Study Of Inhomogeneious Head Model Based On Conductivity Issues

Peng Wen*, Richard Clark**, Fangpo He* & Karl Sammut*

*School of Information and Engineering, Flinders University of S. A
GPO Box 2100, Adelaide 5001, Australia
egpw@flinders.edu.au
**School of Psychology, Flinders University of S. A
GPO Box 2100, Adelaide 5001, Australia
pgcrc@id.psy.flinders.edu.au

ABSTRACT

The aim of this study is to testify the effects of different inhomogeneious tissues on computed electrical potential fields associated with the electroencephalograph. The inhomogeneity of head tissues is included in head model using so-called pseudo conductivity created by limited, experimental measured data. Simulations were performed varying the conductivities assigned to the different head compartments in the model. Comparisons of different conductivity combinations followed one of two basic schemes: 1) a piecewise homogeneous multi-layer head serves as the reference against which we compared simulations with a single tissue assigned its pseudo conductivity, and 2) a fully inhomogeneious head serves as the reference and we remove the effect of individual tissue by assign it the homogeneous conductivity value. The result both in 1) and 2) show that the skull have larger impacts on the head potential distribution than other element. It also show that the size of the effect is not neglectable in all tissue. This study suggest that accurate representation of tissue inhomogeneity has a significant effect on the accuracy of the forward solution.

1. INTRODUCTION

The electrical activity of brain cell is manifest at the surface of the head through the action of the intervening conducting medium. The surface potentials which are recorded as electroencephalogram reflect, therefor, both the brain cell generators and the properties of the surrounding volume conductor [1]. To investigate the effects of the volume conductor on the potential distribution, a model which includes the inhomogeneity of all important head compositions must be constructed [2], [3]. The complexity of most physiological systems far outstrips current modelling ability, further more, the measured conductivity data is very limited and the accuracy varies widely among measured methods and the samples used, as such, models used to study EEG must be limited to a subset of head tissues [1], [2], [3]. The most common one is the so-called multi-layer head model in which the head tissues are represented in different layers. Each layer is assigned different conductivity. Therefore, the inhomogeneity caused by different head compartment is include in the model. But the inhomogeneity inherited in each tissue or tissue inhomogeneity is ignored. In this paper, a method to represent the tissue inhomogeneity is suggested and the effect of tissue inhomogeneity in each layer is studied.

This paper is organized as follows. Section 2 describes the problem and the notation used. Section 3 presents the head tissue inhomogeneity and its representation in the model. Section 4 focus on the simulations and results. The conclusion is given in section 5.

2. PROBLEM SATEMENT

The difference in the scalar potential between two points is what is measured with an idealized voltmeter. The electric field E is obtained as the negative gradient of the scalar potential, Φ. That is, $E = -\nabla\Phi$. According to Ohm's law the current density J, and electric field, E, are related by $J = \sigma E$, where σ is the conductivity of the conducting medium through which the current is following. In the event that a source density $I_v(x, y, z)$ is present, then $\nabla J = I_v$. Finally, the relationship between potentials and current sources and sinks that produce the potentials can be given as [4]

$$\nabla J = I_v = -\sigma\nabla^2\Phi \qquad (1)$$

As mentioned in section 1, the major internal inhomogeneities are each represented by piecewise homogeneous regions. Thus, across an internal interface between two regions, both the potential as well as the normal component of the current remain continuous. This leads to the following boundary condition noting that there is no current getting out of the scalp.

$$(\sigma\nabla\Phi) \bullet \vec{n} = 0 \text{ on } S_1 \qquad (2)$$

Add the applied known voltage

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$\Phi = \Phi_0$ on S_2 (3)

Finally, the problem of potential distribution in head is formed by (1), (2) and (3) [4].

The analytic solution is available for above field potential problem only while the domain Ω is simple and homogeneous. In the human head case, some numerical techniques must be employed since the complicated head structure and inhomogeneity. One of the most common used numerical technique is Finite Element Method (FEM) which has an advantage over other methods for this type of computation since it allows explicit modelling of the inhomogeneity of head tissues. FEM computes an estimate of the potential field over each element, taking into account the material properties of each individual element [2]. Therefor, it is possible to specify different conductivity over different regions, or even for each element.

Both the governing equation (1), (2) and (3) and the FEM have obviously tell us that the conductivity value of the tissues at each point plays a key role in the solution of field potential problem. Unfortunately, the measured conductivity data is very limited and most of them neglect the inhomogeneity of the tissue by only providing the average value for each tissue. Next section will focuses on how to determine the conductivity for each element in a head model.

3. METHOD

Electric conductivity is the material property of interest in head modelling. At a microscopic level, the discrete nature of cell structure dictates that all tissue is anisotropic and inhomogeneious; however, at a macroscopic level, many tissues can be approximated as having isotropic conductivity in 0—100 Hz bandwidth that is considered relevant for EEG but the inhomogeneity can not be neglected. Though there are several comprehensive review articles about conductivity values, all of them just list the conductivity value for various tissues and nothing about the inhomogeneity within the tissue is considered.

In the potential field computation using FEM, the human head is modelled by a large number of elements; each represents a different area of the head with its own unique conductivity. Not only do the elements representing different tissues have unique conductivities, but so do the elements representing the same type of tissue. The latter is due to the complex composition of the tissue. For instance, the elements in the brain may have different conductivities, since they may contain different proportions of blood vessels, white matter, grey matter, etc.. Experimentally measured values of conductivity for grey matter increase as a function of the measuring signal frequency (e.g., $0.33(\Omega m)^{-1}$ at 5Hz, $0.43(\Omega m)^{-1}$ at 5kHz, etc.) [5], [6], [7], [8]. White matter has conductivity $1.76(\Omega m)^{-1}$ at 5Hz, and has been shown to be anisotropic with the ratio of conductivities varying between 5.7-9.4 [5], [6], [7], [8]. In the skull's case, the element conductivity may differ for elements composed purely of cancellous bone, compact bone, bone liquid or the combinations. Its resistivity varies between 1360Ω-cm and 21400Ω-cm, with a mean of 7560Ω-cm and a standard deviation of 4230Ω-cm [8]. All models reported in the literature use the value of $0.33(\Omega m)^{-1}$ for the scalp conductivity [5], [8]. No allowance has been made for the conductivity of the underlying muscle (0.0076-$0.52(\Omega m)^{-1}$), or subcutaneous fat (0.02-$0.07(\Omega m)^{-1}$) [9]. With such widely varying values of conductivity, it is impossible (or at least not easy) to measure and assign an exact conductivity value for each element [10].

Since the element is very small, the points in a element should be very close though the conductivity of each point in the head is different. Then, the conductivity of each element can be estimated using the average conductivity of these points. The elements within the same tissue must have the conductivity values which are very close because their compositions are similar. Given that the conductivities of the elements for the same tissue are relatively close in comparison with those for different tissues, the conductivities of the elements in a tissue can therefore be assumed to follow a normal distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}} \qquad (4)$$

where x is the conductivity, μ is the mean conductivity and σ is the standard deviation. The curve of $f(x)$ is symmetric with respect to $x = \mu$ because the exponent contains $(x-\mu)^2$. Changing μ corresponds to translating the curve to another position. σ^2 is the variance. For small σ^2, the conductivities of the elements within a tissue are tightly centred around the mean, and for $\sigma^2 = 0$, all conductivities are the same – as assumed in the current literature. Conversely, with increasing σ^2, the conductivities of the elements are more widely distributed. From the assumption given in equation (3), a set of statistical parameters (namely, μ and σ) can be derived for a tissue type from the limited data available for that tissue in the literature. For example, the skull has the most scattered distribution, its mean resistivity and standard deviation are 7560 Ω-cm and 4230 Ω-cm. Therefore, the standard deviation assumed to be 4230/7560=50% of the mean. Brain is mainly consist of grey matter and white matter. But most of its composition is white matter. The conductivity of grey matter and white matter is quite different. Therefore, its mean conductivity is assigned as

0.33 s/m and the standard deviation are assigned to 30% of its mean based on the available data in Web site brooks.af.mil/HSC/AL/OE/OER/Report.html. Then, a range of conductivity values – the *pseudo conductivities* – can be generated to fit the normal distribution which is specifically defined by μ and σ. These pseudo conductivities are allocated to the component elements belonging to that tissue.

4. SIMULATIONS AND DISCUSSION

To study the effects of tissue inhomogeneity on the electrical field in head, two type of simulation are carried out. First, a piecewise homogeneous model is used, then a single inhomogeneious layer is included for the rest computations. "Including an inhomogeneious layer" actually means assigning a set of appropriate conductivity values to all the elements in a head compartment in the head model. Then the solutions are compared statistically. The second type of simulation is a complement of the first. Its goal is to evaluate the effect of removing a single inhomogeneity from an otherwise completely inhomogeneious model. In this case, the reference model includes all available inhomogeneities. The conductivity of the two reference models are shown in figure 1 and figure 2.

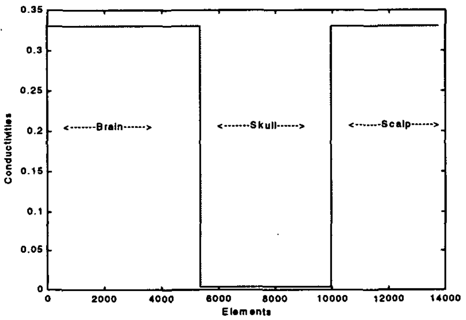

Fig.1 Piecewise Homogeneous Conductivity

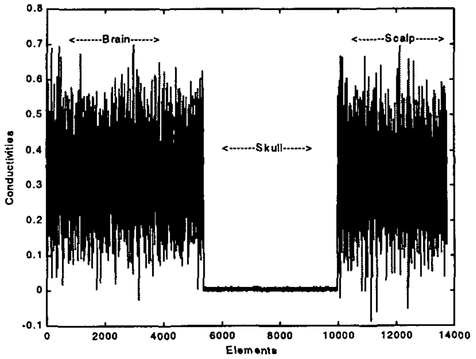

Fig. 2 Inhomogeneious Conductivity

The statistical parameters used to compare are the root mean square error (E_{rms}) and the relative error (E_{re}) computed as follows:

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{N}(\Phi_i^{ref} - \Phi_i)^2}{N}} \quad (4)$$

$$E_{rel} = \sqrt{\frac{\sum_{i=1}^{N}(\Phi_i^{ref} - \Phi_i)^2}{\sum_{i=1}^{N}(\Phi_i^{ref})^2}} \quad (5)$$

where Φ_i^{ref} is potential obtained from the reference model, Φ_i the potential solved using comparing models.

A three-layer 3D meshed geometry with 27478 tetrahedral elements is developed based on the parameters listed in table I. All the layers are meshed separately, so that the scalp, skull and brain are each composed of 7534, 9188 and 10756 elements. Since the concentric sphere model is symmetric, in order to reduce the computation, the finite element model needs only include part of the symmetric domain. However, the partial model must preserve the complete model's boundary conditions. If the dipole source are placed far away from the model's mid-line plane, then the current flow the plane is small enough to be considered approximately satisfied. The following simulations are conducted within the upper half of the concentric sphere model. An analysis program was developed based on the algorithm provides by Yan [11] in which the dipole source is modelled as an Delta function. For the linear base function used in this algorithm, the derivatives are constant. Then a lot of computation is saved. The program is implemented using Matlab in a Unix workstation.

Table 1 Model Parameters

Layers	Brain	Skull	Scalp
Radii(cm)	8.7	9.2	10
Means(sm)	0.33	0.0042	0.33
Variances	0.0099	$4.478*10^{-6}$	0.0099
Elements	10756	9188	7534

The results evaluated from the first set of simulations demonstrated the effect of adding inhomogeneious to the model. The are listed in table II. The E_{rel} did not get within 30 % of the error between homogeneous and fully inhomogeneious model in all cases, suggesting that no signal inhomogeneious can serve as surrogate for the complexity of the full model. The E_{re} shows that the skull layer play a significant role compared to the scalp and the brain layer. Though both scalp and brain share the same distribution and parameters from which their pseudo conductivity are created, it seems that the scalp inhomogeneity can effect the potential field more than the brain inhomogeneity does.

In second simulation, the selective removal of inhomogeneties reinforced some findings observed when individual inhomogeneity were added. At the same time, some difference are also revealed. Common to both sets of results, the effects of inhomogeneious of the skull is much stronger than that of brain and scalp. The E_{rel} and E_{rms} reached their maximum in skull layer.

Table II Against Piecewise Homogeneous Head Model

	Brain	Skull	Scalp
E_{rms}	0.0168	0.0327	0.0201
E_{re}	28%	61%	36%

Table IIIAgainst Inhomogeneious Head Model

	Brain	Skull	Scalp
E_{rms}	0.0275	0.0532	0.0333
E_{rel}	31%	58%	41%

5. CONCLUSIONS

This study demonstrated a new method to include the inhomogeneity of the tissues in head model and developed a 3D analysis program. The preliminary result provided in the paper testified the effects of including and excluding inhomogeneity in potential field computation. Models including only the inhomogeneity of different tissues always incur significant errors compared to these that incorporated a more completely representation of head inhomogeneity. The inhomogeneity within a tissue can be expressed using pseudo conductivity values. which are derived from certain experimental measured data. The comparisons made among the models with different conductivity combination demonstrated that the effect of various inhomogeneity inherited head tissues is very strong. Thus, most of the current models which neglected this effect are inaccurate.

6. REFERENCES

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