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Improving the accuracy of Laplacian estimation with novel multipolar concentric ring electrodes

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ABSTRACT

Conventional electroencephalography with disc electrodes has major drawbacks including poor spatial resolution, selectivity and low signal-to-noise ratio that are critically limiting its use. Concentric ring electrodes, consisting of several elements including the central disc and a number of concentric rings, are a promising alternative with potential to improve all of the aforementioned aspects significantly. In our previous work, the tripolar concentric ring electrode was successfully used in a wide range of applications demonstrating its superiority to conventional disc electrode, in particular, in accuracy of Laplacian estimation. This paper takes the next step toward further improving the Laplacian estimation with novel multipolar concentric ring electrodes by completing and validating a general approach to estimation of the Laplacian for an $(n+1)$-polar electrode with n rings using the $(4n+1)$-point method for $n \geqslant 2$ that allows cancellation of all the truncation terms up to the order of $2n$. An explicit formula based on inversion of a square Vandermonde matrix is derived to make computation of multipolar Laplacian more efficient. To confirm the analytic result of the accuracy of Laplacian estimate increasing with the increase of n and to assess the significance of this gain in accuracy for practical applications finite element method model analysis has been performed. Multipolar concentric ring electrode configurations with n ranging from 1 ring (bipolar electrode configuration) to 6 rings (septapolar electrode configuration) were directly compared and obtained results suggest the significance of the increase in Laplacian accuracy caused by increase of n.

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1. Introduction

Electroencephalography (EEG) is an essential tool for brain and behavioral research and is used extensively in neuroscience, cognitive science, cognitive psychology, and psychophysiology. EEG is also one of the mainstays of hospital diagnostic procedures and pre-surgical planning. Despite scalp EEG's many advantages end users struggle with its poor spatial resolution, selectivity and low signal-to-noise ratio, which are EEG's biggest drawbacks critically limiting the research discovery and diagnosis [1–3].

EEG's poor spatial resolution is primarily due to (1) the blurring effects of the volume conductor with disc electrodes; and (2) EEG signals having reference electrode problems as idealized references are not available with EEG [2]. Interference on the reference electrode contaminates all other electrode signals [2]. The application of the surface Laplacian (the second spatial derivative of the potentials on the body surface) to EEG has been shown to alleviate the blurring effects enhancing the spatial resolution and selectivity, and reduce the reference problem [4–6].

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While several methods were proposed for estimation of the surface Laplacian through interpolation of potentials on a surface and then estimating the Laplacian from an array of disc electrodes [5–9], concentric ring electrodes (CRE) have shown more promise. The CREs can resolve the reference electrode problems since they act like closely spaced bipolar recordings [2]. CREs are symmetrical alleviating electrode orientation problems [10]. They also act as spatial filters reducing the low spatial frequencies and increasing the spatial selectivity [10,11]. Finally, even bipolar CREs, consisting of just two elements including a single ring and the central disc, improve the radial attenuation of the conventional disc electrode from $1/r^3$ to $1/r^4$ with larger numbers of poles having the potential to enhance radial attenuation even further [12].

Tripolar CREs (TCRE; the largest number of CRE poles currently used), consisting of three elements including the outer ring, the middle ring, and the central disc (Fig. 1B), are distinctively different from conventional disc electrodes that have a single element (Fig. 1A). TCREs have been shown to estimate the surface Laplacian directly through the nine-point method (NPM), an extension of the five-point method (FPM) used for bipolar CREs, and significantly better than other electrode systems including bipolar and quasi-bipolar CREs [13,14]. Compared to EEG with conventional disc electrodes Laplacian via TCREs have been shown to have significantly better spatial selectivity (approximately 2.5 times higher), signal-to-noise ratio (approximately 3.7 times higher), and mutual information (approximately 12 times lower) [15]. TCREs also have very high common mode noise rejection providing automatic artifact attenuation, −100 dB one radius from the electrode [14]. Because of such unique capabilities TCREs have found numerous applications in a wide range of areas including brain–computer interface [16,17], seizure onset detection [18,19], seizure attenuation using transcranial focal stimulation applied via TCREs [20–23], detection of high-frequency oscillation and seizure onset zones [24], etc. These applications suggest experimental practicality of further increasing the number of poles in noninvasive electrophysiological electrodes.

Taking a first, preliminary step toward development of multipolar CREs, the Laplacian has been derived for a general case of $(n+1)$-polar CRE with n rings using the $(4n+1)$-point method for $n \geqslant 2$ demonstrating how the accuracy of the Laplacian estimate increases with the increase of n due to elimination of higher order truncation terms [25]. This approach allows canceling all the truncation terms up to the order of $2n$ which has been shown to be the highest order achievable for a CRE with n rings [25]. Furthermore, the proposed general approach has been illustrated with two examples numerically deriving the Laplacian estimates for TCRE and [13–24], for the first time, quadripolar CRE (QCRE) [25].

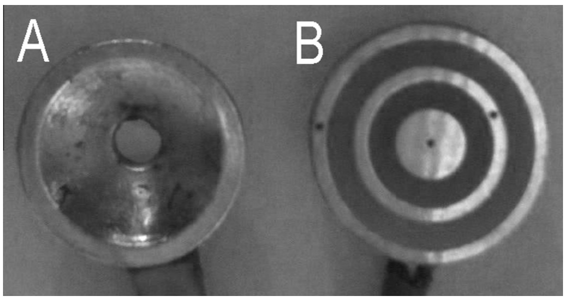

Fig. 1. Conventional disc electrode (A) and tripolar concentric ring electrode (B).

This preliminary study had two fundamental shortcomings. First, for any $n \geqslant 2$ the Laplacian estimates in the form of the null space vectors could be calculated numerically through finding the column echelon form of the matrix using methods like Bareiss algorithm which for exactly given integer matrices have been shown to be more efficient than the standard Gaussian elimination [26]. However, deriving an explicit formula for Laplacian estimates as a function of n would be even more efficient in terms of its computation. Second, computer modeling was needed to confirm the analytic result of the accuracy of Laplacian estimate increasing with the increase of n and to assess the significance of this gain in accuracy for practical applications.

This paper addresses both shortcomings of the preliminary study [25]. First, explicit formula for multipolar Laplacian is derived based on the inversion of a square Vandermonde matrix completing the proposed approach to estimation of multipolar Laplacian. Second, multipolar CRE configurations with n ranging from 1 (bipolar CRE) to 6 (septapolar CRE) were directly compared in accuracy of Laplacian estimation using finite element method (FEM) model analysis with a single dipole. While FEM modeling is commonly used to assess and compare different electrode configurations [27,28], the model used in this paper was adopted from our previous studies where it was used to compare bipolar, quasi-bipolar, and tripolar CRE configurations [13,14].

This paper is organized as follows: preliminaries and notations for the proposed approach for multipolar Laplacian estimation including basic cases of FPM and NPM as well as the general approach for $(n+1)$-polar CRE with n rings are presented in the Material and Methods section. This section also contains all the details on the FEM modeling used to compare different multipolar CRE configurations as well as on statistical analysis of obtained results. Main results including derivation of the explicit formula for multipolar Laplacian estimate based on the inversion of a square Vandermonde matrix and FEM modeling results are presented in the Results section. Discussion of the obtained results and plans for future work are presented in the Discussion section followed by the overall conclusion.

2. Material and methods

2.1. Notations and preliminaries

2.1.1. Five-point method (bipolar CRE)

As shown in Fig. 2 v_0 through $v_{nr,4}$ are the potentials at points p_0 through $p_{nr,4}$, respectively. To simplify the narrative, v_0 through $v_{nr,4}$ may also signify points p_0 through

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