 0.16$ S/m and with 500 μ m of polypropylene insulation. The rectangular geometry of the phantom enabled refining the simulation grid down to 50 μ m around the interface to ensure that an accurate representation of the insulation layer was obtained in all cases.

A more specific vector analysis on the induced current densities was performed in which the total electric current density (\mathbf{J}_{tot}) was decomposed into a conduction currents (\mathbf{J}_c) and displacement currents (\mathbf{J}_d), as follows:

$$\begin{aligned} \mathbf{J}_{\text{tot}} &= \mathbf{J}_c + \mathbf{J}_d \\ &= \sigma \mathbf{E} + j\omega \epsilon_0 \epsilon_r \mathbf{E} \end{aligned} \quad (1)$$

where \mathbf{E} denotes the electric field, j is the imaginary unit, ω is the angular RF frequency, ϵ_0 is the permittivity of vacuum, and σ and ϵ_r represent the conductivity and relative permittivity of the medium, respectively. Conduction currents are associated to energy absorption and RF heating, whereas displacement currents are associated with energy storage and a local enhancement of the B_1^+ field, based on a zero-order approximation of their effect.²⁶

2.3 | MR protocol

Phantom experiments were performed on a 3T MRI system (Ingenia, Philips Healthcare, Best, the Netherlands) using the integrated quadrature body coil for RF transmission and a 32-channel torso array coil for signal reception. The protocol involved B_1^+ magnitude and RF transeive phase mapping using the DREAM sequence²⁷ (4×4 mm² in-plane resolution, 8 mm slice thickness, FOV = 384×384 mm², TR/TE = 4.6/2.3 ms, STEAM/imaging tip angle = $60^\circ/10^\circ$) and MR thermometry via the PRF method²⁸ using a 20 min dynamic series of 3D gradient echo acquisitions (4 mm³ isotropic resolution, FOV = $384 \times 384 \times 384$ mm³, TR/TE = 15/10 ms, tip angle = 10°). A preparation module consisting of a 100 kHz off-resonant rectangular RF pulse was added to increase the average RF power of the sequence to 100 W without interfering with image acquisition. Four cylindrical mineral oil phantoms were added to the setup to perform bias field correction by fitting the phase bias to a third order spherical harmonics basis.²⁹ The experiments were first performed without and then with the dielectric pad positioned directly on top of the phantom material. The polypropylene insulation was then removed and the protocol repeated.

3 | RESULTS

3.1 | EM simulations

Figure 1 shows transverse cross-sections of the B_1^+ efficiency and coronal maximum intensity projections of the SAR_{10g} simulated in the male body model without and with high permittivity pad, either with a 2-mm insulation layer or in direct electrical contact with the body model. The SAR_{10g} data were normalized to an average B_1^+ of 1 μ T in the transverse cross-section of the body model, here, which corresponds to the RF calibration routine performed on many clinical MR systems. Although the 2-mm insulation layer has only a minor effect on the B_1^+ distribution, a 40% increase in peak SAR_{10g} was observed in the torso when the high permittivity material was put in direct

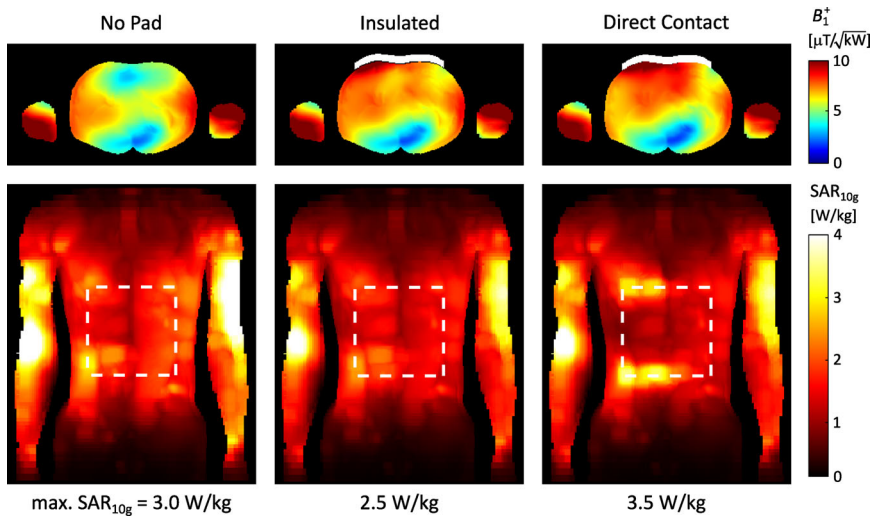


FIGURE 1 Simulated effects of high permittivity material positioned on the anterior side of the male body model, with and without electrical insulation. Shown are transverse cross-sections of the B_1^+ efficiency (top) and coronal maximum intensity projections of SAR_{10g} (bottom). SAR data were normalized to an average B_1^+ magnitude of $1 \mu\text{T}$ within the transverse cross-section of the body model. The position of the high permittivity material is illustrated in white.

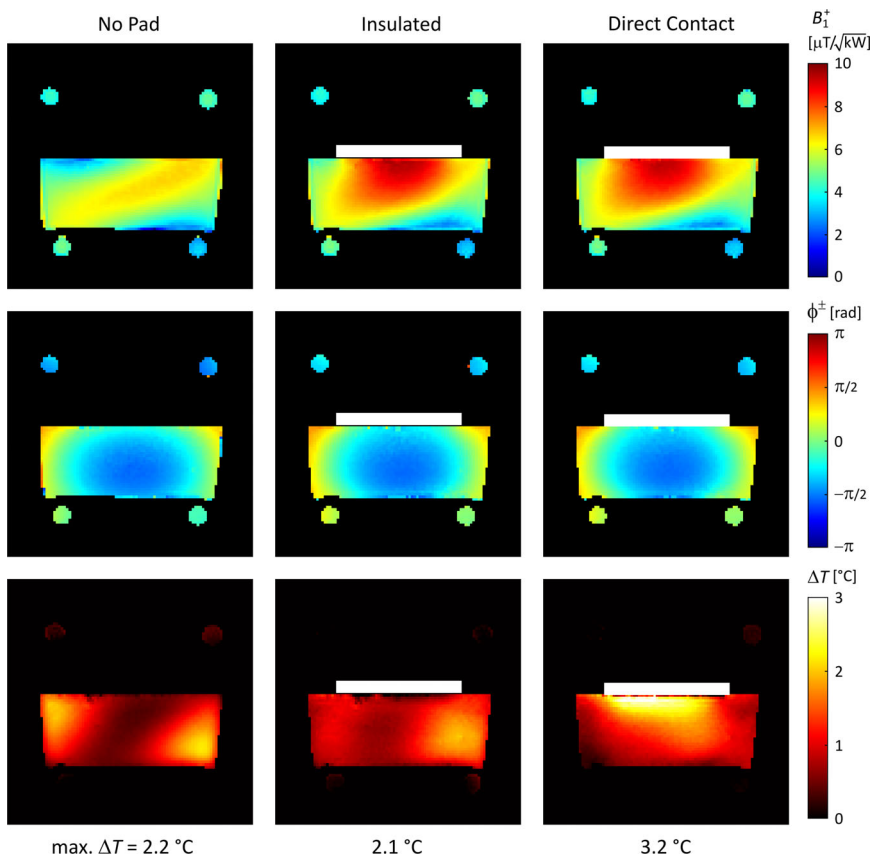


FIGURE 2 Phantom measurements without and with the high permittivity pad in place, with and without electrical insulation. Shown are transverse cross-sections of the B_1^+ efficiency (top), RF transceive phase (middle), and temperature increases (bottom) after 20 min exposure at an average RF power of 100 W. The position of the high permittivity pad is illustrated in white, and the footers denote the maximum temperature increase.

electrical contact with the body, although the value is still well below the maximum value in the arms.

3.2 | Phantom experiments

Figure 2 shows the experimental RF characterization results with transverse cross-sections of the measured B_1^+ efficiency, RF transceive phase, and thermometry maps obtained in the rectangular phantom, both without and

with the high permittivity pad positioned on top, first with the plastic encasing present and then in direct contact with the phantom material. The peak temperature increase with the insulated high permittivity pad was similar to that in the situation without pad, however this increased by 49% when the electrical insulation was removed and the high permittivity material was put in electrical contact with the phantom material. In both configurations with pad, the B_1^+ efficiency and RF transceive phase were minimally affected.

3.3 | Phantom simulations

Simulations of the RF field in the rectangular phantom are shown in Figure 3, where the effects of insulation thickness, insulation resistivity and pad permittivity on the B_1^+ efficiency and SAR_{10g} distribution were evaluated. The graphs show the peak SAR_{10g} value in the phantom material close to the pad. The results indicated that an insulation thickness from 50 μm to 2 mm would result in a reduction of the peak SAR_{10g}, with an optimum thickness at around 500 μm , and that typical values for the electrical resistivity of polypropylene ($>10^8 \Omega \text{cm}$) are more than sufficient not to influence SAR_{10g}. Finally, the pad permittivity is shown to also influence SAR_{10g} with increases in peak SAR_{10g} compared to baseline when the permittivity is excessively high (i.e., such configurations do not produce

a useful B_1^+ distribution), which is in line with previous findings.³⁰

Finally, Figure 4 shows sagittal vector plots of the induced current density and RF power absorption both with and without electrical insulation in between the high permittivity pad and the phantom. In both configurations, a strong displacement current density is evident within the dielectric pad, owing to its high permittivity. The configuration without electrical insulation featured a strong but very localized current density at the interface with the phantom, with both displacement (J_d) as well as conduction (J_c) components, which was not present in the situation with electrical insulation. This indicates that the direct electrical contact allows for a return path for the RF induced currents to be formed through the phantom, with a strong jump at the interface that is associated with local

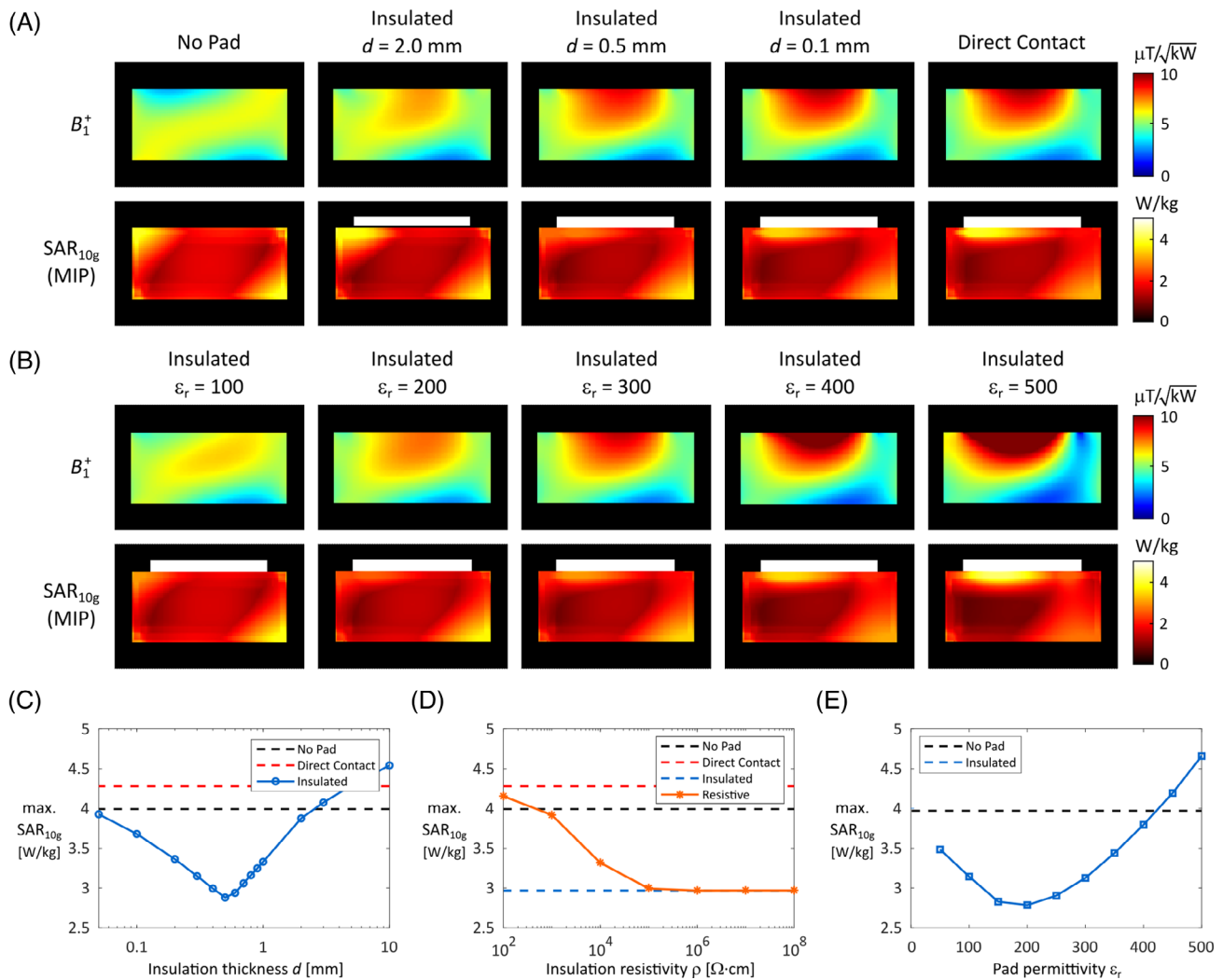


FIGURE 3 Simulated B_1^+ and local SAR for different insulation conditions in the phantom configuration. The maps in (A) show transverse cross-sections of the B_1^+ efficiency and transverse maximum intensity projections of SAR_{10g} for different insulation thicknesses. The maps in (B) show these for different pad permittivities. In (C–E), the variation in peak SAR_{10g} as a function of the insulation thickness d , insulation resistivity ρ and relative permittivity ϵ_r of the pad is shown.

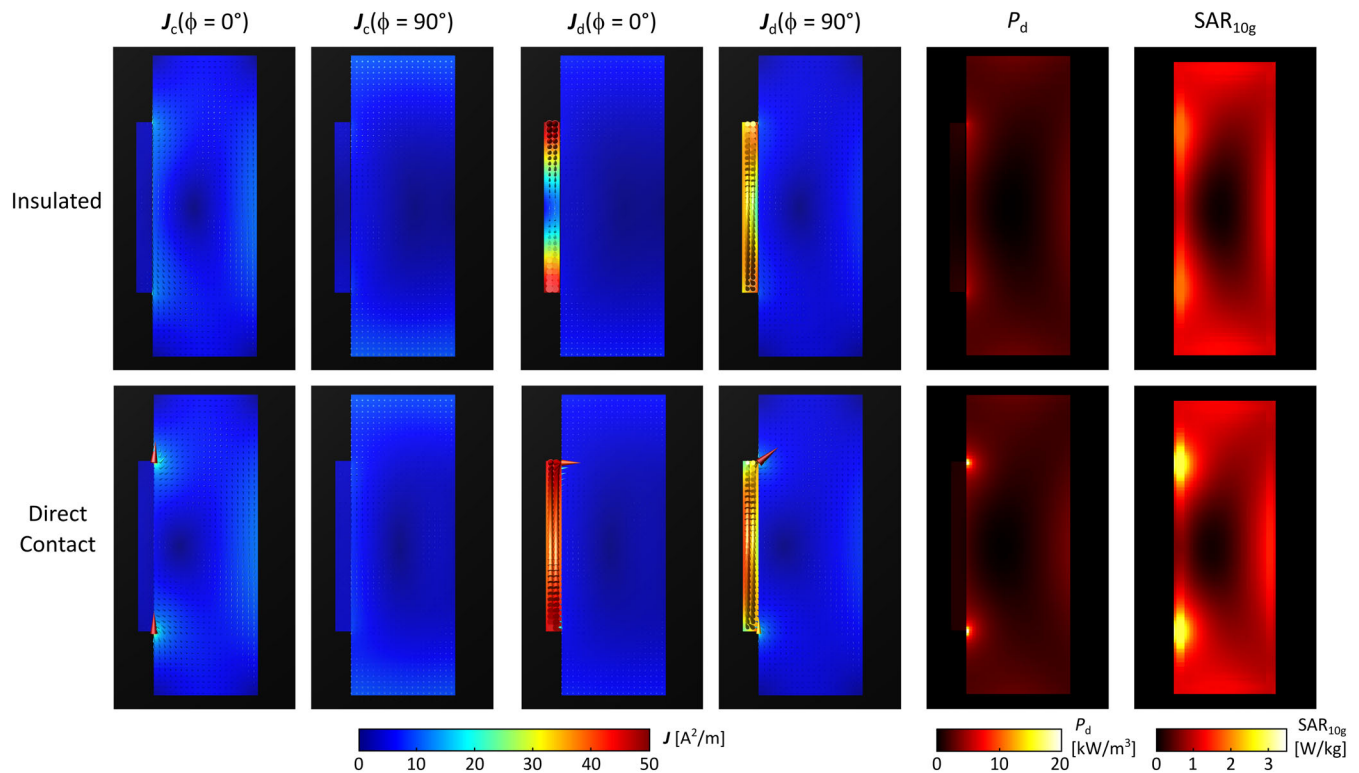


FIGURE 4 Sagittal vector plots of the induced current densities in the simulated phantom configuration with (top) and without electrical insulation (bottom). Shown on the left are the conduction current density (J_c) and displacement current density (J_d), at two time-points within the oscillation. The right two columns show the dissipated power density (P_d) and SAR_{10g} . Without electrical insulation, both the conduction as well as the displacement current density show a strong local current density at the interface with the phantom, reflecting the formation of a return path or RF current “loop” with associated localized RF power absorption within the phantom material.

RF power absorption. An animated version is provided in Supporting Information Video S1.

4 | DISCUSSION AND CONCLUSION

This study demonstrates that a reliable RF safety assessment of high permittivity pads in MRI requires accounting for the insulating materials that are used in between the high permittivity material and the body. Increases in RF heating of up to 49% were observed in a tissue-mimicking phantom after removing the material insulation, confirming simulated effects. Simulations of the insulated configuration indicated that an insulation thickness of 0.5–2 mm is suitable for performing an RF safety assessment. Remarkably, the effect of material insulation on the B_1^+ field was minor, indicating that the material insulation does not need to be accounted for during the design of high permittivity pads.

The EM field analysis in this study showed that when the material insulation is removed, RF currents induced in the high permittivity material are able to form a current

loop via the body. Due to the associated difference in permittivity, this leads to discontinuities in the normal component of the electric field, which is reflected in a strong localized current density that is induced at the interface as shown in Figure 4. This also results in a strong conduction current induced parallel to the interface, which is associated with localized RF power absorption and an increased local SAR.

Both the experimental data as well as simulations indicated that, while the RF heating pattern was considerably affected by the electrical insulation of the high permittivity material, both the magnitude of the B_1^+ field as well as the RF transceive phase were only minimally affected. This contrast may be attributed to the fact that the B_1^+ field is influenced mainly by the displacement current densities in the high permittivity material, while RF heating is dominated by the conduction currents induced in the sample. The strong and localized conduction current density at the sample interface leads to a very strong local increase in power absorption, while the corresponding localized displacement current density is insignificant compared to what is induced in the volume of the dielectric pad. This also indicates that methods to derive local SAR

directly from measured complex B_1^+ field data may not be applicable to configurations that feature strong contrasts in permittivity.³¹

Additional simulations indicated that an insulating layer with a thickness of as little as 50 μm already reduce the RF currents that pass from the high permittivity material into the body. Common polymer thermoplastics provide more than adequate electrical insulation (i.e., 10^7 – 10^{14} Ω cm); however, some conductive counterparts can be found in the electronics industry and should be avoided.³² Also, when a patient gown or clothing is present this would provide additional insulation, although the insulating properties can decrease due to humidity or moisture.³³ These results also indicate that configurations where high permittivity materials are in direct contact with body tissues, such as solid high permittivity ceramics that do not necessarily involve plastic encasings,³⁴ should be evaluated carefully before performing in vivo studies.

Accurate modeling of the thin insulation layer in numerical simulation tools can be a challenge, especially when the pad is positioned close to the curved interface of a voxelized body model. Some numerical simulation techniques such as the finite integration technique incorporate implicit material averaging,³⁵ which can affect the insulating properties of the pad interface. It can generally be recommended to use voxelized models of the high permittivity pads as this allows for the curvature of the pad to follow that of the body model, which improves electrical insulation. When computational resources allow, a discretization grid size of approximately 1–2 mm around the interface is recommended, with corresponding insulation thickness.

These results indicate that reliable RF safety assessments involving high permittivity materials for tailoring the RF field should be evaluated in an application-specific manner with adequate representation of the insulating materials present. The associated B_1^+ field effects show not to be as sensitive to these details, meaning that computational requirements may be relaxed during the design of the material distribution.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Video S1. Sagittal vector animations of the induced current densities in the simulated phantom configuration with (top) and without electrical insulation (bottom) in between the phantom and the high permittivity material. Shown are the total induced current density (J_{tot}) decomposed into the conduction current (J_c) and displacement current (J_d) densities, respectively. The induced current densities show a strong local current density at the phantom interface when the high permittivity material is in direct contact, reflecting the formation of a return path or RF current 'loop' with associated RF power absorption.

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