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Quantizing the Depth of Bioelectrical Sources for Non-Invasive 3D Imaging

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Abstract— **The five point method (FPM) for approximating Laplacian potentials sharply attenuates the potentials due to sources far from the surface electrodes. Similar attenuation is achieved if nine points are used in a variation of the FPM. There is a difference in the attenuation characteristics of the FPM and nine point method (NPM) since the nine points cover more space than the five points. As a result the FPM and NPM behave differently for a dipole source at any specific depth giving rise to quantization of dipole depths. This quantization of depth can be used to determine the depth of the bioelectrical sources from the surface potential measurements. Direct depth perception will be helpful in non-invasive 3D imaging.**

Keywords— **Depth perception, disc electrodes, five point method, inverse problem, nine point method, source localization, 3D imaging**

I. INTRODUCTION

The body surface potentials can be used to aid diagnosis of disease. The sources responsible for these potentials are usually, but not always, lumped or distributed dipoles separated in three-dimensional space inside the body. The accurate information regarding location and propagation over time of these sources is helpful in gaining the knowledge about bioelectrical events taking place inside the body. Electrocardiography (ECG) and electroencephalograms (EEG) are useful for diagnosing abnormalities/diseases of the heart and brain, respectively. As a result, there has been extensive research that will be discussed in the next section, in the field related to recording the bioelectrical potentials on the body surface and attempting to locate their sources. But localizing the sources in 3D, accurately and uniquely is not yet achieved. Current methods are limited to unique 2D localization.

Due to the limitations of current technologies there is an opportunity to design a method that discriminates different electrical sources in the body's volume conductor and directly measure, in 3D, the position of sources that can help diagnose disease or malfunction.

The objective of this paper is to test the hypothesis that the surface potential measurements can be used for quantizing the depth of a dipole source, depth perception. Thus the surface potential measurements acquired using an array of disc electrodes over the body surface, will help directly solve non-invasively the inverse problem.

A novel technique is presented here for determining the depth of the source by direct measurements that can lead to real time localization of sources in 3D. This solution to the inverse problem is expected to reduce the cost and time for 3D localization and thus make it easier to analyze human brain activities for diagnosing malfunctions and treating them more effectively. This technique is essentially independent of the other techniques and at the same time can be totally compatible with any of the current 2D source localization techniques.

II. BACKGROUND

It is exceedingly difficult to discriminate information about sources in the volume conductor with electrode configurations presently used in surface recordings such as the ECG, Laplacian ECG (LECG), and EEG. Commonly used electrodes are usually configured as discs, and in some cases a disc and a concentric ring (annulus). Much advancement has come recently in the field of EEG, making it even more appealing for brain activity analysis. One such advancement is the application of the surface Laplacian to EEG.

The application of Laplacian to EEG started with Hjorth [1] utilizing a five-point difference method. Many other approaches have revealed good results as well, estimating the scalp Laplacian from the potential EEG measurements. Such approaches include the spline Laplacian algorithm by Perrin et al. [2], ellipsoidal spline Laplacian algorithm by Law et al. [3], and the realistic geometry Laplacian algorithms by Babiloni [4]-[5] and He [6]-[7]. He [8]-[9] calculates the surface Laplacian with Hjorth's technique from an array of five disc sensors measuring surface potentials.

These previously mentioned Laplacian techniques dont not need assumptions about the quantity or distribution of the sources in the brain to improve the spatial resolution of EEGs. The inverse problem aims to determine the accurate location of the sources inside the body from the surface potential measurements. There have been many attempts to solve the inverse problem using different approaches [10].

Robinson [11] transforms magnetoencephalographic (MEG) measurements into corresponding three-dimensional images of the electrophysiological activity within the brain. These are not real time images. The image is generated using the data collected for a specific time period, not an instance of time. Van Veen et al. [12] employ a bank of software spatial filters to locate the dipoles and calculate the dipole moments. This technique consumes abundant software resources and does not provide real time solutions. Gevins et al. [13] record the EEG from the head surface. A model is then constructed and potentials are calculated and compared with the measured ones.

He [14] uses the heart-torso geometry information from MRI or CT to make a model of the same and then the body surface potential maps (BSPM) are simulated and compared with the measured potentials. This simulation and comparison is continued until a close approximation of the measured BSPM is achieved. Both [13] and [14] rely on the algorithm and comparison, which are time consuming and/or resource intensive and will not be a real time solution.

Sosa et al. [15] calculate brain and heart functional states using the surface potentials, by determining the inverse solution of the EEG /MEG/ECG problem by applying restrictions. The solution is confined for those specific conditions. Rudy et al. [16] measure the body surface electric potentials (BSEPs) and compute the epicardial surface electric potentials (ESEPs) estimating the inverse of the multidimensional matrix. This procedure requires, CT/MRI/X-ray to determine the geometric position of at least one electrode, and a number of iterations.

In some cases it is not possible to obtain MRI/CT scan at all due to complicated interactions with the patients. None of these techniques yield a portable device that can image 3D bioelectrical activities of human beings. It was shown by Plonsey [17] that there is no unique solution to the quasi-static inverse problem from measurements made on the body surface [18].

III. METHODOLOGY

A. Theory

Disc electrodes can be used to localize sources in 2D when several disc electrodes are used in an array, and then a five-point difference method is performed [1], [8]-[9]. Considering the configuration shown in Fig. 1, where v_0, v_1 through v_8 are potentials measured by disc electrodes placed at those locations respectively, the potential difference P_5 of the five point method (FPM) of Hjroth is given as

$$P_5 = v_0 - \frac{1}{4}(v_1 + v_2 + v_3 + v_4) \qquad (1)$$

Taking the difference between the averaged potentials will attenuate the effect of sources that are at a distance from the electrodes, which is greater than the spacing between the electrodes themselves, since they have nearly equal effects on all of the electrodes. This attenuating effect of the FPM is shown in Fig. 2 and Fig. 3, when an axial dipole source is moved in lateral and vertical directions respectively. For lateral movement the potential difference is the maximum when the dipole is below the center disc, seen as solid line in Fig. 2, and in this case the potential decreases exponentially as the depth of the dipole is increased, seen as solid line in Fig. 3.

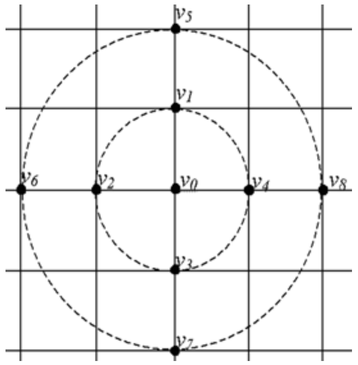

Fig. 1 Configuration of nine electrode positions arranged in an array to be used for five point and nine point calculations.

A variation of five-point method, the nine-point method (NPM) is used to calculated the potential difference P_9 as

$$P_9 = \frac{1}{2}\left(v_0 + \frac{1}{4}(v_1 + v_2 + v_3 + v_4)\right) - \frac{1}{4}(v_5 + v_6 + v_7 + v_8) \qquad (2)$$

It is important to note here that P_9 from (2) is not same as the nine-point difference method recently proposed by Besio [19].

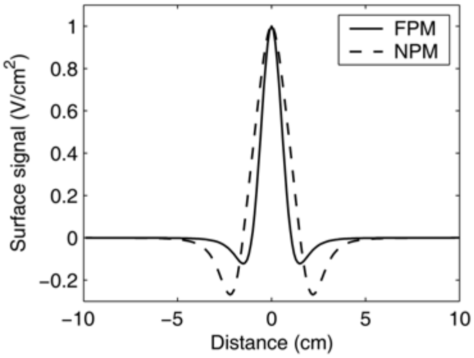

Fig. 2 Surface potential difference seen using five and nine point methods with varying lateral positions of the dipole.

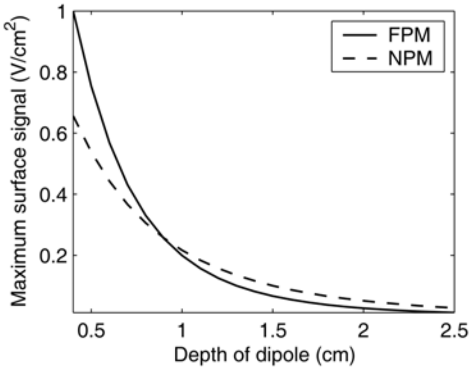

Fig. 3 Maximum potential difference seen using five and nine point methods with varying depths of the dipole.

The NPM has an attenuating effect similar to the FPM. However, since the nine discs cover a larger surface than the five discs, the attenuating effect tends to start at further distances from the source. This rather sluggish effect of the NPM can be seen from the comparison shown in Fig. 2 and Fig. 3. This difference in the response of the FPM and NPM for varying source location can be used to quantize the depth of a dipole source. Quantization can be explained with help of Fig. 3 which plots maximum potential difference vs. depth of the dipole for both of these methods. The solid and dashed lines intersect at a source depth of about 1cm, the depth of intersection. When the source is at a depth less than 1cm the FPM achieves a higher potential difference and when the source is at depth more than 1cm its vise-versa. In this way the depth of the dipole source is quantized into two levels, i.e. depth less than and depth more than the depth of intersection. Computer modeling and tank experimental verifications were carried out to prove this concept and will be described next.

B. Computer Simulations

Disc electrodes of 1cm diameter were modeled as the nine-point configuration shown in Fig. 1, on the surface of a homogeneous volume of a conductive medium. The center-to-center distance between discs was 1cm. The conductivity σ of the medium was taken to be 7.14 mS/cm (to emulate biological tissue). An axial dipole was modeled at three different depths (0.5cm, 1.1cm and 1.5cm) inside the volume conductor. A mesh having 241 nodes on it modeled each of the nine disc electrodes. The potential measured by a disc electrode V is the average of potentials at all nodes of that disc as suggested in [20]

$$V = \frac{1}{S_{Disc}} \iint_{Disc} \phi \tag{3}$$

where S_{Disc} is the surface area of the disc electrode and ϕ is the potential on any point on the surface of the volume conductor.

The configuration of nine disc electrodes was moved 20cm, in 0.18cm increments, along a straight line on the surface of the volume. The surface potential for each of the nine discs was calculated for each incremental movement on the surface of the volume conductor. Nine tracings of surface potentials v_0, v_1 through v_8 were calculated. Using (1) and (2) P_5 and P_9 were calculated. The maxima of P_5 and P_9 are calculated as MP_5 and MP_9 respectively. MP_5 and MP_9 calculated for different depths of the dipole were compared for quantizing the dipole depth.

C. Tank Experiment

The volume conductor was modeled by saline water in a plexiglass tank of 45cm x 12cm x 15cm. The conductivity of the water was the same as in the computer model. The dipole was formed with two copper dots on each side of a two-sided fiberglass printed circuit board (PCB). Two 10V pk-pk, 100Hz AC square wave were then applied between the poles. The two poles were given alternating polarity square waves in order to limit the corrosion of the dipole. The nine disc electrodes were etched on a PCB, in an array as in the computer model. Care was taken so that discs did not touch one another.

The electrode system was fixed to a movable stage and translated along the surface of the water at a speed of 1.8cm/s. The dipole was positioned at a certain depth normal to the surface of the electrode in the middle of the tank and energized while the electrode was moved. The potential on each of the nine elements of the electrode was recorded using a DATAQ system into a laptop computer with a sampling frequency of 1 kHz.

The data were low pass filtered to remove ambient and A/C noise and (1) and (2) were used to calculate P_5 and P_9 to determine measured MP_5 and MP_9. The experiment was repeated for different dipole depth i.e., 0.5cm, 1.1cm and 1.5cm and the relative amplitudes of MP_5 and MP_9 were compared with the computer model results.

IV. RESULTS

A. Computer Simulations

The calculated maximum potential differences MP_5 and MP_9 for the three depths are plotted in Fig. 4. For the depth of 0.5cm, MP_5 has a greater value than MP_9. For dipole depths of 1.1cm and 1.5cm MP_9 has a greater value than MP_5. For different depths of dipole different method gives greater maximum potential difference.

B. Tank Experiment

The measured maximum potential differences for the three depths are plotted in Fig. 5. For the first depth of 0.5cm, MP_5 has a greater value than MP_9. For dipole depths

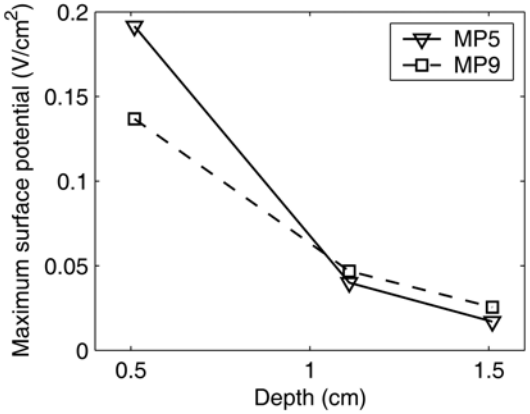

Fig. 4 MP_5 and MP_9 vs. depth of the dipole for three depths, as calculated from computer model.

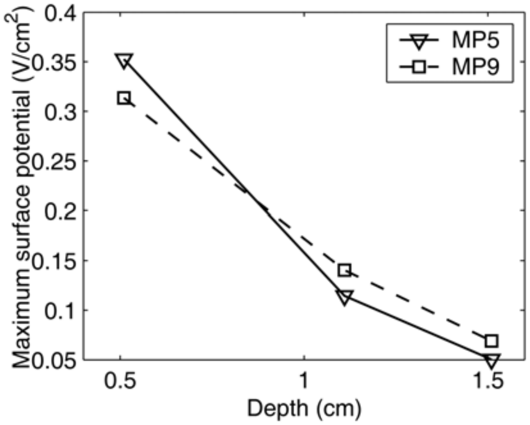

Fig. 5 MP_5 and MP_9 vs. depth of the dipole for three depths, as measured from tank experiments.

of 1.1cm and 1.5cm MP_9 has a greater value than MP_5. The relative amplitudes of MP_5 and MP_9 are similar to the computer model results.

V. DISCUSSION

The maximum potential difference was determined using FPM and NPM and compared for different depths of the dipole; their relative amplitudes were found to be different. The maximum potential difference is greater with the FPM at smaller depths and greater with NPM as the depth increases. Hence the dipole source depth is quantized into two depth zones, i.e. when FPM and NPM have different relative amplitudes. This difference helps in determining the depths of the sources by using surface potential measurements.

In this paper authors considered only an axial dipole sources. Similar results would hold true for other orientations of the dipoles because the attenuating effect of the FPM and NPM that yields the quantization of depth depends on the distance between the electrodes and the sources and not on the orientation of the source. However a different orientation of the source would give smaller amplitudes than axial dipoles.

The source depth below the surface of electrode was quantized from zero to the depth of intersection as one level and from the depth of intersection to infinite depths as the other level. This method in its present form has very coarse depth perception; further research can lead to finer depth perception. Computer models were simulated and tank experiments were carried out to validate the results. The dimensions of the electrodes were typical of the commonly used EEG electrodes.

VI. CONCLUSION

This paper presented a promising method to quantize the depth of the dipole sources, which can eventually lead to unique solutions to the inverse problem. It can be used for depth perception in conjunction with any of the current methods of source localization and hence lead to non-invasive 3D imaging of bioelectrical sources.

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