Improving Quantitative Brain Tumor Conductivity Mapping with Feature-Based Calibration of Phase-Based MR Electrical Properties Tomography

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ABSTRACT

Phase-based MR electrical properties tomography (PB-MR-EPT) enables noninvasive conductivity mapping, but tumor conductivity estimates may be systematically affected by tumor-related features. This study evaluated whether tumor depth, tumor diameter, peritumoral edema, and local conductivity context introduce reconstruction bias, and whether feature-based calibration can reduce this error. Controlled phantom simulations were used to isolate individual feature effects under known ground-truth conductivity conditions, and matched phantom MRI acquisitions tested whether simulation-derived calibration trends were experimentally reproducible. A standard brain model was then used to integrate multiple tumor features into a multivariable calibration model that outputs a tumor-specific correction coefficient, followed by validation in independent brain-test models. PB-MR-EPT bias varied consistently with tumor features: deeper and smaller tumors showed greater underestimation, while edema and tumor-to-adjacent-tissue conductivity contrast altered the magnitude and direction of bias. Phantom acquisitions reproduced the main simulation-derived trends, supporting the relevance of the calibration approach. In independent brain-test models, tumor-only calibration improved conductivity accuracy while preserving background brain tissue values, reducing mean relative error from 33.8% to 3.5%. These findings suggest that tumor features should be considered in PB-MR-EPT technical development and quantitative brain tumor conductivity assessment.

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INTRODUCTION

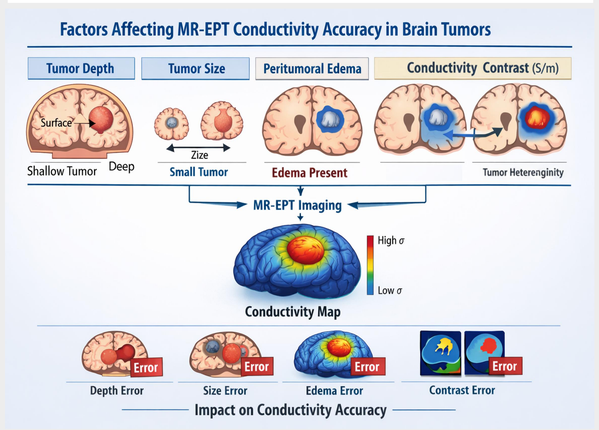
MR electrical properties tomography (MR-EPT) enables noninvasive mapping of tissue conductivity from MRI-derived radiofrequency phase information. Because conductivity reflects tissue water content, ion concentration, cellular structure, and microenvironmental composition, it may provide complementary quantitative information for brain tumor assessment.

Phase-based MR-EPT (PB-MR-EPT) is attractive because it can estimate conductivity from phase images without requiring full transmit-field mapping. However, PB-MR-EPT relies on spatial phase derivatives, making the reconstruction sensitive to image resolution, phase smoothing, partial-volume effects, and tissue interfaces.

Tumor-related features such as depth, diameter, peritumoral edema, and local conductivity context are often treated as incidental anatomic conditions. We hypothesized that these features systematically influence PB-MR-EPT tumor conductivity estimates and that feature-based calibration could reduce reconstruction bias.

METHODS AND MATERIALS

Controlled phantom simulations tested how tumor depth, diameter, peritumoral edema, and local conductivity context affect PB-MR-EPT reconstruction under known ground-truth conditions. Matched phantom MRI acquisitions evaluated whether simulation-derived trends and calibration effects were reproducible experimentally. Tumor conductivity was extracted using a predefined tumor-core ROI to reduce boundary effects. A standard brain model was used to integrate multiple tumor features into a multivariable calibration model that generated one tumor-specific correction coefficient. Independent brain-test models then validated tumor-only conductivity correction while preserving background brain tissue values.



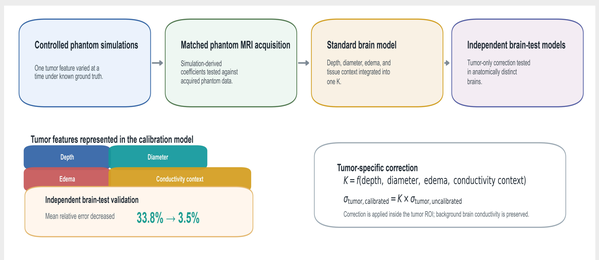


Fig.1. Feature-Aware Calibration Workflow for PB-MR-EPT Tumor Conductivity Mapping

RESULTS

Controlled phantom simulations showed that PB-MR-EPT reconstruction bias depended systematically on tumor features. Deeper tumors and smaller tumors showed greater conductivity underestimation. Peritumoral edema altered reconstructed tumor conductivity according to edema conductivity category and shell configuration, while tumor-to-adjacent-tissue conductivity contrast changed both the magnitude and direction of bias.

Matched phantom MRI acquisitions reproduced the main simulation-derived trends, supporting the experimental relevance of the feature-dependent bias. Calibration coefficients derived from phantom simulations reduced reconstruction error in acquired phantom data, indicating that the observed bias was not only a numerical simulation effect.

In standard brain-model simulations, multiple tumor features were integrated into one calibration coefficient using a multivariable model. Independent brain-test validation showed that tumor-only calibration improved conductivity accuracy while preserving background brain tissue values. Across validation tumors, mean relative error decreased from 33.8% before calibration to 3.5% after calibration.

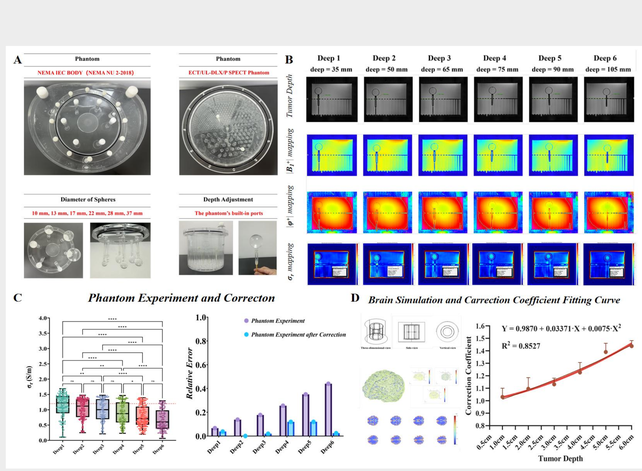


Fig.2. Depth-Dependent Tumor Conductivity Reconstruction Bias and Feature-Based Correction Coefficient Derivation in Phase-Based MR Electrical Properties Tomography Using Phantom Experiments and Numerical Simulations

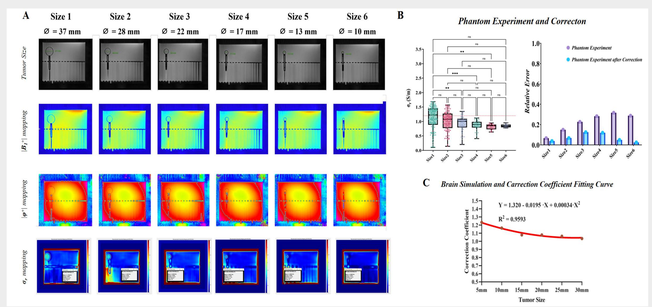


Fig.3. Tumor Size–Dependent Conductivity Reconstruction Bias and Calibration Model Development in Phase-Based MR Electrical Properties Tomography Based on Phantom Validation and Heterogeneous Brain Simulations

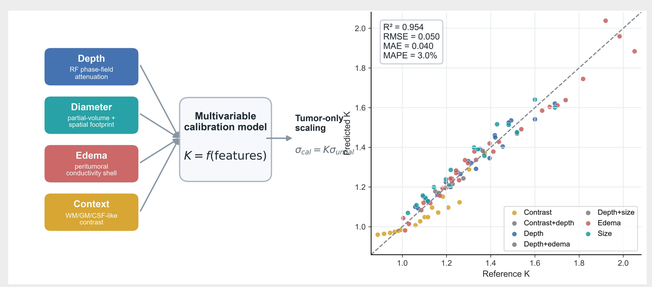


Fig.4. Multivariable Tumor-Feature Model for Predicting the Calibration Coefficient K

DISCUSSION

This study shows that PB-MR-EPT tumor conductivity bias is not only a reconstruction-noise problem, but also a tumor-feature-dependent phenomenon. Tumor depth, diameter, peritumoral edema, and local conductivity context each altered the phase-derived conductivity estimate under controlled conditions.

The depth and size effects suggest that PB-MR-EPT accuracy depends on how strongly a tumor perturbs the local RF phase field and how well that perturbation is sampled on the image grid. Smaller tumors provide fewer reliable core voxels and are more vulnerable to derivative-based estimation, while deeper tumors showed weaker phase-field support.

Peritumoral edema and conductivity contrast produced more context-dependent effects. Surrounding edema changed the local phase environment around the tumor, and different adjacent-tissue conductivity settings altered the interface conditions sampled by the reconstruction. These effects may be especially relevant for brain tumors, where edema, CSF, gray matter, and white matter interfaces are common.

The calibration framework reduced error by linking measurable tumor features to a tumor-specific correction coefficient. Importantly, correction was applied only within the tumor region, preserving background brain conductivity maps and avoiding global rescaling of the entire image.

These findings highlight the need to consider tumor features during PB-MR-EPT technical development and interpretation. Future studies should test this framework in patient data and evaluate how clinical segmentation uncertainty, biologic heterogeneity, and acquisition noise affect feature-aware conductivity calibration.

CONCLUSIONS

Tumor-related features can systematically influence PB-MR-EPT conductivity quantification and should not be treated as incidental anatomic conditions. Feature-based calibration reduced reconstruction bias across phantom experiments and independent brain-test models, supporting a tumor-aware approach for more reliable quantitative conductivity mapping in brain tumor assessment.

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