

REMMA

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Medical Applications

BOOK OF ABSTRACTS

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Passive Shimming for Improving B_0 Homogeneity in a Low-Field MRI System

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Abstract—Low-field MRI based on permanent magnets can reduce system cost and complexity, but sufficient B_0 homogeneity is essential for image quality. This work presents passive shimming for a low-field MRI scanner, that is being developed at the Faculty of Biomedical Engineering, Czech Technical University in Prague. The magnetic field was measured at 3567 points within a 20 cm diameter spherical volume (DSV) using an automated Hall-probe system. A Monte Carlo-based Python optimization was used to select the positions and orientations of corrective magnets. The final configuration used 917 NdFeB N45 magnets ($8 \times 8 \times 8$ mm) and reduced simulated field inhomogeneity from 27,291 ppm to 1,953 ppm. 3D-printed holders and carriers were also designed for practical implementation.

1. INTRODUCTION

Magnetic resonance imaging provides detailed anatomical images without ionizing radiation. Its correct operation requires a sufficiently homogeneous static magnetic field B_0 , because field variations change the local Larmor frequency and can produce image artifacts. [1] Low-field MRI systems using permanent magnets offer lower acquisition and operating costs, but manufacturing tolerances and surrounding ferromagnetic materials can significantly affect field homogeneity. Passive shimming compensates for these variations using appropriately positioned magnetic elements without additional power [2], [3]. The aim of this work was to reduce B_0 inhomogeneity below 2,000 ppm within a 20 cm DSV.

2. METHODS

The magnetic field distribution was measured using an automated three-axis positioning system with a Hall probe connected to a teslameter. The dominant B_x component was measured at 3567 positions within a 20 cm DSV. Data were stored in CSV format and processed in Python.

A numerical MRI model with predefined shim positions was optimized using a Monte Carlo-based algorithm. Random configurations differing in magnet position and orientation were evaluated and only solutions improving field homogeneity were retained. We also compared cubic $8 \times 8 \times 8$ mm NdFeB magnets of grades N40, N45 and N48. The field inhomogeneity was calculated as:

$$PPM = \frac{B_{max} - B_{min}}{B_{avg}} \cdot 10^6$$

where B_{max} , B_{min} and B_{avg} are the maximum, minimum and average measured magnetic flux densities. Shim holders were subsequently designed in Autodesk Fusion and manufactured from PETG using a Prusa XL 3D printer.

3. RESULTS

The initial field inhomogeneity was 27,291 ppm. Table 1 summarizes the investigated magnet configurations. Increasing the number of magnets progressively improved homogeneity. The best result was obtained with 917 N45 magnets, reaching 1,953 ppm and therefore satisfying the required value below 2,000 ppm.

Figure 5.2 shows the optimized MRI magnet geometry and the predefined shim region. The optimization determines which shim positions are occupied and the orientation of individual magnets so that their fields compensate for the measured B_0 inhomogeneity. N45 magnets were selected as a suitable compromise between achieved homogeneity, magnetic properties, cost and mechanical implementation.

Table 1. Results of numerical simulations for different shim magnet configurations.

Magnet grade	Dimensions [mm]	Number of magnets	Average remanence [T]	Final homogeneity [ppm]
N48	$8 \times 8 \times 8$	168	1.40	5043
N48	$8 \times 8 \times 8$	336	1.40	2901
N48	$8 \times 8 \times 8$	772	1.40	2093
N40	$8 \times 8 \times 8$	168	1.29	5430
N40	$8 \times 8 \times 8$	336	1.29	3336
N40	$8 \times 8 \times 8$	772	1.29	2515
N45	$8 \times 8 \times 8$	168	1.35	5131
N45	$8 \times 8 \times 8$	336	1.35	3036
N45	$8 \times 8 \times 8$	833	1.35	2051
N45	$8 \times 8 \times 8$	917	1.35	1953

Figure 5.2 shows the optimized MRI magnet system and the predefined shim region. The optimization determines which shim positions are occupied and the orientation of individual magnets so that their fields compensate for the measured B_0 inhomogeneity. N45 magnets were selected as a suitable compromise between achieved homogeneity, magnetic properties, cost and mechanical implementation.

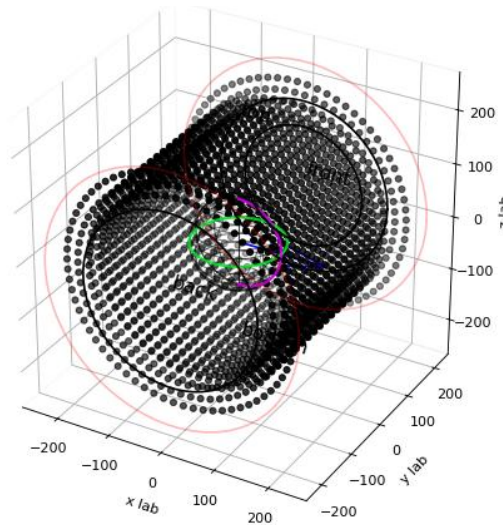


Figure 5.2. Final arrangement of the optimized magnet system and shim positions.

4. DISCUSSION

The simulations indicate that passive shimming can substantially improve B_0 homogeneity in the investigated low-field MRI system. [4] However, the achieved value is numerical and practical performance may differ because of magnet manufacturing tolerances, positioning errors and differences between the simulated and real field. Another limitation is that only the dominant B_x component was measured. In addition, the optimization used a single field map; nearby ferromagnetic objects may alter the field distribution in a mobile scanner. Experimental installation should therefore be followed by repeated field measurements and iterative optimization.

5. CONCLUSION

A passive shimming system for a low-field MRI scanner was designed from measured field data. Monte Carlo-based optimization reduced simulated inhomogeneity from 27,291 ppm to 1,953 ppm using 917 cubic NdFeB N45 magnets. This fulfilled the target of less than 2,000 ppm within the 20 cm DSV. 3D-printed holders and carriers were developed for accurate magnet placement. Future work will focus on installation of the complete shim configuration and experimental verification of the resulting field homogeneity.

REFERENCES

- [1] JUCHEM, Christoph a Robin A. DE GRAAF. B_0 Magnetic Field Homogeneity and Shimming for In Vivo MR Spectroscopy. *Analytical Biochemistry*. 2017, roč. 529. DOI 10.1016/j.ab.2016.06.003. [cit. 2026-09-06]
- [2] QUESTIONS AND ANSWERS IN MRI. *Passive magnetic shimming* [online]. [cit. 2026-09-06]. Dostupné z: <https://mriquestions.com/passive-shimming.html>
- [3] BLÜMLER, Peter a Federico CASANOVA. Hardware development: Halbach magnet arrays. In: *Hardware Developments for Low-Field Magnetic Resonance*. [cit. 2026-09-06]
- [4] KULIKOV, Ilia, David SCHOTE, Helge HERTHUM et al. *Shimmer: End-to-End Open-Source Passive B_0 Shimming Methodology for Low-Field MRI Magnets* [online]. 2026 [cit. 2026-09-06]. arXiv:2608.22351. Dostupné z: <https://arxiv.org/abs/2608.22351>

Assessment of mitral valve dynamics in patients with suspected mitral annular disjunction using cine CMR data

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Abstract—Mitral annular disjunction (MAD) is a structural abnormality of the mitral valve associated with altered mechanical behavior of the mitral apparatus and an increased risk of ventricular arrhythmias. A semiautomatic annotation system was developed and tested on a pilot dataset from one patient. Cine cardiac magnetic resonance (CMR) images covering seven systolic phases were annotated using four reference points defining the mitral valve plane and the papillary muscle (PM) apex and base. The resulting coordinates were used to quantify PM to mitral valve distance, PM length, changes in distance over time, and PM apex velocity throughout systole. The developed system successfully enabled tracking and quantitative assessment of the selected structures, while comparison with previously published findings indicated physiological PM behavior in the pilot patient without substantial functional abnormalities. Validation in a larger patient cohort is required to determine its clinical relevance.

1. INTRODUCTION

Mitral annular disjunction (MAD) is a structural abnormality of the mitral valve characterized by separation of the mitral annulus from the left ventricular myocardium [1][2]. It is frequently associated with mitral valve prolapse (MVP), occurring in more than 30% of patients with MVP[3], which itself affects approximately 2–3% of the population in Western countries[4][5]. Although MVP generally has a favorable prognosis, MAD and arrhythmogenic MVP phenotypes have been associated with ventricular arrhythmias (VA) and, in some cases, sudden cardiac death (SCD)[6][7]. Current evidence suggests that MAD may increase mechanical stress on the mitral apparatus, contributing to myocardial remodeling, fibrosis, and electrical instability[8][2]. Other features, including systolic curling, myxomatous valve degeneration, and myocardial fibrosis, may further contribute to arrhythmic risk[9][10][11]. Cardiac magnetic resonance (CMR) enables detailed assessment of cardiac anatomy and function and can detect myocardial fibrosis using late gadolinium enhancement (LGE)[12]. However, the mechanical behavior of the papillary muscles (PM) and its relationship with MAD remain insufficiently understood. Previous CMR findings have suggested altered trajectories and increased mobility of PM in patients with MVP[13]. Therefore, this study aims to assess mitral valve dynamics, with particular emphasis on PM motion and its relationship with MAD, using cine CMR data.

2. METHODS

A pilot cine CMR dataset from one patient was used to develop and test the proposed annotation and analysis system. The original dataset consisted of 168 DICOM files acquired in multiple imaging series and views. After automated quality control and selection of the series with the required visualization of the mitral apparatus and a resolution of 300×384 pixels, 84 images were retained for analysis. Based on their spatial position and acquisition time, the images were organized into 12 anatomical slices, each containing seven temporal frames covering systole.

Automatic annotation system was developed to enable interactive tracking of the mitral valve and PM throughout systole. In each frame, four reference points were manually annotated, two defining the mitral valve plane and two representing the PM apex and base. The resulting coordinates were exported in MAT and CSV formats and processed by a separate analytical module, where pixel coordinates were converted to real distances in millimeters using spatial information from the DICOM metadata. The calculated parameters included the perpendicular distance between the PM apex and the mitral valve plane, PM length, the rate of change in PM to mitral valve distance, and the actual velocity of PM apex displacement between consecutive frames. Temporal information was derived from the DICOM trigger time, and all measurements were normalized to the relative duration of systole (0–100%) to enable comparison of mitral apparatus dynamics throughout the cardiac cycle.

3. RESULTS

The developed annotation system enabled successful identification and tracking of the mitral valve and PM throughout the systolic phase of the cardiac cycle. The four reference points defining the mitral valve plane and the PM apex and base were annotated across consecutive cine CMR frames. An example of the resulting annotation is shown below.

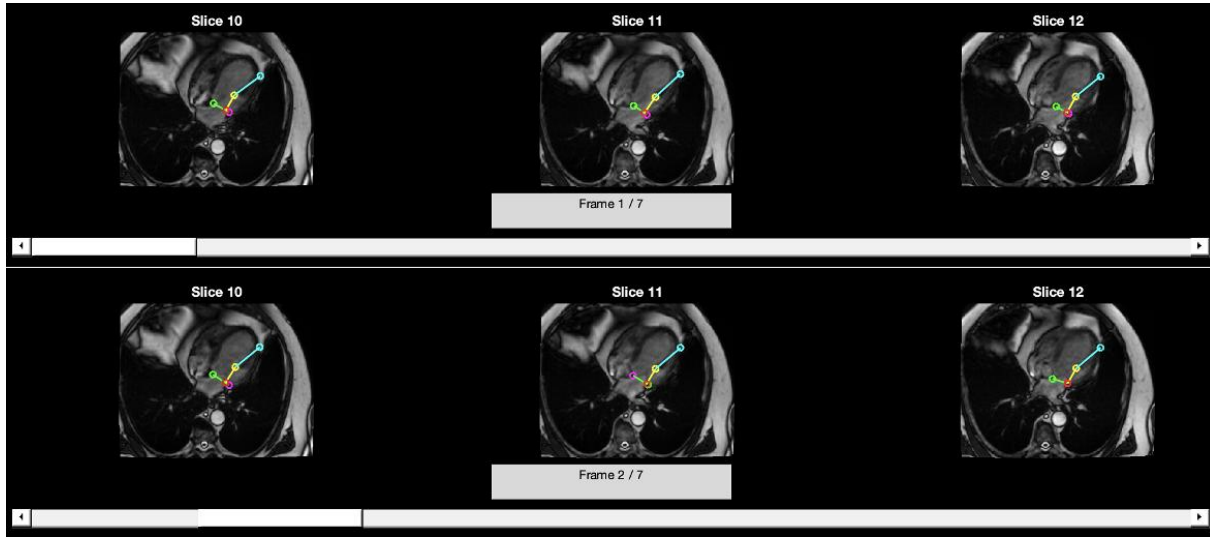


Figure 1: Example of annotation for three slices at two timeframes

4. DISCUSSION

The proposed semiautomatic approach demonstrated the feasibility of quantifying mitral apparatus dynamics from cine CMR data and may provide a useful framework for investigating mechanical alterations associated with MAD. The measurements obtained in the pilot patient were generally consistent with the findings reported by Han et al. [27] and indicated physiological PM behavior without substantial functional abnormalities. Manual expert guided annotation was preferred over fully automated detection because of the limited dataset, anatomical variability, and low contrast

between some cardiac structures, which reduced the reliability of automatic localization. However, manual annotation introduces potential observer dependent variability that should be evaluated in future studies. The current analysis was further limited to PM motion within the imaging plane and was performed on a single pilot dataset, therefore, no conclusions regarding the relationship between PM dynamics, MAD, and arrhythmic risk can yet be drawn. Future work should include a larger patient cohort, multiple independent observers, assessment of reproducibility, and more detailed analysis of PM motion.

5. CONCLUSION

A methodology for assessing mitral apparatus dynamics using cine CMR data was developed and implemented, including a semiautomatic annotation system for tracking the mitral valve and PM and quantifying selected geometric and dynamic parameters.

REFERENCES

- [undefined] PENG, Lin, Jun YUAN, Yu FENG, Chuanbao DENG, Hui MA, Yuying CHEN a Yang PENG. Age-related changes in mitral annular disjunction: A retrospective analysis using enhanced cardiac CT. *International Journal of Cardiology* [online]. 2024, **2024**(414), 6 [cit. 2026-06-10]. Dostupné z: doi:10.1016/j.ijcard.2024.132424
- [undefined] TSIMPIRIS, Vasileios, Georgia KOUSOURNA, Aristi BOULMPOU, et al. Mitral Annular Disjunction: Epidemiology, Diagnostic Methods, Prognosis, and Novel Implications. *Journal of Cardiovascular Development and Disease* [online]. 2025, **2025**(8), 2-5 [cit. 2026-03-29]. Dostupné z: doi:10.3390/jcdd12080311
- [undefined] SIEGEL, Robert, Konstantinos MYLONAS, Dimos 5, 1, 6,7, 4 KROMMYDAS, et al. Mitral Annular Disjunction: Pathophysiology, Pro-Arrhythmic Profile and Repair Pearls. *Reviews in Cardiovascular Medicine* [online]. 2022, **2022**(23), 6 [cit. 2026-06-06]. Dostupné z: doi:10.31083/j.rcm2304117
- [undefined] LODIN, Klara, Cristina Oliveira DA SILVA, Anne WANG GOTTLIEB, et al. Mitral annular disjunction and mitral valve prolapse: long-term risk of ventricular arrhythmias after surgery. *European Heart Journal* [online]. 2025, **2025**(46), 11 [cit. 2026-06-06]. Dostupné z: doi:10.1093/eurheartj/ehaf195
- [undefined] TASTET, Lionel, Shalini DIXIT, Rohit JHAWAR, et al. Interstitial fibrosis and arrhythmic mitral valve prolapse: Unraveling sex-based differences. *Journal of Cardiovascular Magnetic Resonance* [online]. 2024, **2024**(26), 11 [cit. 2026-06-06]. Dostupné z: doi:10.1016/j.jocmr.2024.101117
- [undefined] PISCIONE, Mariagrazia, Barbara PALA, Francesco CRIBARI, Walter VIGNAROLI, Jad MROUE, Vivek MEHTA, Fadi MATAR a Marco Alfonso PERRONE. The Arrhythmogenic Spectrum of Mitral Valve Disease: Pathophysiology, Risk Stratification, and Surgical Management. *Journal of Clinical Medicine* [online]. 2026, **2025**(865), 24 [cit. 2026-06-07]. Dostupné z: doi:10.3390/jcm15020865
- [undefined] CHIANESE, Salvatore, Leopoldo ORDINE, Daniela PACELLA, Grazia CANCELLLO, Salvatore DI NAPOLI, Raffaella LOMBARDI, Giovanni ESPOSITO a Maria Angela LOSI. Arrhythmic risk in mitral valve prolapse with mitral annular disjunction: meta-analysis of longitudinal studies. *Scientific Reports* [online]. 2025, **2026**(2428), 8 [cit. 2026-06-07]. Dostupné z: doi:https://doi.org/10.1038/s41598-025-32285-3
- [undefined] VAN DER BIJL, Jan STASSEN, Kristina HAUGAA, et al. Mitral Annular Disjunction in the Context of Mitral Valve Prolapse. *JACC: Cardiovascular Imaging* [online]. 2024, **2024**(10), 1-13 [cit. 2026-03-29]. Dostupné z: doi:10.1016/j.jcmg.2024.03.006
- [undefined] BASSO, Cristina, Sabino ILCETO, Gaetano THIENE a Martina Perazzolo MARRA. Mitral Valve Prolapse, Ventricular Arrhythmias, and Sudden Death. *American Heart Association Journal-Circulation* [online]. 2019, **2019**(140), 13 [cit. 2026-06-07]. Dostupné z: doi:https://doi.org/10.1161/CIRCULATIONAHA.118.034075
- [undefined] HINDERER, Svenja a Katja SCHENKE-LAYLAND. Cardiac fibrosis – A short review of causes and therapeutic strategies. *Advanced Drug Delivery Reviews* [online]. 2019, **2019**(146), 6 [cit. 2026-06-10]. Dostupné z: doi:https://doi.org/10.1016/j.addr.2019.05.011
- [undefined] A DE BOER, Rudolf, Gilles DE KEULENAER, Johann BAUERSACHS, et al. Towards better definition, quantification and treatment of fibrosis in heart failure. A scientific roadmap by the Committee of Translational Research of the Heart Failure Association (HFA) of the European Society of Cardiology. *European Society of Cardiology* [online]. 2019, **2019**(21), 14 [cit. 2026-06-10]. Dostupné z: doi:10.1002/ejhf.1406
- [undefined] SABBAG, Avi, Benjamin ESSAYAGH, Juan David RAMÍREZ BARRERA, et al. EHRA expert consensus statement on arrhythmic mitral valve prolapse and mitral annular disjunction complex in collaboration with the ESC Council on valvular heart disease and the European Association of Cardiovascular Imaging endorsed cby the Heart Rhythm Society, by the Asia Pacific Heart Rhythm Society, and by the Latin American Heart Rhythm Society. *European Society of Cardiology* [online]. 2022, **2022**(24), 23 [cit. 2026-06-10]. Dostupné z: doi:10.1093/europace/euac125
- [undefined] HAN, Yuchi, Dana PETERS, Kraig KISSINGER, Beth GODDU, Susan YEON, Warren MANNING a Reza NEZAFAT. Evaluation of Papillary Muscle Function Using Cardiovascular Magnetic Resonance Imaging in Mitral Valve Prolapse. *The American journal of cardiology* [online]. 2010, **2010**(106), 12 [cit. 2026-06-14]. Dostupné z: doi:10.1016/j.amjcard.2010.02.035

DESIGN OF A MATCHING CIRCUIT FOR A LOW-FIELD MRI RF COIL

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Abstract— The aim of this study was to analyze an existing matching network topology for a predesigned RF (Radio Frequency) coil of a LF (Low-Field) MRI. The goal being the determination of component values such that the reflection coefficient was at an acceptable level. The determination of the values of the circuit elements was achieved using analytical calculations, numerical simulations, as well as a combined process of both mentioned approaches. The final circuit configuration led to a reflection coefficient of approximately -7.8 dB at a centre frequency of 2.2 MHz. Future work will focus on further improvement of both the coil designs as well as the matching network topology.

1. INTRODUCTION

Since the time of the first MRI systems being commercialized, they have always been limited by their high acquisition costs, large size and expensive operation. This has severely restricted the availability of this modality in developing regions, mobile care as well as individual hospital departments. Portable LF MRI systems offer a solution for Point-of-Care diagnostics. Current available examples include the commercially available 64 mT Hyperfine Swoop (640 kg) [1] and experimental 72 mT systems (150 to 200 kg total weight) [2]. While these LF systems successfully capture T2w images, their image quality remains relatively low and unsuitable for reliable clinical diagnostics. Examples of captured images can be seen in Figure 1. The primary bottleneck is the low Signal-to-Noise Ratio (SNR), which depends heavily on RF coil impedance matching. Without proper matching of the coil and the RF signal amplifier, severe signal reflection occurs. This, as mentioned, can result in low quality images, or in the worst case, results in damage of the amplifier. The minimization of the S_{11} scattering parameter to at least -10 dB at the operating Larmor frequency, significantly improves SNR. The aim of this project was to fabricate an RF coil and matching network based on an available GitLab repository [3], measure its performance, and optimize its component values to minimize the reflection coefficient / S_{11} scattering parameter.

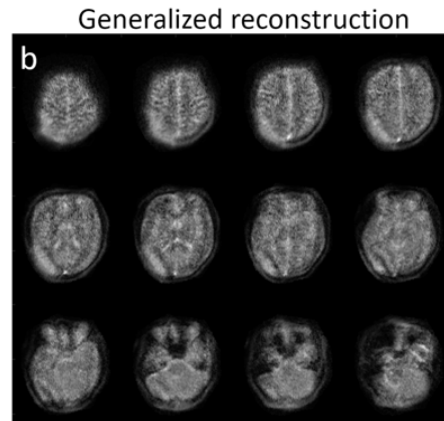


Fig. 1: Example T2w image of cranium with 1.5mm x 2.8mm x 7mm voxels; reconstructed via generalized algorithm [2]

2. METHODS

The design process of the matching network had three distinct approaches. The first approach was purely analytical, this meant treating the entire assembly, RF coil and network, as one big circuit made of ideal circuit elements. Its total impedance was derived into a simplified closed-form expression. This expression was algebraically manipulated to isolate the real and imaginary impedance components, as well as the resonant frequency, enabling direct evaluation of all key circuit parameters. Figure 2 shows the equivalent circuit.

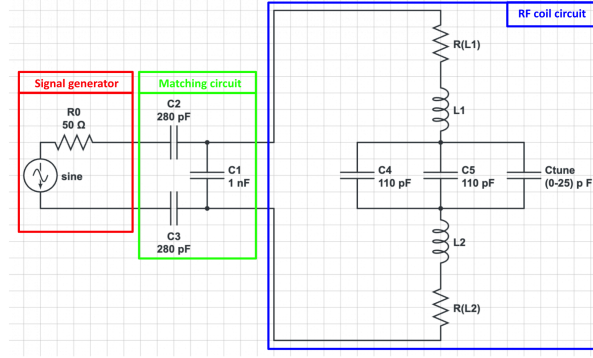


Figure 2 - Equivalent circuit schematic used in analytical and hybrid approaches

The second approach was purely numerical, and was conducted with the use of COMSOL Multiphysics® (COMSOL AB, Stockholm, Sweden). The process modeled the assembly behaviour by linking a 3D Electromagnetic Waves model of the RF coil to an Electrical Circuit interface of the matching network through a Lumped Port mapped to an External I-Terminal. Each iteration utilized sequential parametric sweeps across three steps: first varying C1, then adjusting C4' (representing the parallel combination of C4, C5, and Ctune), and finally varying C2 and C3 symmetrically. All mentioned components can be seen above in Fig. 2. The scattering parameters were plotted against frequency and component values to identify optimal configurations. The last approach, or the hybrid approach, combined both mentioned approaches, by using the COMSOL software to model the entire assembly, however, using only the electrical circuit interface feature. Then, the same optimization sequence as in the numerical method was used. Once suitable component values that seemed realistic based on gained insight were reached, the values were substituted into the formulas generated by the first approach to verify the assembly's centre frequency, reflection coefficient and impedances. The reflection coefficient of each configuration was measured using a Vector Network Analyzer (VNA FSH8, Rohde & Schwarz, Germany).

3. RESULTS

The resulting performance of all the tested configurations can be seen below in table 1.

Table 1: All capacitor values, centre frequency, S_{11} scattering parameter per design iteration (Iter.)

Iteration	C1 (nF)	C4' (pF)	C2,3 (pF)	Centre Frequency (MHz)	S_{11} (dB)
1	1	224.5 - 245	280	1.60	-3.5
2	1.068	104.5 - 125	280	2.20	-1.73
3	1.6	104.5 - 125	325	2.20	-2.28
4	7	104.5 - 125	321	NA	NA
5	0.7	151.5 - 172	280	2.07	-8.60
6	0.7	104.5 - 125	280	2.21	-8.23

7	0.7	114.5 - 135	280	2.20	-7.82
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4. DISCUSSION

Initial measurements of the original repository circuit [3] revealed poor overall performance as the S_{11} scattering parameter was 65% below the target threshold of -10 dB and the centre frequency drifted 27% downward from the required value of 2.2 MHz. Subsequent design variations successfully corrected the centre frequency, but the reflection coefficient remained sub-optimal. This was likely driven by excessively large C1 and/or C2,3 capacitances, which lowered capacitive reactance and prevented efficient energy storage within the LC resonant tank. Ultimately, the hybrid design approach resulted in the most favorable performance. The centre frequency was precisely at 2.2 MHz, while bringing the S_{11} to -7.82 dB. Although the S_{11} parameter was still 22% away from the ideal threshold. After discussion with the project supervisor, this final configuration was deemed as acceptable.

5. CONCLUSION

The hybrid design approach yielded the most effective matching network, achieving the target frequency of 2.20 MHz and an improved S_{11} of -7.82 dB, representing a significant performance upgrade over the initial baseline design. However, due to strict time constraints, final physical fabrication and soldering of the custom PCB could not be completed. Future work should explore standard matching network topologies, such as Pi, L, or T networks. These networks have been well-documented, making optimization much easier. Additionally, fabricating and populating the dedicated PCB remains essential to improving overall signal quality.

REFERENCES

- [1] HYPERFINE. *Swoop System (v1.9) Summary Specifications Sheet: LBL-003696 v4* [online]. [accessed 2026-04-20]. Available from: https://www.hyperfinemri.com/assets/files/Swoop_System_%28v1.9%29_Summary_Specifications_Sheet_-LBL-003696_v4.pdf
- [2] ISMRM. Conference abstract 0559. *Proceedings of the International Society for Magnetic Resonance in Medicine: 29th Annual Meeting* [online]. [accessed 2026-04-20]. Available from: <https://cds.ismrm.org/protected/21MProceedings/PDFfiles/0559.html>
- [3] OSII. a4im-rf-head-coil. *GitLab* [online]. 2025 [accessed 2026-04-26]. Available from: <https://gitlab.com/osii/rf-system/rf-coils/a4im-rf-head-coil>

Efficient Inversion Methodologies for MR-EPT and Microwave Imaging

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Abstract—This work presents a two-step inversion methodology for Magnetic Resonance-based Electrical Properties Tomography (MR-EPT), later extended to Microwave Imaging (MWI). The non-linear reconstruction problem is reformulated into two sequential linear steps: an auxiliary current and the total electric field are first estimated via conjugate-gradient minimization, and the dielectric contrast is then retrieved in closed form. A prior-informed, anatomically segmented representation further reduces the number of unknowns. Numerical validation on the anatomical head model “Ella” was performed.

1. INTRODUCTION

The dielectric properties of biological tissues, permittivity and conductivity, govern the interaction between electromagnetic fields and the human body, and their characterization is relevant for diagnosis, therapy and monitoring. Traditional techniques (e.g., coaxial probes, short antennas) are invasive and limited to in vitro or ex vivo use. Novel non-invasive, in vivo, patient-specific techniques have therefore emerged, among which Magnetic Resonance Electrical Properties Tomography (MR-EPT) and Microwave Imaging (MWI).

MR-EPT reconstructs the electrical properties from the RF magnetic field measured by an MRI scanner. Early water-content-based methods lack a physical grounding, forward Helmholtz-EPT assumes local homogeneity and is noise-sensitive, and inverse EPT methods improve robustness at a higher cost. MWI retrieves the dielectric map of an unknown target from the scattered field measured outside the body, for applications such as breast cancer screening or brain stroke monitoring. MWI and MR-EPT share a common mathematical framework as nonlinear and ill-posed inverse problems, where the unknown induced current distribution is related to measured electromagnetic fields through a forward operator. In MWI, the electric field is measured externally and is directly linked to the induced currents, $\mathbf{E}_{\text{scatt}} = \mathbf{A}_e[\mathbf{w}]$, with $\mathbf{w} = \chi \mathbf{E}_{\text{tot}}$. In MR-EPT, the RF field is generated within the body and only the components detectable by MRI are measured, requiring an additional mapping between the induced currents and the measured magnetic field. Thus, while the two techniques share the same underlying inverse-problem structure, they differ in the source configuration and, consequently, in the measurement operator connecting the unknown currents to the available data.

2. METHODS

The proposed approach decomposes the nonlinear inverse problem into two sequential steps. First, the induced current density $\mathbf{w}$ and the total electric field $\mathbf{E}_{\text{tot}}$ are jointly estimated from the acquired RF magnetic field data. This is formulated as a regularized optimization problem that simultaneously accounts for the agreement with the measurements and the physical relationship between $\mathbf{w}$ and $\mathbf{E}_{\text{tot}}$. The resulting optimization problem is linear but remains ill-posed and is solved iteratively using a conjugate-gradient minimization scheme. In the second step, the electromagnetic contrast χ is retrieved directly from the estimated quantities,

from which the relative permittivity and electrical conductivity are subsequently obtained without further iterative optimization [1]. To improve computational efficiency and stability, anatomical segmentation can be incorporated into the inversion by assigning a single unknown parameter to each tissue class rather than to each image voxel, thereby reducing the dimensionality of the problem and enabling tissue-specific refinement [2].

3. RESULTS

The proposed approach was numerically validated on the “Ella” full-anatomical head phantom at 64 MHz. The incident RF field was simulated using CST Studio Suite® 2021, with reference data obtained through the Method of Moments (MoM). To assess the robustness of the proposed formulation, noise was added to the simulated data at two SNR levels (25 dB and 19 dB). As reported in Table I, the average reconstruction error for both relative permittivity and conductivity remained below 3% across all considered tissues at both noise levels [1]. The limited variation in reconstruction error between the two SNR conditions demonstrates the robustness of the proposed approach to noisy measurements. In comparison with the conventional iterative CSI-EPT method, the proposed two-step formulation provides comparable reconstruction accuracy while substantially reducing the computational cost.

Table 1. Average reconstruction error (%) for relative permittivity and conductivity at different SNR levels

SNR	Relative permittivity error (%)	Conductivity error (%)
25 dB	$\approx 0.362\%$	$\approx 0.732\%$
19 dB	$\approx 0.9\%$	$\approx 1.72\%$

[†] Averaged over skin, skull, grey matter, white matter and cerebellum.

4. DISCUSSION

The results support the potential of the proposed formulation as an efficient strategy for electromagnetic inverse problems in biomedical imaging. In particular, the use of anatomical prior information provides a flexible way to control the complexity of the reconstruction while preserving a tissue-specific description of the electrical properties. More generally, the formulation offers a framework that can be adapted to different electromagnetic imaging configurations. Its extension to MWI will require accounting for the different measurement operator and acquisition geometry, while retaining the same underlying inverse-problem strategy.

5. CONCLUSION

This work investigated an efficient inversion strategy for MR-EPT based on the decomposition of the reconstruction problem into sequential estimation steps. The results demonstrate the potential of this approach for reducing the computational complexity of electromagnetic property reconstruction while maintaining reliable estimates of tissue electrical properties. Future work will investigate its extension to MWI and its application to anatomically realistic 2D and 3D models, with the broader aim of developing efficient and robust inversion methodologies for biomedical electromagnetic imaging.

REFERENCES

- [1] F. Capitanio, M. Cavagnaro, L. Crocco, and R. Scapaticci, “A Novel Two-step Approach for Magnetic Resonance Electrical Properties Tomography,” *IEEE Transactions on Antennas and Propagation*, submitted for publication.
- [2] M. T. Bevacqua, G. G. Bellizzi, T. Isernia, and L. Crocco, “A method for effective

permittivity and conductivity mapping of biological scenarios via segmented contrast source inversion,” *Progress In Electromagnetics Research*, vol. 164, pp. 1–15, 2019, doi: 10.2528/PIER18071704.

- [3] A. Christ, W. Kainz, E. G. Hahn, K. Honegger, M. Zefferer, E. Neufeld, W. Rascher, R. Janka, W. Bautz, J. Chen, B. Kiefer, P. Schmitt, H.-P. Hollenbach, J. Shen, M. Oberle, D. Szczerba, A. Kam, J. W. Guag, and N. Kuster, “The Virtual Family—development of surface-based anatomical models of two adults and two children for dosimetric simulations,” *Physics in Medicine and Biology*, vol. 55, no. 2, pp. N23–N38, 2010.

Towards a Portable Microwave Imaging System for Brain Stroke Monitoring: Hardware Assessment and Experimental Validation

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Abstract—Stroke is a major neurological condition that disrupts blood flow and oxygen delivery to the brain, potentially causing severe disability or death. The resulting physiological changes alter the dielectric properties of the affected tissues, producing variations in their microwave scattering response that can be exploited for imaging and monitoring purposes. This contribution presents the assessment and progressive development of a portable microwave imaging (MWI) system for brain stroke monitoring, aimed at providing a non-ionizing, potentially low-cost complementary tool for repeated bedside examinations. Building on previous proof-of-concept systems, the research investigates a 22-antenna architecture, custom antenna-matching modules, compact microwave hardware based on off-the-shelf components, and switching-network performance. Three-dimensional dielectric contrast maps are reconstructed using a low-complexity, standalone differential imaging algorithm based on the distorted Born approximation. Experimental validation with tissue-mimicking head phantoms has demonstrated the localization and tracking of hemorrhage-like volume changes, while anthropomorphic multi-tissue phantoms enable assessment under more realistic anatomical and dielectric conditions. Dedicated studies have also addressed measurement stability and simplified multichannel calibration. Current developments focus on an adjustable pneumatic helmet designed to improve antenna-to-head contact and measurement repeatability across different head shapes. Overall, these activities contribute to the development of a compact, reliable, and portable MWI scanner for bedside stroke monitoring, with future work directed toward experimental validation under increasingly realistic conditions and eventual clinical translation.

Keywords—microwave imaging; brain stroke; portable scanner; antennas; phantom validation; calibration; repeatability.

1. INTRODUCTION

Stroke is a neurological emergency caused by an interruption of blood flow to the brain, either due to a vessel obstruction (ischemic stroke) or bleeding (hemorrhagic stroke), potentially resulting in severe disability or death [1]. These conditions induce physiological changes in the affected tissues, altering their dielectric properties and, consequently, their electromagnetic scattering response.

Microwave imaging (MWI) exploits these dielectric variations to reconstruct spatial maps of dielectric contrast, providing a non-ionizing and potentially low-cost complementary technology to conventional neuroimaging techniques, such as computed tomography (CT) and magnetic resonance imaging (MRI) [2], [3]. Its potential for compact implementation makes it particularly attractive for repeated bedside monitoring of stroke evolution.

In this context, the present research focuses on the assessment and progressive development of a portable MWI system for brain stroke monitoring. Building on previous experimental validations [3], the work investigates compact acquisition hardware, antenna-matching modules, low-complexity image reconstruction, and measurement repeatability [4]. The ultimate goal is to develop a standalone, bedside-compatible scanner capable of monitoring stroke evolution under increasingly realistic conditions.

2. PORTABLE-ORIENTED SCANNER AND ANTENNA DESIGN

The investigated system employs 22 antenna-matching modules (Ant-MMs) distributed around a head-shaped target. Each module uses a printed monopole on an FR4 substrate together with a purpose-designed dielectric matching element based on urethane rubber and graphite powder. Operation near 1 GHz offers a practical trade-off between penetration and spatial resolution; conformal positioning and dielectric matching are intended to improve coupling and limit air gaps. [5], [6], [7]. A vector network analyzer (VNA) acquires complex scattering parameters, while a switching network sequentially connects the antennas to the available transceiver channels. An initial study compared a custom electromechanical switching matrix with a compact commercial solid-state solution, considering insertion loss, isolation and acquisition settings [6].

3. EXPERIMENTAL VALIDATION AND CALIBRATION

A dedicated anthropomorphic, multi-tissue head phantom was manufactured using 3D-printed molds and mixtures designed to emulate skin, fat, skull, brain tissues and cerebrospinal fluid [8]. Its dielectric properties were characterized over 0.5–2 GHz using an open-ended coaxial probe [9], and a versatile dielectric characterization method that combines the open-ended coaxial probe method with a measurement in a double ridge waveguide via a multi-objective optimization to invert the scattering response [10].

In the switching-matrix assessment, controlled experiments reproduced transitions from a healthy state to a 20 cm³ hemorrhage-like inclusion and from 20 to 40 cm³. Both electromechanical and solid-state configurations localized the evolving target, although image quality with the solid-state matrix depended on VNA acquisition settings and signal attenuation [6], as shown in Fig 1. Tests with the compact configuration also retained the ability to image the mimicked lesion [7]. Calibration is equally important: the investigated approach combines a conventional two-port calibration with

an extension to the remaining channels to compensate, under specified assumptions, for multiplexing-related losses and phase shifts. Repeatability and stability tests support this simplified procedure for the evaluated hardware, without making it a universal replacement for a full multipoint calibration [11], [12].

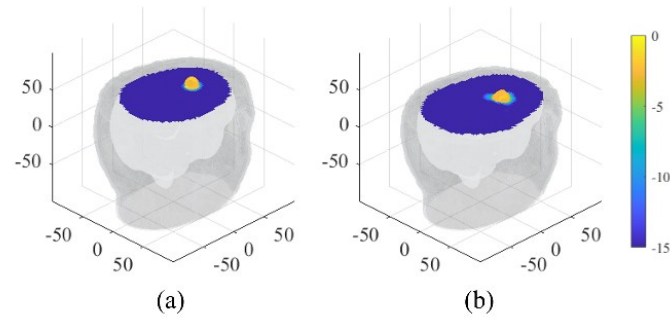


Figure 1. Transverse views extracted from 3-D reconstructions of the normalized dielectric contrast in dB.
(a) Electromechanical, (b) Solid-state switching matrix.

4. TOWARDS REPEATABLE ANTENNA CONTACT

A further obstacle to bedside use is variability in head shape and size: a fixed support may leave different antenna–head air gaps at different locations, producing changes in the scattering data unrelated to a pathological evolution. The current design therefore incorporates a helmet with individually actuated pneumatic elements and guided antenna motion. Each module can move toward the local surface, with the goal of more uniform contact and repeatable positioning. Initial mechanical fitting tests are encouraging, but a quantitative reduction in microwave measurement variability and improved robustness of the reconstructed images still require experimental demonstration.

5. CONCLUSION

The work summarizes a preclinical assessment pathway from multistatic antennas and compact switching hardware to differential reconstruction, phantom experiments and calibration. The results obtained so far support further development of a portable-oriented MWI scanner for repeated brain stroke monitoring, while identifying coupling and reproducibility as critical engineering requirements. Next steps include testing the pneumatic helmet, quantifying measurement stability and image robustness across head shapes, and extending validation toward realistic hospital use; clinical utility and overall cost have not yet been demonstrated.

REFERENCES

- [1] World Health Organization, “Stroke,” Fact Sheet, Dec. 2025. WHO – Stroke .
- [2] D. O. Rodriguez-Duarte, C. Origlia, J. A. Tobon Vasquez, R. Scapaticci, L. Crocco, and F. Vipiana, “Experimental Assessment of Real-Time Brain Stroke Monitoring via a Microwave Imaging Scanner,” *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 824–835, 2022. doi: 10.1109/OJAP.2022.3192884.
- [3] D. O. Rodriguez-Duarte, M. Gugliermينو, C. Origlia, J. A. Tobon Vasquez, R. Scapaticci, L. Crocco, and F. Vipiana, “Advancements in the Experimental Validation of a Wearable Microwave Imaging System for Brain Stroke Monitoring,” in *Proc. 18th European Conference on Antennas and Propagation (EuCAP)*, Glasgow, UK, 2024. doi: 10.23919/EuCAP60739.2024.10501483.
- [4] M. Gugliermينو, D. O. Rodriguez-Duarte, C. Origlia, J. A. Tobon Vasquez, R. Scapaticci, J.-C. Bolomey, L. Crocco, and F. Vipiana, “On the Use of an Electromechanical and a Solid-State Switching Matrix for a Portable Microwave-Based Brain Stroke Scanner,” *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 11, pp. 3342–3346, 2024. doi: 10.1109/LAWP.2024.3435341.
- [5] D. O. Rodriguez-Duarte et al., “Experimental validation of a microwave system for brain stroke 3-D imaging,” *Diagnostics*, vol. 11, no. 7, Art. no. 1232, 2021, doi: 10.3390/diagnostics11071232.
- [6] M. Gugliermينو et al., “On the use of an electro-mechanical and a solid-state switching matrix for a portable microwave-based brain stroke scanner,” *IEEE Antennas Wireless Propag. Lett.*, vol. 23, no. 11, pp. 3342–3346, 2024, doi: 10.1109/LAWP.2024.3435341.
- [7] M. Gugliermينو et al., “Portable microwave (pMWI) system for brain stroke imaging using off-the-shelf components,” in *Proc. 54th Eur. Microw. Conf. (EuMC)*, 2024, pp. 485–488, doi: 10.23919/EuMC61614.2024.10732037.
- [8] C. Origlia et al., “Anthropomorphic multi-tissue head phantom for microwave imaging devices testing,” in *Proc. EuCAP*, 2023, pp. 1–4, doi: 10.23919/EuCAP57121.2023.10133539.
- [9] A. La Gioia et al., “Open-ended coaxial probe technique for dielectric measurement of biological tissues: Challenges and common practices,” *Diagnostics*, vol. 8, no. 2, Art. no. 40, 2018, doi: 10.3390/diagnostics8020040.
- [10] M. Gugliermينو, D. O. Rodriguez-Duarte, J. A. Tobon Vasquez, M. Lumia, G. Virone, and F. Vipiana, “Hybrid simulation-measurement method for broadband dielectric characterization of synthetic human head tissues,” in *2023 IEEE Conference on Antenna Measurements and Applications (CAMA)*, 2023, pp. 17–21.
- [11] M. Gugliermينو et al., “Simplified multi-channel calibration for microwave imaging systems,” in *Proc. IEEE LACAP*, 2024, pp. 1–2, doi: 10.1109/LACAP63752.2024.10876286.
- [12] M. Gugliermينو et al., “Assessment of extending a two-port calibration to a multi-port microwave scanner,” in *Proc. EuCAP*, 2025, pp. 1–3, doi: 10.23919/EuCAP63536.2025.10999292.

Design and implementation of a compact microwave system for experimental detection of brain strokes

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Abstract—This study investigates the design and development of a microwave imaging system for stroke detection. A prototype of the main structural framework was designed and fabricated, alongside an electronic control circuit for fluid circulation. Additionally, multiple internal liners were developed to optimize the system's anatomical adaptation to the patient's head. The developed prototype demonstrates the potential for practical clinical application, offering a pathway to significantly accelerate stroke diagnosis, though further development and optimization remain necessary.

1. INTRODUCTION

In the field of medical imaging, microwave systems represent a promising alternative to conventional modalities such as computed tomography and magnetic resonance imaging [1],[2]. Stroke remains a leading cause of long-term disability and mortality worldwide. According to 2021 statistical data, stroke ranked as the second leading cause of death among non-communicable diseases and the third leading cause of combined mortality and long-term disability, with the global incidence having increased by 70% over recent decades [3]. Early and accessible diagnostics are therefore crucial [4].

2. METHODS

The 3D model of the system was designed using Fusion 360 (Autodesk Inc.). A comprehensive hardware assembly was developed, consisting of a helmet, a helmet stand, a base plate, a component mounting shelf, and a cable management bracket (Figure 1). All structural components were fabricated using a Prusa XL 3D printer (Prusa Research). The internal liner was manufactured using multiple layers of liquid latex. The electrical fluid pumping system comprises a peristaltic pump, a DC motor, an Arduino NANO microcontroller, two electromagnetic valves, a motor shield, power supplies, and control push-buttons.

3. RESULTS

The final iteration of the 3D-printed microwave imaging system and its support structures were successfully assembled (Figure 1). The fluid circulation system was integrated into the structural framework and tested for both filling and draining operations. Furthermore, three variants of the internal latex liners were produced: one comprising 33 layers, another with 62 layers, and a third reinforced with medical gauze.

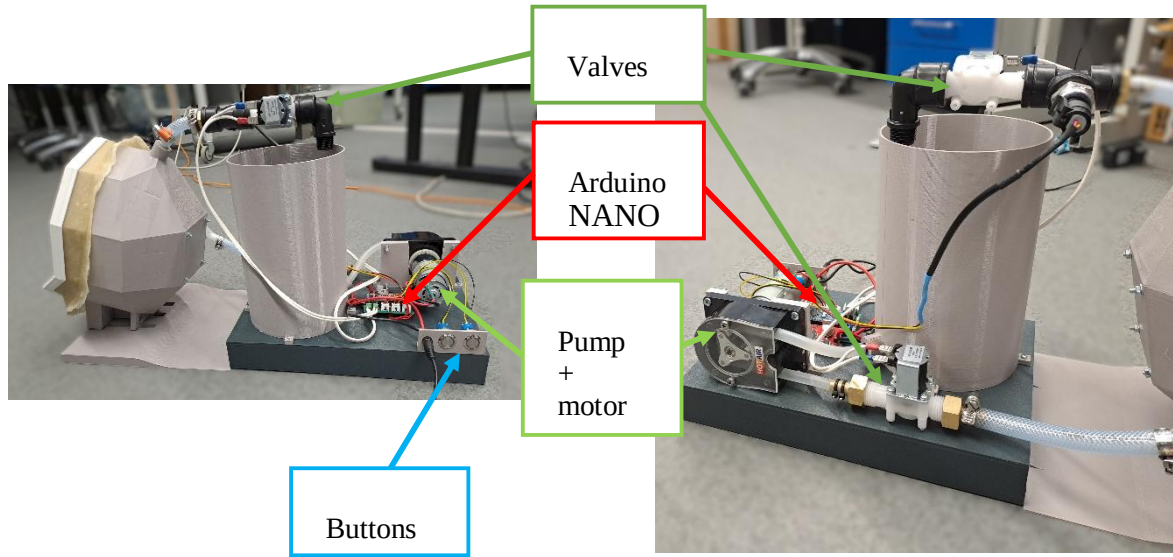


Figure 1. The complete assembled system, including the latex liner, fluid circulation system, and its mounting hardware.

4. DISCUSSION

The proposed microwave system demonstrates significant potential as a compact and portable diagnostic device. The 3D-printed structures, latex liners, and electronic controls proved conceptually viable. However, testing revealed functional limitations in the fluid management system, specifically a consistent failure to drain, which will be addressed in future development. Furthermore, as the system is still in an early developmental phase, no microwave measurements have been performed on tissue-mimicking phantoms or human subjects. Once a fully functional prototype is achieved, experimental testing will be required to validate the system's accuracy in stroke detection.

5. CONCLUSION

This work successfully realized the structural design and laboratory testing of a microwave system prototype for stroke detection. The main benefits of the developed device are its compactness, portability, and capacity for optimal anatomical adaptation to the patient's head. Testing of the system revealed design limitations that will need to be addressed in subsequent development.

REFERENCES

- [1] A. Fhager, S. Candefjord, M. Elam, and M. Persson, "Microwave Diagnostics Ahead: Saving Time and the Lives of Trauma and Stroke Patients," *IEEE Microwave Magazine*, vol. 19, no. 3, pp. 78–90, May 2018, doi: 10.1109/MMM.2018.2801646.
- [2] J.-C. Chiao *et al.*, "Applications of Microwaves in Medicine," *IEEE Journal of Microwaves*, vol. 3, no. 1, pp. 134–169, Jan. 2023, doi: 10.1109/JMW.2022.3223301.

[3] “World Stroke Organization: Global Stroke Fact Sheet 2025 - Valery L Feigin, Michael Brainin, Bo Norrving, Sheila O Martins, Jeyaraj Pandian, Patrice Lindsay, Maria F Grupper, Ilari Rautalin, 2025.” Accessed: Apr. 25, 2025. [Online]. Available: <https://journals.sagepub.com/doi/10.1177/17474930241308142>

[4] M. O. Owolabi, A. G. Thrift, A. Mahal, M. Ishida, S. Martins, and et al., “Primary stroke prevention worldwide: translating evidence into action,” *The Lancet Public Health*, vol. 7, no. 1, pp. e74–e85, Jan. 2022, doi: 10.1016/S2468-2667(21)00230-9.

Noise-Dependent TSVD Regularization for Differential Microwave Imaging Temperature Reconstruction

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Keywords: microwave imaging, hyperthermia, temperature monitoring, truncated singular value decomposition, measurement noise

Therapeutic hyperthermia (HT) improves the outcome of radiotherapy and chemoradiotherapy in locally advanced head and neck cancer, but its benefit depends strongly on reaching and maintaining an adequate temperature rise within the target volume, which makes accurate, non-invasive temperature monitoring essential. Microwave imaging (MWI) is an attractive candidate for this task because it is non-invasive, spatially resolved and compatible with existing HT applicators. However, reconstructing the temperature-induced dielectric changes from scattered-field data is a non-linear, ill-posed inverse problem that requires regularization. Truncated singular value decomposition (TSVD), one of the most common regularization strategies for Born-approximation-based MWI, is typically applied with an empirically fixed truncation index, N_{TSVD} , even though the stability of the inverse solution is directly governed by the noise present in the measured signals. This link between measurement noise and the optimal N_{TSVD} has not yet been systematically characterized for differential microwave temperature imaging.

Objective and methods

This work examines how the optimal N_{TSVD} for differential-MWI temperature reconstruction depends on the measurement noise level, and whether this dependence is frequency-sensitive. Dielectric-property maps were reconstructed with the Born approximation combined with TSVD, applied to a differential scattering matrix that isolates heating-induced changes by normalizing the post-heating/pre-heating difference against the pre-heating measurement. A 2.5D neck model, built from the Duke v3.1.1 anatomical model as homogeneous muscle tissue with a localized region mimicking a 7 °C heating-induced contrast, was simulated in Sim4Life (GPU-accelerated FDTD, UPML boundaries) surrounded by 24 ultra-wideband antennas, over 0.5–1.2 GHz in 0.1 GHz steps. Each simulated scattering matrix was independently corrupted with realizations of additive white Gaussian noise at floors ranging from –65 to –108 dB. The numerical findings were validated against measurements on a matching 3D-printed phantom setup, using an M-sequence radar (Ilmsens SH-3100) and transmission-coefficient thresholding (lowest 20% removed), following a previously established methodology. Reconstruction quality was quantified with the contrast-to-background quotient (CBQ), which weights the reconstructed intensity inside the true contrast region against the whole imaging domain without requiring image binarization.

Results

For every investigated frequency and noise level, the CBQ exhibited a well-defined optimum as a function of N_{TSVD} , reflecting the trade-off between preserving informative singular components and amplifying noise-dominated ones. As the noise floor increased, the optimal N_{TSVD} consistently shifted toward lower values, whereas its dependence on frequency remained limited. Representative reconstructions at 0.6 GHz illustrated the practical impact of this trade-off: an under-estimated N_{TSVD} produced poorly localized contrasts, an over-estimated N_{TSVD} introduced noise-driven artefacts, and the optimal index yielded the best-localized reconstruction with the least surrounding fluctuation. Experimental CBQ curves followed the same trend as the numerical simulations, supporting the validity of the numerical model for real measurement conditions.

Conclusion

A fixed, empirically chosen N_{TSVD} cannot maintain reconstruction quality as measurement noise varies during an HT session. Instead, the regularization strength should be selected adaptively from an estimate of the actual noise level in the measured data. Because the optimal N_{TSVD} depended only weakly on frequency, a single noise-based selection rule appears applicable across the investigated band, which would simplify practical implementation. These results support the feasibility of adaptive, noise-aware TSVD regularization for robust MWI-based temperature monitoring, while future work should extend the analysis to heterogeneous, anatomically realistic tissue models and pursue automated, real-time noise estimation for clinical use.

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References

- [1] Shea JD, Van Veen BD, Hagness SC. A TSVD Analysis of Microwave Inverse Scattering for Breast Imaging. *IEEE Trans Biomed Eng* 2012;59:936–45.
- [2] Ley S, Schilling S, Fiser O, Vrba J, Sachs J, Helbig M. Ultra-Wideband Temperature Dependent Dielectric Spectroscopy of Porcine Tissue and Blood in the Microwave Frequency Range. *Sensors* 2019;19:1707.
- [3] Šmahelová B, Kollár J, Linha Z, Redr J, Laierová H, Pokorný T, Drizdal T, Novák M, Fiser O, Vrba D, Vrba J. Differential Microwave Temperature Monitoring with Transmission Coefficient Thresholding in Superficial Hyperthermia: Phantom Study. *IEEE Trans Antennas Propag*, in press.
- [4] Fiser O, Hruby V, Vrba J, Drizdal T, Tesarik J, Vrba Jr J, Vrba D. UWB Bowtie Antenna for Medical Microwave Imaging Applications. *IEEE Trans Antennas Propag* 2022;70:5357–72.

Numerical Models of Ex Vivo Hepatic Ablation Zones for Microwave-Imaging-Based Ablation Monitoring

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Introduction

Microwave ablation (MWA) is a widely used minimally invasive treatment for early-stage hepatocellular carcinoma (HCC), the dominant form of liver cancer [1,2]. Complete treatment success requires reliable feedback on the progress of ablation, yet conventional monitoring approaches — manufacturer power-time protocols, invasive temperature probes, ultrasound, CT, and MR thermometry — are limited by inaccuracy, ionizing dose, or cost [3,4]. Microwave imaging (MWI) is a promising non-ionizing, low-cost alternative that exploits the strong dielectric contrast produced by coagulation and desiccation during ablation [5]. Before competing MWI approaches, such as multifrequency tomography or differential radar imaging, can be developed and compared [6,7], they must be validated in numerical studies based on a clinically realistic model of the ablation zone that captures both its geometry and its frequency-dependent dielectric behaviour. The aim of this study was to build such a model from ex vivo experimental data.

Methods

Four ablation zones (AZ1–AZ4) were created in ex vivo porcine liver using an in-house helical dipole applicator (2.45 GHz, 25 W) for 1, 3, 6, and 10 minutes, respectively, yielding zones at progressively increasing stages of tissue coagulation. Impedance matching of the applicator to the tissue was verified with a vector network analyzer. The geometry of each zone was reconstructed from calibrated photographs by extracting the major and minor semi-axes and approximating the zone as a rotationally symmetric prolate spheroid. The dielectric properties across the largest zone (AZ4) were measured with an open-ended coaxial probe at three radial positions and in the surrounding intact tissue, over 0.5–7 GHz, yielding four representative tissue states (intact, interface, middle, centre). Each dataset was fitted with a two-pole Debye model compatible with finite-difference time-domain (FDTD) solvers [10]. The resulting geometric and dielectric data were combined into nested-zone material assignments representing four ablation stages.

Results

The applicator was well matched to the liver tissue at 2.45 GHz ($|S_{11}|$ below -15 dB), and the reflected power remained below 1 W throughout ablation, confirming stable energy transfer. The reconstructed ablation zones grew from 12.1×4.2 mm (AZ1, 1 min) to 14.5×8.1 mm (AZ4, 10 min) in major and minor semi-axis, forming a set of nested ellipsoids. The dielectric properties of intact tissue agreed with the IT'IS reference database [9], while both permittivity and conductivity decreased progressively from the ablation interface toward the near-carbonized centre, reflecting the loss of tissue water content through coagulation and desiccation, consistent with prior reports [8]. The fitted two-pole Debye models reproduced the measured permittivity and conductivity with a relative RMS error below 0.7 % across the whole 0.5–7 GHz band.

Conclusion

A complete pipeline for building clinically motivated, FDTD-compatible numerical models of hepatic ablation zones from ex vivo measurements is presented, integrating experimentally derived ablation-zone geometry with radially resolved dispersive dielectric properties. The resulting nested-zone model reproduces the measured data with sub-1 % error and provides a ready-to-use test case for future numerical studies comparing MWI-based approaches to ablation monitoring.

Keywords: microwave imaging, microwave ablation, dielectric properties, FDTD, ablation monitoring, ablation zones

Acknowledgement: This work was supported by the Interreg Central Europe grant (2024–2026) "Microwave imaging technology transfer to innovate the medical sector," CE0200670 – MedWaveImage.

References

- [1] Bray F, Laversanne M, Sung H, et al. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA Cancer J Clin* 2024;74:229–63.
- [2] Galle PR, Forner A, Llovet JM, et al. EASL Clinical Practice Guidelines: Management of hepatocellular carcinoma. *J Hepatol* 2018;69:182–236.
- [3] Brace CL. Microwave Ablation Technology: What Every User Should Know. *Curr Probl Diagn Radiol* 2009;38:61–7.
- [4] Lopresto V, Pinto R, Farina L, et al. Treatment planning in microwave thermal ablation: clinical gaps and recent research advances. *Int J Hyperthermia* 2016;33:83–100.
- [5] Origlia C, Rodriguez-Duarte DO, Tobon Vasquez JA, et al. Review of Microwave Near-Field Sensing and Imaging Devices in Medical Applications. *Sensors* 2024;24:4515.
- [6] Kollar J, Drizdal T, Vrba J, et al. Microwave Catheter Navigation System for the Radiofrequency Liver Ablation. *Cancers* 2022;14:5296.
- [7] Kollar J, Novak M, Babak M, et al. Potential of UWB Radar Systems in Monitoring Liver Ablation: A Phantom Model Study. *IEEE Trans Antennas Propag* 2024;1–1.
- [8] Lopresto V, Pinto R, Lovisolo GA, et al. Changes in the dielectric properties of ex vivo bovine liver during microwave thermal ablation at 2.45 GHz. *Phys Med Biol* 2012;57:2309.
- [9] Hasgall PA, Di Gennaro F, Baumgartner C, et al. IT'IS Database for Thermal and Electromagnetic Parameters of Biological Tissues, Version 4.0. IT'IS Foundation, Zurich, 2022.
- [10] Gabriel S, Lau RW, Gabriel C. The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Phys Med Biol* 1996;41:2271.

Inverse Design of Liquid Dielectric Phantoms for Selected Microwave Frequencies

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Abstract: Dielectric phantoms are widely used for experimental validation of biomedical microwave systems [1]. Their preparation is, however, often based on previously published recipes or iterative trial-and-error adjustment of mixture composition [2].

This work presents a data-driven inverse-design approach for liquid phantoms composed of water, isopropyl alcohol (IPA), and sodium chloride (NaCl). An experimental database of mixtures with IPA concentrations from 0 to 100% and NaCl concentrations up to 4 g/L was characterized between 200 MHz and 3 GHz using an open-ended coaxial probe. Gaussian Process Regression models [3] were trained to describe the forward relationship between composition, frequency, relative permittivity, and effective conductivity.

The trained forward models were subsequently combined with constrained optimization to determine IPA and NaCl concentrations from predefined dielectric targets. This separation between forward modeling and inverse optimization allows the same models to be used for different design objectives, including multiple target frequencies, without retraining.

The approach was experimentally demonstrated using a phantom optimized simultaneously at 1 GHz and 2.45 GHz. The target relative permittivities were 31.0 and 21.0, while the measured values were 34.1 and 25.7. Target effective conductivities of 0.95 and 1.90 S/m were experimentally reproduced as 0.66 and 1.93 S/m, respectively.

The results demonstrate the feasibility of inverse design for application-specific dielectric phantoms and indicate that multiple dielectric constraints can be incorporated into a single optimization problem.

Keywords: dielectric phantom, inverse design, Gaussian Process Regression, dielectric properties, tissue-mimicking materials

[1] D. O’Loughlin, M. O’Halloran, B. M. Moloney, M. Glavin, E. Jones, and M. A. Elahi, “Microwave Breast Imaging: Clinical Advances and Remaining Challenges,” *IEEE Transactions on Biomedical Engineering*, vol. 65, no. 11, pp. 2580–2590, 2018, doi: 10.1109/TBME.2018.2809541.

[2] R. Singh, D. Singh, and M. Gupta, “Liquid Based Phantom Preparation and Dielectric Characterization for Breast Cancer Imaging,” in *17th European Conference on Antennas and Propagation (EuCAP)*, 2023, pp. 1–4, doi: 10.23919/EuCAP57121.2023.10132947.

[3] C. E. Rasmussen and C. K. I. Williams, *Gaussian Processes for Machine Learning*. Cambridge, MA, USA: MIT Press, 2006.

Two-layer Hybrid Optimization for Hyperthermia Treatment Planning: Surrogate Optimization Combined with Pattern Search

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Keywords: hyperthermia treatment planning; SAR optimization; surrogate optimization; pattern search; hybrid optimization; head and neck; brain tumor

Introduction: Optimization is a crucial step in hyperthermia treatment planning [1,2]. Several optimization algorithms have been proposed, including Particle Swarm Optimization (PSO) [8] and other global or local methods [5]. The selected algorithm influences both the quality of the resulting plan and its reproducibility across repeated runs. Combining a global search algorithm with a local refinement step within a single workflow may improve solution quality while maintaining acceptable computation time.

Goals: The aim of this study was to evaluate a two-layer hybrid optimization strategy for SAR-based HTP in brain tumor and head and neck tumor patient models, combining Surrogate Optimization (SGO) [6] for initial global search with Pattern Search (PS) [7] for deterministic local refinement, and to compare it with standalone SGO and PS in terms of treatment quality, computation time, and stability.

Materials & Methods: SGO+PS was implemented in MATLAB and evaluated on patient-specific 3D models of three brain tumor and three head and neck tumor patients simulated using a 12-channel generic dipole antenna array at 434 MHz [4]. Antenna amplitudes and phases were optimized using THQ [3] as the objective function. In the hybrid workflow, SGO was first run with a reduced evaluation budget to obtain an initial solution, which was subsequently refined by PS within a narrowed search space. Standalone SGO and SGO+PS were repeated five times per patient; standalone PS was evaluated once as a deterministic reference. All computations were performed on CPU without GPU acceleration.

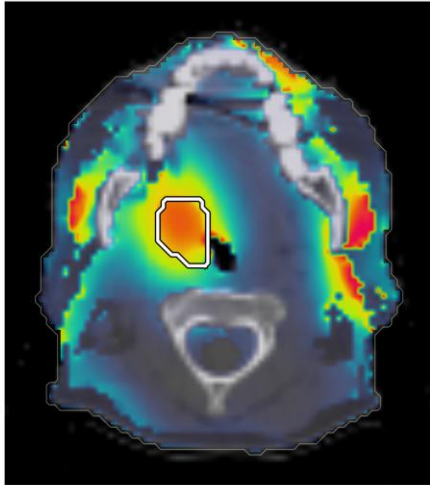
Results: For most evaluated patients, all methods achieved TC25 of 100%, indicating complete target coverage. The only exception was one head and neck patient, where standalone PS achieved notably lower TC25 than both SGO-based methods. THQ was comparable across all methods, with PS refinement improving the initial SGO solution in all 30 runs. SGO+PS substantially reduced computation time compared with standalone PS while remaining comparable to standalone SGO. Key results are summarized in Table 1 and example SAR distributions are shown in Figure 1.

Table 1. Comparison of optimization strategies.

Metric	Patient group	SGO (median)	PS	SGO+PS (median)
TC25 (%)	Brain	100	100	100
	H&N	100	46.2	93.5
THQ	Brain	0.398	0.432	0.394
	H&N	0.358	0.347	0.357
Runtime (s)	Brain	642	3013	535
	H&N	565	2036	528
Runs per patient	—	5	1	5

H&N = head and neck. Values for SGO and SGO+PS are medians over five runs per patient; PS was run once per patient.

Favourable case — HN_004
SGO+PS · TC25 = 100.0 % · THQ = 0.51



Challenging case — HN_013
SGO+PS · TC25 = 93.5 % · THQ = 0.12

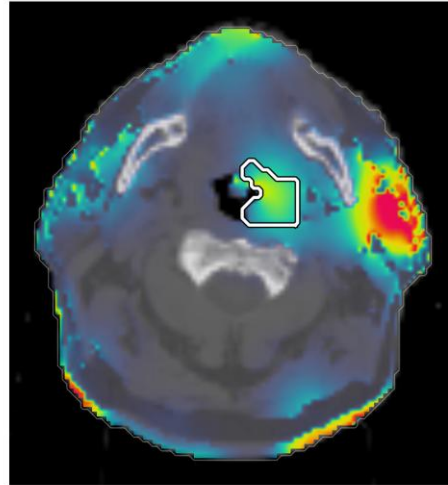


Figure 1. Normalized SAR distributions (axial slice through the GTV centre) obtained with the hybrid SGO+PS strategy for a favourable head and neck case (HN_004, TC25 = 100 %, THQ = 0.51) and a challenging one (HN_013, TC25 = 93.5 %, THQ = 0.12). White contour: GTV.

Summary: SGO+PS achieved treatment quality comparable to both standalone methods while substantially reducing computation time relative to standalone PS. TC25 of 100% was reached in five of six patients, with stable and consistent results across repeated runs. These preliminary results suggest that combining surrogate-based global exploration with deterministic local refinement may represent an efficient approach for SAR-based HTP.

References

- [1] Paulides MM, Stauffer PR, Neufeld E, et al. Simulation techniques in hyperthermia treatment planning. *Int J Hyperthermia*. 2013;29(4):346–357.
- [2] Kok HP, Wust P, Stauffer PR, Bardati F, van Rhooen GC, Crezee J. Current state of the art of regional hyperthermia treatment planning: a review. *Radiat Oncol*. 2015;10:196.
- [3] Canters RAM, Wust P, Bakker JF, van Rhooen GC. A literature survey on indicators for characterisation and optimisation of SAR distributions in deep hyperthermia, a plea for standardisation. *Int J Hyperthermia*. 2009;25(7):593–608.
- [4] Rijnen Z, Bakker JF, Canters RAM, et al. Clinical integration of software tool VEDO for adaptive and quantitative application of phase shift hyperthermia. *Int J Hyperthermia*. 2013;29(3):181–193.
- [5] Bellizzi GG, Drizdal T, van Rhooen GC, Crocco L, Isernia T, Paulides MM. The potential of constrained SAR focusing for hyperthermia treatment planning: analysis for the head & neck region. *Phys Med Biol*. 2019;64(1):015013.
- [6] Regis RG, Shoemaker CA. A stochastic radial basis function method for the global optimization of expensive functions. *INFORMS J Comput*. 2007;19(4):497–509.
- [7] Audet C, Dennis JE Jr. Analysis of generalized pattern searches. *SIAM J Optim*. 2002;13(3):889–903.
- [8] Kennedy J, Eberhart R. Particle swarm optimization. *Proc IEEE Int Conf Neural Networks*. 1995;4:1942–1948.