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EEG Forward Problem Solution for a Multi-Shell Head Model

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Abstract*: The forward problem of EEG deals with estimation of electrical potential difference measured over the scalp generated due to neural activity inside the brain. These signals measured over scalp are highly affected by the head characteristics taken into account. This work envisages the effect of taking white matter and gray matter into account while solving the forward EEG problem. The work shows that a five layered head model, comprising scalp, skull, cerebrospinal fluid, gray matter and white matter, is more accurate in finding forward EEG solution in comparison to a four layered comprising scalp, skull, CSF & Brain or three layered head model represented by scalp, skull & brain.

Index Terms: ***EEG, Forward Problem, Head Model.***

I. INTRODUCTION

The electroencephalogram (EEG) is the measurement of the electric potential differences on scalp caused by neural activity inside the brain [1]. The computation of the potential distribution, when the geometry of the sources and the medium are given is called the forward problem [2]. The inverse problem is to estimate the sources, for a given medium and a known potential distribution on a set of electrodes [2]. Since for the inverse algorithm, the solution of the forward problem has to be known, it is of prime importance to calculate the forward problem as accurately as possible in order to reconstruct the source location precisely. To solve the forward problem, a head model is needed. A variety of head models exist with all their specific advantages and disadvantages. Spherical head models simplify the real human head, but have the advantage that the solution of the forward problem can be stated as an analytical formula, which can be solved very fast [3].

II. HEAD MODELING

In the effective dipole based forward model of the ERP measurements, there are two important components: the conductivity model for the head, and the source model of the neural activity [7]. The most commonly used head model assumes that it is made up of a set of nested concentric spheres, each with homogeneous and isotropic conductivity [4]. Different spherical head models have been proposed till now. Some of them are: the homogeneous sphere model [5], the three sphere model [6], the four sphere model [7] [8], the isotropic multisphere model [9] [11], the anisotropic multisphere model [10] [11], the five layer model [11].

Almost all EEG head models include a skull region as one of the layer; reason for this being that theoretical studies [12] have shown that neglecting the skull in a spherical model of the head can produce localization errors as large as 0.7 cm. The simplest conductivity model for the head is chosen as a multi-shell model where the head is represented as three concentric spheres corresponding to brain, skull and the scalp. However, most recently, Wendel *et al.* proved the significant of CSF to construct an accurate head model [11]. The source model of neural activity can be represented by a dipole. The dipole is described by its location parameter R (r_x, r_y, r_z) and its moment D (m_x, m_y, m_z). Figure 1 shows a five spherical head model with a dipole located at R_o and the surface electrode at R_e.

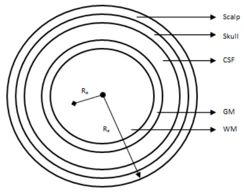

Fig. 1. A five spherical head model showing scalp, skull, CSF, gray matter (GM), white matter (WM)
R_o represents the dipole location and R_e shows the location of surface electrode.

III. PROBLEM FORMULATION

Supported by anatomical concept and literature [13] [14], this work considers five spherical head model comprising scalp, skull, cerebrospinal fluid (CSF), gray matter (GM) and white matter (WM). The radii and conductivity of each layer is given in Table I.

For four layer head model white matter and gray matter together is considered as brain for which the radii and conductivity value is 8.5 cm and 0.33 mho respectively. For three layer head model scalp and skull values remain the same as in table I. The third layer is brain with radii 8.7 cm and conductivity 0.33 mho. Forward solutions of five layer models are compared with those of four layered head model and three layered head model where it was found that Head model with five layers produces less error in comparison to other two models. In this work, a single dipole has been used as source model. In our study, we used a measurement setup of 21 electrodes placed according the international 10–20 system, 19 electrodes for potential measurement and 2 electrodes as reference electrodes.

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Table I
Radii and Conductivity of a Five Spherical Head Model

Layer	White Matter	Gray Matter	Cerebrospinal Fluid (CSF)	Skull	Scalp
Radii (cm)	6.7	8.5	8.7	9.4	10
Conductivity (mho)	0.14	0.33	1.0	0.0042	0.33

IV. EXPERIMENT AND RESULTS

To solve the forward problem of multi-layer model, a relation between observed potential at any surface point over the scalp and dipole location inside head has to be made. This work uses equation (1) supported by literature [15]. The forward solution given by equation (1) is an infinite series. This infinitive series must be truncated or approximated for the reason that these analytic expressions are computationally expensive. In this work, to solve the computational problem, approximations based on mathematical analysis of infinite sums of Legendre and associated Legendre polynomial [16] has been developed.

This work assumes a single dipole acting as source model defined by six parameters, dipole location vector R_0 , (r_x, r_y, r_z) and dipole moment vector D , $(|D|cos\beta\ cos\alpha, |D|cos\beta\ sin\alpha, |D|cos\alpha)$. The magnitude $|D|$ is taken to be unity.

A dipole with moment D is located at R_0. V is the potential measured by surface electrode over the scalp at location R_e. α is the angle between dipole location R_0 and dipole moment D. γ is the angle between R_0 and R_e. R_0 and Ddefine another plane P1. R_0 and R_e define another plane P2. β is the angle between P1 and P2. P_n and P_n^1 are the Legendre and the associated Legendre polynomials, respectively [15].

To evaluate the performance of each multi-spherical head model, a cost function or the fitness function is used. This fitness value of the cost function will tell the closeness of forward solution obtained by the proposed multi layer head model to the reference forward EEG solution (EEG signal). Lower is the value of the cost function, F, for a particular head model, better is the solution represented by that head model. Synthetic EEG signals are generated by using the forward model (1) for six known test dipole location.
The cost function, F, for a single test dipole with six parameters, is defined by (2),where V_m represents the potential obtained by solving the forward problem using equation (1) for three layer, four layer or five layer head model.

V_{meas} is the measured potential from synthetic EEG signal (taken as reference forward solution).

$$V = \frac{D}{4\pi\sigma_n R_e^2} \sum_{n=1}^{\infty} \frac{2n+1}{n} \left(\frac{R_0}{R_e}\right)^{n-1} f_n [ncos\alpha P_n(cos\gamma) + \quad cos\beta\ sin\alpha\ P_n^1(cos\gamma)] \quad , \qquad (1)$$

where,

$$f_n = \frac{n}{[nm_{22} + (1+n)m_{21}]}; \qquad \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \frac{1}{(2n+1)^{N-1}} \text{x} \prod_{k=1}^{N-1} \begin{bmatrix} n + (n+1)\frac{\sigma_k}{\sigma_{k+1}} & (n+1)(\frac{\sigma_k}{\sigma_{k+1}} - 1)\left(\frac{R_e}{R_k}\right)^{2n+1} \\ n(\frac{\sigma_k}{\sigma_{k+1}} - 1)\left(\frac{R_k}{R_e}\right)^{2n+1} & \left[(n+1) + n\frac{\sigma_k}{\sigma_{k+1}}\right] \end{bmatrix}$$

$$F(r_x, r_y, r_z, m_x, m_y, m_z) = \sum_{n=1}^{N} \Big(V_m(r_x, r_y, r_z, m_x, m_y, m_z) - \ V_{meas}(r_x, r_y, r_z, m_x, m_y, m_z)\Big), \qquad (2)$$

Table II
Fitness value for Five Layer, Four Layer and Three Layer Spherical Head Model

Test Dipole Location		Fitness Value (F)	
(r_x, r_y, r_z) (in mm)	Three Layer	Four Layer	Five Layer
(52, 64, 59)	4.268 x 10^{-5}	1.976 x 10^{-8}	1.378 x 10^{-10}
(10, -50, 50)	4.256 x 10^{-5}	2.038 x 10^{-8}	2.111 x 10^{-10}
(-10, 31, 70)	4.261 x 10^{-5}	2.009 x 10^{-8}	1.377 x 10^{-10}
(-10, 10, 0)	4.234 x 10^{-5}	2.129 x 10^{-8}	1.198 x 10^{-10}
(-30, -10, 55)	4.251 x 10^{-5}	2.056 x 10^{-8}	2.125 x 10^{-10}
(30, 30, 30)	4.253 x 10^{-5}	2.040 x 10^{-8}	3.479 x 10^{-12}
(30, 20, 30)	4.252 x 10^{-5}	2.041 x 10^{-8}	1.452 x 10^{-34}

Table II shows the results of fitness values obtained after comparing solution of the forward problem using equation (1) for various test dipole locations with the reference EEG signal. Table II clearly indicates that a five spherical head model performs better in comparison to a four spherical or a three spherical head model.

V. CONCLUSION

Most of the spherical head models are either three-layered or four layered. Spherical head models comprising five layers are very limited because of the fact that it is quite difficult to segment GM and WM from brain. In this paper, we implemented three layered, four layered and five layered isotropic spherical head models. This work considers a five spherical head model showing the effects of distribution of GM and WM on EEG scalp potentials for forward solution. The preliminary results obtained in this research clearly show that the head model consisting GM and WM produces better fitness values than the head model excluding GM and WM. Therefore, this work suggests that it is important to model the head as accurately as possible. Improvement in forward solutions to EEG will also lead to better source localization which is very important and useful in identifying diseases such as epilepsy, seizure disorders, tumors and many other neurological disorders.

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