31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

An Optimal Spatial Filtering Electrode For Brain Computer Interface

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Abstract— **There are millions of people in the U.S. and many more worldwide who could benefit from a noninvasive-based electroencephalography (EEG) brain computer interface (BCI). A BCI is an alternative or augmentative communication method for people with severe motor disabilities. However, EEG suffers from poor spatial resolution and signal-to-noise ratio (SNR). To improve the spatial resolution and SNR many researchers have turned to implantable electrodes. We have previously reported on significant improvements in BCI recognition rates using tripolar concentric ring electrodes compared to disc electrodes. We now report on a optimal method for combining the outputs from the independent elements of the tripolar concentric ring electrodes to improve the spatial resolution further. We used minimum variance distortionless look (MVDL), a beamformer, on simulated data to compare the spatial sensitivity of the optimal combination to disc electrodes and the tripolar concentric ring electrode surface Laplacian. The optimal combination shows the highest spatial sensitivity with the Laplacian a close second and disc electrodes resulting in a distant third. Further analysis is necessary with a more realistic computer model and then real signals. however it appears that the optimal combination may improve the spatial resolution of EEG further which in turn can be utilized to improve noninvasive EEG-based BCIs.**

I. INTRODUCTION

Nearly two million people in the U.S., and many more worldwide, suffer from severe motor disabilities brought on by neuromuscular impairments, such as amyotrophic lateral sclerosis (ALS), brainstem stroke, cereberal palsy and spinal cord injury (SCI) [1]. For those who have very high-level paralysis, or are "locked-in", conventional augmentative technologies will not help because most of the devices require some voluntary muscle control [2]. Over approximately the last 20 years, a new communication method, the brain computer interface (BCI), has been explored as a valuable augmentative communication channel. For a communication system that"does not depend on the brain's normal output pathways of peripheral nerves and muscles" [3], a BCI provides persons who cannot use their muscles but are cognitively intact with an alternative for communication and control.

Despite considerable advances, BCI development is still in its infancy and warrants further considerations to make a significant impact in most fields [4][5][6]. Implantable systems (intracortical electroencephalography (EEG) based or electrocorticography (ECoG) based), led by the BrainGate device, have better spatial resolution and signal-to-noise ratio (SNR) and require less time for training but are associated with increased risks to the patients and technical challenges. Noninvasive conventional EEG based BCIs, such as the BCI2000 [2], have minimum risk but suffer from a reduced spatial resolution and increased noise due to measurements on the scalp [7]. The increased risks associated with implantable BCIs and the poor spatial resolution of EEG demonstrate the need to improve the performance of conventional EEG based BCIs.

Low spatial resolution is a major hindrance in the effectiveness of conventional EEG. The lack of high spatial resolution is primarily due to (1) the blurring effects of the volume conductor; and (2) conventional EEG signals have reference electrode problems as idealized references are not available with EEG [8]. To resolve the reference electrode problems, Nunez et al. [8] proposed a common average reference and concentric electrodes which act like closely spaced bipolar recordings. However, in the common average reference recordings, it is possible that components present in most of the electrodes but absent or minimal in the electrode of interest may appear as "ghost potentials" [9].

To improve the spatial resolution of EEG researchers have relied on the Laplacian, the second spatial derivative of the scalp potentials. The surface Laplacian produces an image proportional to the cortical potentials and enhances the high spatial frequency components of the brain activity close to the electrode [10]. The application of the Laplacian method to study EEG began with [11] utilizing a 5-point difference method. He [12] also used the 5-point difference method derived from an array of disc electrodes measuring surface potentials. Other Laplacian techniques include: a) spline Laplacian algorithm [13], b) the ellipsoidal spline Laplacian algorithm [14], c) realistic Laplacian estimation techniques [15], and d) realistic geometry Laplacian algorithms [16]. It was found by [17] that the common average and the Laplacian derivation, the 5-point difference method, yield good performance on EEG BCI classification. Babiloni et al. demonstrated that surface Laplacian transformation of EEG signals can improve the recognition scores of imagined motor activity [18].

Laplacian filtering has been proven to be a high-pass filter for cortical imaging [19][20][21]. Fattorusso and Tilmant [22] were the first investigators to report the use of concentric ring electrodes. He and Cohen [23] proposed bipolar concentric ring Laplacian electrodes for measuring the Laplacian potential directly from the body surface and an array of

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these electrodes were used to create body surface Laplacian maps for cardiac signals. Besio et al. [24] [25] has reported on significant improvements in SNR, spatial selectivity, and mutual information using a tripolar concentric ring electrode (shown in Fig. 1.) to estimate the Laplacian. The model for this was to approximate the Laplacian as closely as possible and to attenuate distant sources sharply. It has also been reported [26] that tripolar concentric ring electrodes provided a significant improvement in BCI recognition rates over conventional disc electrodes.

One possible method to improve BCI would be to improve the spatial resolution in hopes of discriminating more independent sources. In this report we propose a new method for combining the outputs from the tripolar concentric ring electrode elements to increase the spatial sensitivity. Analysis was performed to sharpen the attenuation of distant sources. The effect of rejecting distant sources is to focus the spatial filter for local sources. Following are the methods used to determine the optimal combination of the simulated signals from the tripolar concentric ring electrode elements.

II. METHOD

To perform a relative comparison of spatial sensitivity between disc, tripolar concentric, and the optimal combination a simplified planer model of the head with a single conductivity was used to calculate the potentials on the electrode elements of a tripolar concentric ring electrode (Fig. 1.). The elements of the electrodes were divided into 16 and 32 discrete points for the middle and outer rings, respectively, with an average taken of all the discrete potentials as the potential for the element. A unity point source was moved from $r = 0.0$ cm to $r = 1.5$ cm radially from the center of the electrode. The depth of the point source was 2.0 cm below the surface of the electrode. The calculated potentials from the disc, middle ring, and outer ring are $s_1(r)$, $s_2(r)$ and $s_3(r)$ respectively.

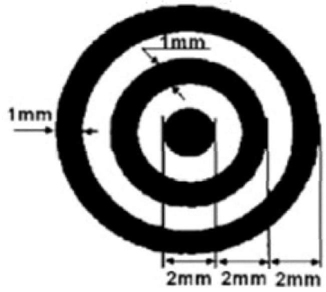

Fig. 1: Tripolar concentric ring electrode

III. OPTIMAL COMBINATION OF TRIPOLAR ELECTRODES

To improve the spatial sensitivity, and thereby the spatial resolution, as much as possible we need to derive an algorithm to combine the three simulated signals to optimize the spatial cutoff. For this application we adjust the weights $\mathbf{w} = [w_1, w_2, w_3]^T$, so that the magnitude of the signals in the region of interest, which is around $r = r_0$, where r_0 is an unknown radial distance to the source that we would like to detect and r is the radius from the tripolar concentric electrode, would be distinguished. To determine the weights we used minimum variance distortionless look (MVDL), a beamformer [27] to maximize $P(\mathbf{w})$:

$$P(\mathbf{w}) = \frac{(\sum_{i=1}^{3} w_i s_i(r_0))^2}{\int_0^r (\sum_{i=1}^{3} w_i s_i(r))^2 dr} \tag{1}$$

We first form the sum:

$$x(r) = \sum_{i=1}^{3} w_i s_i(r) \tag{2}$$

where $\mathbf{w} = [w_1, w_2, w_3]^T$ are the weights for the signals from the three different elements of the electrode. For the maximum output at $r = r_0$ we constrain $x(r_0) = 1$ so that

$$x(r_0) = \sum_{i=1}^{3} w_i s_i(r_0) = 1 \tag{3}$$

Then to maximize $P(\mathbf{w})$ we consider $J(\mathbf{w})$:

$$J(\mathbf{w}) = \int_0^r (\sum_{i=1}^{3} w_i s_i(r))^2 dr \tag{4}$$

and minimize $J(\mathbf{w})$ over $\mathbf{w} = [w_1, w_2, w_3]^T$. To do this, let $\mathbf{s}(r) = [s_1(r), s_2(r), s_3(r)]^T$ and:

$$J(\mathbf{w}) = \mathbf{w}^T C \mathbf{w} \tag{5}$$

In which,

$$C = \int_0^r \mathbf{s}(r)\mathbf{s}^T(r) dr \tag{6}$$

Now we must minimize $J(\mathbf{w})$ and the solution can be obtained from (3) and (5) using the Lagrange multiplier:

$$F(\mathbf{w}) = \mathbf{w}^T C \mathbf{w} + \lambda(\mathbf{w}^T \mathbf{s}(r_0) - 1) \tag{7}$$

Where we perform the gradient:

$$\frac{\partial F}{\partial \mathbf{w}} = 2C\mathbf{w} + \lambda \mathbf{s}(r_0) = 0 \tag{8}$$

However, since $x(r_0) = \sum_{i=1}^{3} w_i s_i(r_0) = 1$, which means $\mathbf{w}^T \mathbf{s}(r_0) = 1$, then the solution takes the form of:

$$\mathbf{w}_{opt} = \frac{C^{-1}\mathbf{s}(r_0)}{\mathbf{s}^T(r_0) C^{-1} \mathbf{s}(r_0)} \tag{9}$$

And the combined signal is:

$$x(r) = \frac{\mathbf{s}^T(r) C^{-1} \mathbf{s}(r_0)}{\mathbf{s}^T(r_0) C^{-1} \mathbf{s}(r_0)} \tag{10}$$

Which is the optimized combination of the signals from the tripolar concentric ring electrode elements.

IV. RESULTS

The potentials for a 1.0 cm diameter tripolar concentric ring electrode shown in Fig. 1 were calculated and squared for a point source that was 2.0 cm below the surface of the plane of the electrode. The point source was moved from $r = 0$, the center of the middle disc, to $r = 1.5$ cm. As would be expected with a spacing of 1.0 mm between the electrode elements there is very little difference in amplitude of the signals as seen in Fig. 2. The units are normalized squared potential to show the relative differences. In Fig. 3 there is a comparison of the radial roll off of the Laplacian spatial filter, the optimal combination, and a disc electrode. The Laplacian spatial filter was reported by [24] and formulated by:

$$L = 16 * (Pmiddle - Pdisc) - (Pouter - Pdisc) \quad (11)$$

Where Pmiddle, Pdisc, and Pouter are the potentials on the middle ring, central disc, and outer ring, respectively. The potentials for the disc were calculated by summing the potentials of the three individual elements of the tripolar electrode and dividing by three to get the average of the potentials. We can see from Fig. 3 that the optimal combination forms a steeper roll off that reaches zero at approximately 0.4 cm, before the outer radius of the electrode (0.5 cm). The Laplacian spatial filter reaches zero at 0.55 cm, just beyond the outer radius of the electrode. In comparison the disc electrode does not reach zero even after 3 radii, 1.5 cm. It can also be seen that the side lobe of the Laplacian spatial filter is larger than the one for the optimal combination. A perfect spatial filter would remain flat at zero beyond the space that it passes signals from.

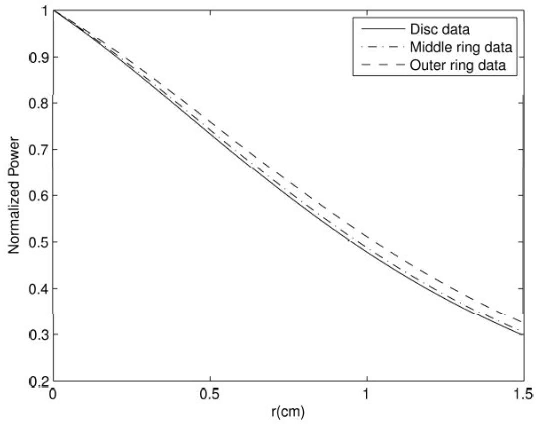

Fig. 2: A comparison of the normalized squared potentials calculated for the three elements of the tripolar concentric ring electrode. It can be seen that there is little relative difference between each element.

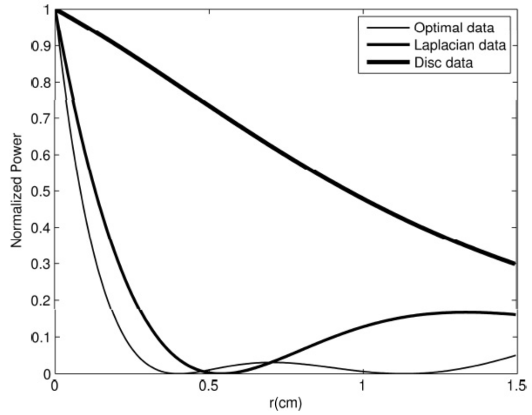

Fig. 3: A comparison of the radial roll off for the Laplacian spatial filter, the optimal combination, and the disc electrode.

V. DISCUSSION/CONCLUSION

We previously showed that tripolar concentric ring electrodes provide significantly better spatial selectivity over bipolar concentric ring electrodes and conventional disc electrodes [24]. With the optimal combination showing the steepest roll off and least ringing in the side lobes it should result in the best spatial resolution of the different methods that we have analyzed.

Observing Fig. 3, if our region of interest is directly under the electrode, we can see that if a source is beyond the radius of the electrode by one radius (1.0 cm) then the Laplacian spatial filter only passes approximately 10% of the power and the optimal combination attenuates nearly all of the power. However, the disc electrode is not vary discriminating it would pass approximately 50% of the power of a source located in an area outside of the region of interest.

It should also be noted that we used a simplified model to calculate the potentials for the electrodes. It was a single conductivity model and no noise was added. The results may vary if these circumstances are changed. In particular, if a multiconductivity model was used which distorts the potentials on the surface the disc electrode roll off would be even worse. The Laplacian spatial filter may not be affected as severely since it takes the second spatial derivative of the potentials which results in potentials that are proportional to those of the source modeled on the brain. Adding noise would also alter the signal from disc electrodes but as we showed in [28] for the tripolar concentric ring electrode Laplacian if the noise is correlated between the elements it is attenuated sharpley. In conclusion, the MVDL beamformer provides the optimal radial roll off of the methods we have tested. This increased spatial sensitivity should also increase the spatial resolution of the tripolar concentric ring electrode. Further work must be completed to verify the results still hold true in the presence of noise and with a more realistic multiconductivity model.

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