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Indice

Effetti Biologici (Sessione 1)

- Improved protection against methylglyoxal and re-programming of energy metabolism as novel features of the proliferative response of human neuroblastoma cells to 50 Hz magnetic field
S. Falone, S. Santini Jr, M. Cacchio, S. Di Loreto, F. Amicarelli _____ p. 5
- A Low-Frequency Electromagnetic (LF-EMF) Exposure Scheme Induces Autophagy Activation to Counteract in Vitro A β -Amyloid Neurotoxicity
F. Manai, L. Fassina, L. Venturini, F. Angeletti, C. Osera, N. Marchesi, M. Amadio, A. Pascale, G. Ricevuti, S. Comincini, S. Caorsi _____ p. 7
- Pulsed electromagnetic field prevents H₂O₂-induced reactive oxygen species production by increasing MnSOD activity in SK-N-BE neuronal cells
N. Marchesi, M. Amadio, S. Falone, C. Osera, L. Fassina, G. Magenes, S. Comincini, S. Caorsi, F. Amicarelli, G. Ricevuti, S. Govoni, A. Pascale _____ p. 9
- Pulsed Electromagnetic Fields Stimulate Osteogenic Differentiation in Human Bone Marrow and Adipose Tissue Derived Mesenchymal Stem Cells
A. Ongaro, A. Pellati, L. Bagheri, C. Fortini, M. De Mattei _____ p. 11
- Effect of Magnetic Field (MF) on Alkaline Phosphatase Activity of Human Osteosarcoma Cells
T. Rescigno, M. Caputo, B. Bisceglia, M. F. Tecce _____ p. 13
- Exposure Of SH-SY5Y Cells To Inhomogeneous Static Magnetic Field (31.7-232.0 mT) During Cisplatin Administration
C. Vergallo, M. Ahmadi, H. Mobasheri and L. Dini _____ p. 15
- Human Fibroblasts Exposed to THz Radiation: Study of Genotoxic Effects by Micronucleus Assay
A. Sgura, E. Coluzzi, C. Ciccia, A. De Amicis, S. De Sanctis, S. Di Cristofaro, V. Franchini, E. Regalbutto, A. Doria, E. Giovenale, R. Bei, M. Fantini, M. Benvenuto, L. Masuelli, F. Lista, G. P. Gallerano _____ p. 17

Valutazione Esposizione Elettromagnetica

- Exposure by WLAN in an Indoor Environment
L. Mondini, C. Sbrana, F. Arreghini _____ p. 19
- Human exposure evaluation to mobile phone electromagnetic emissions
G. d'Amore, L. Anglesio, A. Benedetto, M. Mantovan, M. Polese _____ p. 21
- Indoor levels of ELF magnetic fields in buildings with built-in transformers
S. Lagorio, L. Kheifets _____ p. 23
- General public co-exposure to electromagnetic fields and radon in urban environment
R. Massa, M. Pugliese, M. Quarto, V. Roca, S. Romeo, O. Zeni _____ p. 25

Applicazioni Medicali (Sessione 1)

- Dielectric and Thermal Properties of Tissues Undergoing Microwave Thermal Ablation Procedures
L. Farina, V. Lopresto, R. Pinto, M. Cavagnaro _____ p. 27
- Modelling of Deep Transcranial Magnetic Stimulation: Electric Field Distributions Induced in a Realistic Human Model by Different Coil Designs
V. Guadagnin, M. Parazzini, S. Fiocchi, I. Liorni and P. Ravazzani _____ p. 29

Computational Modeling of Transcranial Direct Current Stimulation: Effect of Human Anatomical Variability M. Parazzini, S. Fiocchi, I. Liorni, V. Guadagnin, A. Priori, P. Ravazzani	p. 31
Non-invasive imaging of biological microstructures by VHF waves G. Ala, P. Cassarà, E. Francomano, S. Ganci, G. Caruso, P. D. Gallo	p. 33
Selective Targeting of Magnetic Nanoparticles for Contrast Enhanced Microwave Imaging: a Preliminary Study F. Costa, A. Sannino, O. M. Bucci	p. 35
Magnetic Nanoparticles Enhanced Microwave Breast Cancer Imaging: towards a First Experimental Assessment O. M. Bucci, G. Bellizzi, L. Crocco, R. Scapatucci, G. Di Massa, S. Costanzo, A. Borgia	p. 37
A Novel Electromagnetic Guiding System to Support Running Athletes Affected by Visual Diseases G. Cerri, A. De Leo, V. Di Mattia, G. Manfredi, V. Mariani Primiani, V. Petrini, M. Peralisi, P. Russo, L. Scalise	p. 39

Effetti biologici (Sessione 2)

Effects of ELF magnetic field tuned on “parametric resonance” conditions on single channel K ⁺ currents in a human neural cell line I. Zironi, A. Virelli, E. Gavoçi, D. Remondini, B. Del Re, G. Giorgi, G. Castellani, G. Aicardi, F. Bersani	p. 41
Effects on Newborn Mice Irradiated with ELF Magnetic Fields and X-rays I. Udrouiu, A. Antoccia, C. Tanzarella, L. Giuliani, A. Sgura	p. 43
Denaturation of Proteins Induced by Exposure to Electromagnetic Fields E. Calabrò, S. Magazù	p. 45
Millimeter wave radiation- induced movement in giant vesicles S. Romeo, R. Massa, A. Ramundo Orlando	p. 47
Protective effects of non-ionizing radiofrequency fields in mammalian cells damaged by mutagens: a possible involvement of DNA repair mechanism A. Sannino, O. Zeni, S. Romeo, R. Massa, Vijayalaxmi, M. R. Scarfi	p. 49
On the Ergodicity of Molecular Dynamics Simulations: a Single DNA Strand Under the Action of a Continuous Wave Electric Field. P. Marracino, A. Paffi, A. Bannò, F. Apollonio, M. Liberti, G. d’Inzeo	p. 51

Effetti Biologici (Sessione 2)

Effects of 2,45 GHz Exposure on the Growth of Phaseolus vulgaris L. Plants N. D’Ambrosio, M.D. Migliore, R. Montuori, I. Petriccione, M. Somma, R. Massa	p. 53
The Orientation of Zebrafish (<i>Danio rerio</i>): Roles of Rheotaxis and Magnetotaxis A. Cresci, R. De Rosa, C. Agnisola	p. 55
Capillaroscopic and thermographic monitoring as a biological indicator in exposure to electromagnetic radiation R. Pennarola, R. Delia, A. A. Russo, E. Pennarola, R. Barletta	p. 57

MRI

A numerical tool to evaluate occupational exposure in MRI S. Romeo, A. Sannino, O. Zeni, M. R. Scarfi, R. Massa, V. Cerciello, R. d’Angelo	p. 59
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Implications of Directive 2013/35/UE on Protection of MRI Workers M. Tomaiuolo, R. Falsaperla, A. Polichetti	p. 61
Evolution of Subjective Symptoms in a Group of Operators Recently Engaged in Magnetic Resonance Imaging (MRI) G. Zanotti, F. Gobba	p. 63
Calculation of the ultimate intrinsic signal-to noise ratio in MRI for elliptical dielectric objects using Mathieu Functions B. Grivo, G. Carluccio, V. Angellotti, C. Ianniello, R. Massa, R. Lattanzi	p. 65
Electrical Characterization of Materials in the Frequency Range of MRI Applications V. Angellotti, G. Panariello, C. Ianniello, B. Grivo, M.D. Migliore, R. Massa, R. Lattanzi	p. 67
A Two-Compartment Tissue-Mimicking MRI Phantom for the Validation of Electrical Properties Mapping C. Ianniello, R., V. Angellotti, B. Grivo, R. Massa, R. Lattanzi	p. 69
Electromagnetic and Thermal Dosimetric Assessment of MRI Patients During the RF Exposure with Birdcage Coils N. Cesario, R. Massa	p. 71
 <i>Applicazioni medicali (Sessione 2)</i>	
A numerical and experimental analysis of electroporation in mammalian cells exposed to ns pulsed electric fields P. Lamberti, S. Romeo, A. Sannino, M. R. Scarfi, V. Tucci, O. Zeni	p. 73
Radar Detection Technique Based on Artificial Neural Network in Breast Cancer Diagnosis: Preliminary Assessment Study S. Caorsi, C. Lenzi	p. 75
Remote Breath Activity Monitoring by Using UWB and CW Radar Sensors S. Pisa, P. Bernardi, R. Cicchetti, R. Giusto, E. Pittella, E. PiuZZi, O. Testa	p. 77
 <i>Dosimetria numerica e sistemi espositivi</i>	
A Meshfree Boundary Method for M/EEG Forward Computations G. Ala, G. E. Fasshauer, E. Francomano, S. Ganci, M. I. J. McCourt	p. 79
Numerical Dosimetry of In Vitro Biological Samples Exposed to an Induction Magnetic Field at 50 Hz C. Merla, V. Lopresto, C. Consales, B. Benassi, C. Marino, R. Pinto	p. 81
Numerical dosimetry inside an extremely-low-frequency electromagnetic bioreactor M. E. Mognaschi, P. Di Barba, G. Magenes, L. Fassina	p. 83
An exposure system for in vitro bioelectromagnetic studies under multiple-frequency scenarios S. Romeo, C. D'Avino, D. Pinchera, O. Zeni, M.R. Scarfi, R. Massa	p. 85
Design and development of a continuous wave functional near infrared spectroscopy system D. Agrò, R. Canicatti, M. Pinto, A. Tomasino, G. Adamo, L. Curcio, A. Parisi, S. Stivala, N. Galioto, C. Giaconia, A. Busacca	p. 87
A versatile, nanosecond electric pulse generation system for in vitro bioelectric research studies" S. Romeo, O. Zeni, A. Sannino, L. Zeni, M. R. Scarfi	p. 89

Valutazione del rischio ed implicazioni legali

Evaluation of the occupational risk for workers exposed to the magnetic field of an induction heater
L. Cerra_____ p. 91

Electromagnetic Radiation by the MUOS Satellite Earth Station in Sicily (Italy): Health Risk Assessment
A. Polichetti, R. Pozzi_____ p. 93

Health Effects from Cell Phone Radiations. The Verdict of the Supreme Court of Cassation in Italy
B. Bisceglia, V. Ivone, P. Persico_____ p. 95

Sessione di chiusura

What is the state of present bioelectromagnetic research? Lesson from the activity in the editorial board of Bioelectromagnetics and from the School of Bioelectromagnetism “Alessandro Chiabrera”
Riflessioni sulla ricerca in Bioelettromagnetismo: Conversazione di Ferdinando Bersani, Direttore Scuola Internazionale di Bioelettromagnetismo-Alessandro Chiabrera_____ p. 97

A Meshfree Boundary Method for M/EEG Forward Computations

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Abstract—The brain activity can be investigated in a noninvasive way by means of electromagnetic techniques, i.e., electroencephalography (EEG) and magnetoencephalography (MEG), which requires a typical inverse problem to be solved. Therefore, an accurate and fast forward solver is needed. As a truly meshfree alternative to the Boundary Element Method (BEM), we propose the Method of Fundamental Solutions (MFS) for solving the M/EEG forward problem. The solution of the forward problem is obtained, via the Method of Particular Solutions (MPS), by numerically solving a set of coupled boundary value problems for the Laplace equation. By investigating both numerical accuracy and computational load for spherical geometries and comparing them with a state-of-the-art BEM solver, we show that the proposed method is attractive.

I. THE M/EEG FORWARD PROBLEM

The EEG forward problem for a piecewise-constant conductivity head model can be formulated as a set of coupled Boundary Value Problems (BVPs) for the 3D Laplace operator. Let L be the number of nested regions in the linear domain Ω that represents the head, Ω_ℓ be the generic region, with boundary $\partial\Omega_\ell$ and conductivity σ_ℓ , and let $\mathcal{I}_{\ell,\ell+1} = \partial\Omega_\ell \cap \partial\Omega_{\ell+1}$ be the interface between the region ℓ and the region $\ell+1$. The region Ω_{L+1} surrounding the head corresponds to the ambient air which is unbounded and has negligible conductivity. A model with three regions (brain, skull and scalp) is common. However, other regions could be added to improve the model of the head, e.g., cerebrospinal fluid and/or distinct regions for gray and white matter.

For the sake of simplicity, let us consider the case of a single neural source, representable by a current dipole of moment \mathbf{Q} located at $\mathbf{p}' \in \Omega$. With this position, the source current density at a point $\mathbf{p} \in \Omega$ is given by

$$\mathbf{J}_s(\mathbf{p}) = \mathbf{Q}\delta(\mathbf{p} - \mathbf{p}'), \quad (1)$$

where $\delta(\mathbf{p} - \mathbf{p}')$ is the value at \mathbf{p} of the Dirac delta function centered at \mathbf{p}' . However, since the media are supposed to be linear, what follows can be easily extended to the general case of many dipoles by applying the superposition principle.

The EEG forward problem can be formulated as the follow-

ing set of BVPs coupled by interface conditions:

$$\begin{cases} \sigma_\ell \nabla^2 \phi_\ell(\mathbf{p}) = S_\ell(\mathbf{p}), & \mathbf{p} \in \Omega_\ell, \\ \phi_\ell(\mathbf{p}) = \phi_{\ell+1}(\mathbf{p}), & \mathbf{p} \in \mathcal{I}_{\ell,\ell+1} | \ell \neq L, \\ \sigma_\ell \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_\ell(\mathbf{p}) = \\ = \sigma_{\ell+1} \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_{\ell+1}(\mathbf{p}), & \mathbf{p} \in \mathcal{I}_{\ell,\ell+1}, \end{cases} \quad \ell = 1, \dots, L, \quad (2)$$

where ϕ_ℓ is the electric scalar potential in the ℓ -th region, $\mathbf{n}(\mathbf{p})$ denotes the outward unit normal vector to the interface $\mathcal{I}_{\ell,\ell+1}$ at \mathbf{p} and the source term $S_\ell(\mathbf{p})$ can be expressed as follows:

$$S_\ell(\mathbf{p}) = \begin{cases} \nabla \cdot (\mathbf{Q}\delta(\mathbf{p} - \mathbf{p}')), & \text{source at } \mathbf{p}' \in \Omega_\ell, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

In considering a certain region independently, it is clear that the governing PDE is a Poisson equation if a neural source is located in that region or a Laplace equation otherwise.

Here we focus the attention on the solution of the EEG forward problem. This is the crucial step also in solving the MEG forward problem which involves the evaluation of the electric potential at the interfaces between different media [1].

So far, traditional mesh-based methods have been used to address the M/EEG forward problem [2]. Among these methods, the Boundary Element Method (BEM) has become the method of choice because of its efficiency with respect to the Finite Elements Method, and it is currently implemented in widely used software packages for M/EEG source analysis. However, the BEM requires high quality meshing of the domain boundaries, which is not a trivial task, involves costly numerical integration and could potentially introduce mesh-related artifacts in the reconstructed neural activation patterns.

II. METHODOLOGY

To remedy the drawbacks of the BEM, we propose the application of the Method of Fundamental Solutions (MFS) [3] via the Method of Particular Solutions (MPS) for solving the M/EEG forward problem. The MFS approximates the solution u of the given homogeneous BVP by a linear combination of *fundamental solutions* K of the governing homogeneous PDE, i.e.,

$$u(\mathbf{p}) \approx \sum_{\xi_j \in \Xi} c_j K(\mathbf{p}, \xi_j), \quad \mathbf{p} \in \Omega, \quad (4)$$

where Ξ is a set of *centers* located on a *fictional boundary* outside the physical domain Ω (Figure 1) in order to avoid the singularities of K in the representation of the solution.

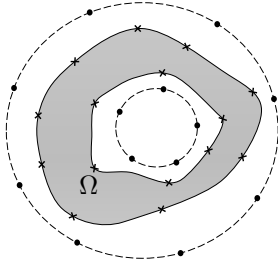


Fig. 1. Collocation points (crosses) and centers (dots) distributions on physical and fictitious boundaries, respectively.

The coefficients of the combination are determined by enforcing it to satisfy the boundary conditions by means of a collocation procedure.

An inhomogeneous problem can be reduced to a homogeneous one by the MPS, i.e., by considering the solution u as the sum of a particular solution u_p and its associated homogeneous solution u_h .

As shown in Section I, the governing PDE of the EEG forward problem in the region ℓ may be homogeneous or inhomogeneous depending on the absence or the presence, respectively, of a neural source in the region. While MFS can be applied directly in the former case, in the latter case the solution has to be sought via MPS. For the sake of generality, let us introduce a parameter α_ℓ such that $\alpha_\ell = 1$ if the source is in Ω_ℓ , and $\alpha_\ell = 0$ otherwise. This enables us to express the potential function in the ℓ -th region as $\phi_\ell(\mathbf{p}) = \phi_{h,\ell}(\mathbf{p}) + \alpha_\ell \phi_{p,\ell}(\mathbf{p})$.

An analytical expression for a particular solution $\phi_{p,\ell}$ of the PDE of the BVP in the ℓ -th region, when a neural source is located at $\mathbf{p}' \in \Omega_\ell$, is known [4].

Therefore, the homogeneous term $\phi_{h,\ell}$ is given by the solution of the following BVP:

$$\begin{cases} \nabla^2 \phi_{h,\ell}(\mathbf{p}) = 0, & \mathbf{p} \in \Omega_\ell, \\ \phi_{h,\ell}(\mathbf{p}) - \phi_{h,\ell+1}(\mathbf{p}) = \\ = \alpha_{\ell+1} \phi_{p,\ell+1}(\mathbf{p}) - \alpha_\ell \phi_{p,\ell}(\mathbf{p}), & \mathbf{p} \in \mathcal{I}_{\ell,\ell+1} | \ell \neq L, \\ \sigma_\ell \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_{h,\ell}(\mathbf{p}) + \\ - \sigma_{\ell+1} \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_{h,\ell+1}(\mathbf{p}) = \\ = \alpha_{\ell+1} \sigma_{\ell+1} \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_{p,\ell+1}(\mathbf{p}) + \\ - \alpha_\ell \sigma_\ell \mathbf{n}(\mathbf{p}) \cdot \nabla \phi_{p,\ell}(\mathbf{p}) & \mathbf{p} \in \mathcal{I}_{\ell,\ell+1}. \end{cases} \quad (5)$$

and it can be approximated, by means of MFS, as a linear combination of fundamental solutions for the 3D Laplace equation:

$$\hat{\phi}_{h,\ell}(\mathbf{p}) = \sum_{\xi_j \in \Xi_\ell} c_j^\ell K(\mathbf{p}, \xi_j), \quad \mathbf{p} \in \Omega_\ell, \quad (6)$$

where Ξ_ℓ is the set of centers relative to the region Ω_ℓ and the fundamental solution for the Laplace equation in 3D is $K(\mathbf{p}, \mathbf{q}) = \frac{1}{4\pi\|\mathbf{p}-\mathbf{q}\|}$.

Normals to boundaries and pairwise distances between points are the only geometric quantities that are needed: the proposed method is truly meshfree. Moreover, no numerical integration has to be performed, the method has the potential for spectral accuracy and its implementation is straightforward.

III. NUMERICAL RESULTS

We have compared the proposed method with the state-of-the-art implementation of the BEM in solving the EEG forward problem for a unitary dipolar current source in a multi-layered sphere representing the head, with realistic geometric proportions and electric conductivities.

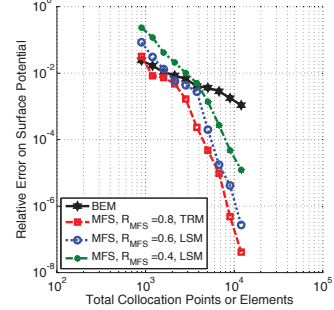


Fig. 2. Dipole in a three-layered sphere – Convergence

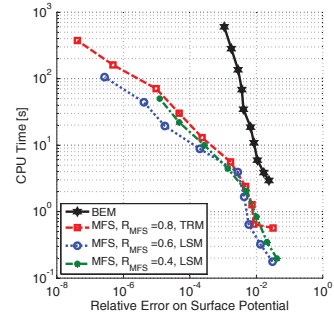


Fig. 3. Dipole in a three-layered sphere – Cost per Accuracy

Figure 2 shows that the proposed method, implemented for different ratios R_{MFS} between the number of collocation points and the number of centers, is spectrally convergent while the BEM convergence is only algebraic. Moreover, as shown in Figure 3, the proposed method is extremely competitive when compared to BEM from an accuracy vs. CPU time standpoint. This advantage is important in the perspective of the iterative solution of the inverse problem and it becomes more significant as the desired accuracy increases.

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