Time and frequency domain synchrony of current and optimal Laplacian estimates via t-Lead electrodes on human electroencephalogram data

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Abstract*—t-Lead is a commercial tripolar concentric ring electrode designed for noninvasive electrophysiological measurement applications. Utilizing the unique ability of concentric ring electrodes to estimate the second spatial derivative (surface Laplacian) at each individual electrode by combining differential voltages recorded between the central disc and the rings with specific coefficients makes them of significant importance in biomedicine. Our recent research showed that optimal coefficients (6, -1) for the electrodes with dimensions similar to the t-Lead that maximize the accuracy of Laplacian estimation are different from the currently used coefficients (16, -1). This study applies time and frequency domain (cross-correlation and coherence respectively) signal synchrony measures to resting electroencephalogram data from six healthy humans to assess the difference due to current and optimal coefficients. This task is important since diagnostic value may be impacted by the differences in the estimated Laplacian signal. Two bipolar Laplacian estimates (each ring minus the central disc) were also added to the analysis resulting in six pairwise comparisons including all combinations of optimal and suboptimal tripolar as well as larger and smaller bipolar Laplacian estimates. Three of the comparisons resulted in very high average cross-correlation and coherence (0.9 to 1.0) while remaining three (all including larger bipolar estimate) did not. High signal synchrony between tripolar Laplacian estimates could indicate that the difference due to optimal and suboptimal coefficients may not be significant though further investigation is required going beyond synchrony measures. Results for larger bipolar Laplacian estimate are consistent with prior results of Laplacian estimation accuracy increasing with increase in the number of concentric rings and with decrease in the electrode size.

Keywords*—*electroencephalogram, synchrony, cross-correlation, coherence, Laplacian, estimation, tripolar, concentric ring electrode, t-Lead, CREmedical

I. Introduction

Concentric ring electrodes (CREs) are wearable and noninvasive electrophysiological measurement sensors that found numerous applications ranging from brain-computer interfaces [1], [2], [3] and source localization of high-frequency activity [4] in epilepsy patients data to moment of activation isochronal mapping [5] and sleep [6] in healthy human subject data. Previously, realistic finite dimensions model of CRE was used to optimize the coefficients for the second spatial derivative (surface Laplacian) estimate obtained via said CRE maximizing the estimation accuracy [7]. For a tripolar CRE configuration (Fig. 1) in particular it lead to using the dimensions approximating the commercially available t-Lead electrode (CREmedical, Kingston, RI), specifically designed for noninvasive electrophysiological measurement applications. t-Lead electrodes have been used in studies ranging from animal model based ones as early as [8], [9] (around the time of CREmedical's incorporation) to human data based ones as recent as [10], [11]. The ability of CREs to directly estimate the surface Laplacian at each individual electrode by combining differential voltages recorded between the central disc and the rings with specific coefficients makes them of significant importance in biomedicine. Our most recent research showed that maximizing the accuracy of Laplacian estimation could be done by optimizing the CRE configurations using their finite dimensions models and obtained results can be confirmed using finite element method modeling [12]. The finite element method

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modeling results suggest that optimal tripolar CRE configuration may also offer improved sensitivity and spatial resolution compared to constant and linearly increasing inter-ring distances TCRE configurations of the same size [12]. Moreover, compared to finite dimensions models approximating t-Lead dimensions the optimal configuration corresponded to over four times smaller Laplacian estimation errors [13]. Most importantly, the same study indicated that optimal coefficients (6, -1) maximizing the accuracy of Laplacian estimation for the electrodes with dimensions similar to ones of t-Lead are different from the currently used coefficients (16, -1) [13]. This study applies time and frequency domain (cross-correlation and coherence respectively) signal synchrony measures to human electroencephalogram (EEG) data to access the difference due to current and optimal coefficients. The human dataset for this study was adopted from [14], [15] where it was also used to assess synchrony between EEG signals. In particular, it was used to demonstrate equivalency between signals from conventional disc electrodes and outer ring of tripolar CRE via cross-correlation and coherence. This makes this dataset and the same signal synchrony measures a good fit for this study as well since in a similar manner it assesses for potential equivalency between Laplacian estimates corresponding to optimal and currently used suboptimal coefficients. This task is important since the diagnostic value may be impacted by the differences in the estimated Laplacian signal. Two bipolar Laplacian estimates were also added to the analysis.

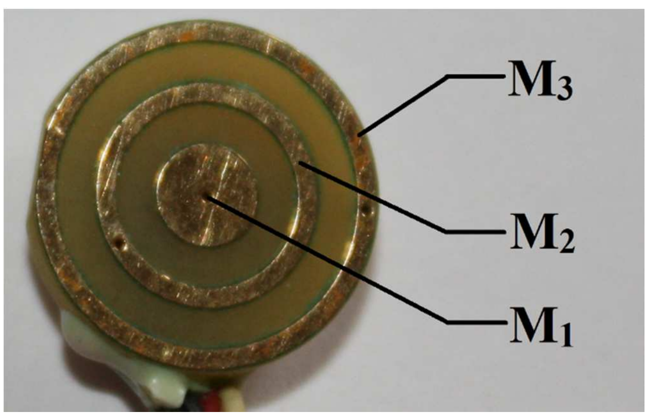

Fig. 1. Tripolar concentric ring electrode with the same dimensions as t-Lead electrodes from CREmedical and labeled monopolar signals/recording surfaces: central disc (M_1), middle ring (M_2), and outer ring (M_3).

II. Methods

A. Signal Recording

The EEG dataset for this study was adopted from [14], [15]. Six healthy human subjects (ages 24-40, one female) had their resting EEG data band pass filtered (0.1-100Hz) and recorded at 1200 samples per second via gUSB amplifier with normalized unit gain (g.tec medical engineering GmbH, Schiedlberg, Austria), resulting in a total duration of 1730s, 173 segments total when divided into non-overlapping segments of 10s each. The subjects were instructed to remain motionless and seated in a chair to reduce artifacts due to movement. Some of the monopolar/recording surface (e.g. M_3) and differential (M_2 - M_1 and M_3 - M_1) signals from t-Lead electrode and from conventional disc electrode were simultaneously monitored at location P4 of the standard 10-20 system with the right mastoid process serving as ground and reference. Skin-to-electrode impedances were kept under 5kΩ. Signals from the t-Lead were additionally preamplified via custom preamplifier with a gain of 6. All the signal processing was performed using Matlab (Mathworks, Natick, MA) including digital filtering (zero-phase fifth-order Butterworth) with a band pass of 1-100Hz and 60Hz notch.

B. Signal Analysis

Neuronal signal synchrony measures in the time and frequency domains were applied to six pairs of signals. Cross-correlation and coherence were calculated for all 173 10s signal segments normalized to zero mean and unit variance. Cross-correlation coefficients were calculated at lag zero as well as at the optimal lag to account for any time delay between signals. The coherence coefficients corresponding to the frequency range of 1-100Hz were averaged for each segment using Welch's averaged modified periodogram method with overlapping (50%) and Hanning window of 1024 samples. The magnitude squared coherence estimate was calculated for each segment and the coefficients corresponding to the pairwise comparisons were averaged using the 1-100Hz frequency range (also referred to as "full spectrum" below) as well as individual frequency bands including delta (1-4Hz), theta (4-7Hz), alpha (7-14Hz), beta (14-30Hz), and gamma (30-100Hz). Six pairwise comparisons including all the combinations of optimal and suboptimal tripolar (tEEG) as well as of larger and smaller bipolar (bEEG) Laplacian estimates were performed. The Laplacian estimation involves combining differential voltages between the rings and central disc. For the suboptimal estimate current coefficients (16, -1) were originally derived for t-Lead using a simple model of electrode dimensions with a median ring radii ratio of 1 to 2. The optimal estimate used coefficients (6, -1) from [13]. Estimate of the Laplacian via BCREs is the differential voltage between a ring and central disc. The estimates for smaller and larger BCREs were derived using the middle ring and the outer ring, respectively. Formulas for all four surface Laplacian estimates used in this study in terms of labeled monopolar signals/recording surfaces from Fig. 1 are as follows:

$$tEEG\ (suboptimal) = 16\cdot(M_2 - M_1) - 1\cdot(M_3 - M_1) \quad (1)$$

$$tEEG\ (optimal) = 6\cdot(M_2 - M_1) - 1\cdot(M_3 - M_1) \quad (2)$$

$$bEEG\ (smaller) = M_2 - M_1 \quad (3)$$

$$bEEG\ (larger) = M_3 - M_1 \quad (4)$$

III. Results

Three signal synchrony measures obtained for all of the pairs of signals compared are presented in Tables 1 and 2. Specifically, maximum and zero lag cross-correlation are presented in Table 1 and average coherence across the full spectrum as well as for individual frequency bands are presented in Table 2. Three of the comparisons resulted in very high cross-correlation and coherence (0.9 to 1.0) while the remaining three (all including the larger bipolar estimate) did not. Detailed discussion of all the results in Tables 1 and 2 is presented in the following section.

TABLE 1. Two signal synchrony measures (maximum and zero lag cross-correlation) calculated to compare six pairs of Laplacian estimate signals.

Signals being compared	Cross-correlation (mean ± standard deviation)	
	Maximum	Zero lag
tEEG (suboptimal) vs tEEG(optimal)	0.997 ± 0.0008	0.997 ± 0.0008
tEEG (suboptimal) vs bEEG (smaller)	0.999 ± 0.0003	0.999 ± 0.0003
tEEG (optimal) vs bEEG (smaller)	0.992 ± 0.0019	0.992 ± 0.0019
tEEG (suboptimal) vs bEEG (larger)	0.707 ± 0.0939	0.706 ± 0.0941
tEEG (optimal) vs bEEG (larger)	0.648 ± 0.1078	0.647 ± 0.1086
bEEG (smaller) vs bEEG (larger)	0.736 ± 0.0859	0.736 ± 0.086

TABLE 2. Average coherence calculated to compare six pairs of Laplacian estimate signals.

Signals being compared	Average coherence (mean ± standard deviation)					
	Full spectrum	Delta	Theta	Alpha	Beta	Gamma
tEEG (suboptimal) vs tEEG (optimal)	0.991 ± 0.0007	0.997 ± 0.0012	0.995 ± 0.0015	0.994 ± 0.0016	0.992 ± 0.0018	0.99 ± 0.0009
tEEG (suboptimal) vs bEEG (smaller)	0.997 ± 0.0003	0.999 ± 0.0003	0.999 ± 0.0004	0.998 ± 0.0005	0.998 ± 0.0006	0.997 ± 0.0004
tEEG (optimal) vs bEEG (smaller)	0.979 ± 0.0019	0.994 ± 0.0027	0.988 ± 0.0036	0.985 ± 0.0038	0.982 ± 0.0046	0.976 ± 0.0024
tEEG (suboptimal) vs bEEG (larger)	0.281 ± 0.1011	0.824 ± 0.065	0.632 ± 0.0999	0.539 ± 0.136	0.378 ± 0.1516	0.193 ± 0.1071
tEEG (optimal) vs bEEG (larger)	0.231 ± 0.088	0.785 ± 0.0791	0.568 ± 0.1132	0.468 ± 0.1448	0.312 ± 0.1452	0.15 ± 0.0897
bEEG (smaller) vs bEEG (larger)	0.313 ± 0.107	0.843 ± 0.0581	0.665 ± 0.0922	0.577 ± 0.1294	0.417 ± 0.1525	0.224 ± 0.1155

Variation between human subjects (i.e. inter-subject) is illustrated via boxplots for the case of optimal versus suboptimal tEEG: maximum cross-correlation in Fig. 2 and average full spectrum coherence in Fig. 3 respectively.

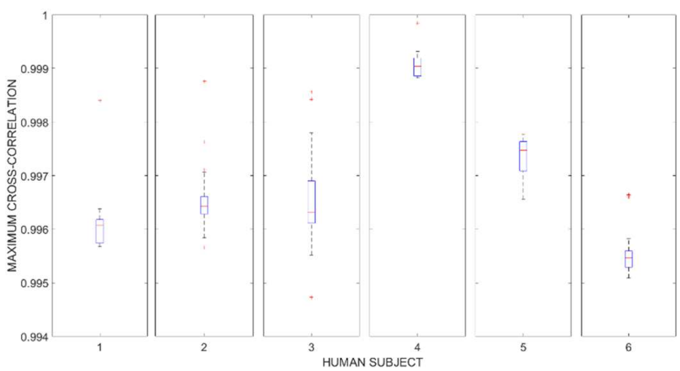

Fig. 2. Maximum cross-correlation for optimal versus suboptimal tEEG among six human subjects.

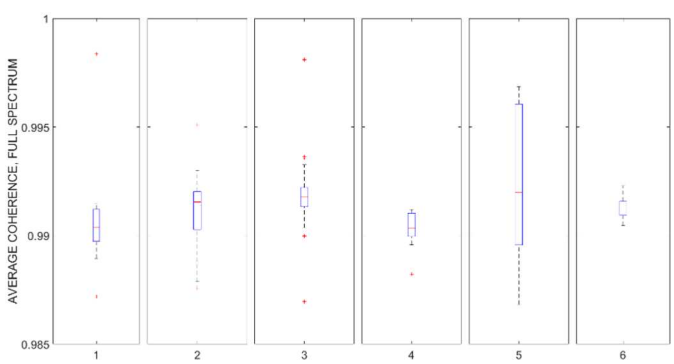

Fig. 3. Average full spectrum coherence for optimal versus suboptimal tEEG among six human subjects.

IV. Discussion

To the best of our knowledge this study is the first attempt of using signal synchrony in both time and frequency domains when comparing different Laplacian estimates for the same electrode geometry. High signal synchrony between tripolar Laplacian estimates (first row in Tables 1 and 2) could indicate that the difference due to optimal and suboptimal coefficients may not be significant though further investigation is required going beyond synchrony measures based on additional considerations below. Overall lower cross-correlation and average coherence values for larger bipolar Laplacian estimate (rows four through six in Tables 1 and 2) are consistent with prior results of Laplacian estimation accuracy increasing with increase in the number of concentric rings and with decrease in the electrode size [16], [17], [18]. The larger bipolar estimate corresponding to the lowest Laplacian estimation accuracy out of all four estimates included in this study is the likely reason why it corresponds to lower signal synchrony with other, higher accuracy Laplacian estimates.

Another notable result is the high cross-correlation (0.7 to 0.9) between smaller and larger bipolar estimates (row six in Table 1) suggests that although both signals are quite alike, there are some differences in the sensed activity due to larger distance from the central disc.

Finally, it is worth noting that larger bipolar estimate corresponds to higher cross-correlation and average coherence with suboptimal tripolar estimate than with the optimal tripolar one (rows four and five in Tables 1 and 2) and suboptimal tripolar estimate corresponds to higher cross-correlation and average coherence with smaller bipolar estimate than with the optimal tripolar one (first and second rows in Tables 1 and 2). However, the very high cross-correlation and coherence values obtained between the two tripolar estimates and the smaller bipolar one show that both tripolar estimates are almost equal (rescaled) versions of the smaller bipolar one. This may be partially due to the higher Laplacian estimation accuracy of these three estimates (compared to the larger bipolar estimate) and partially due to the fact that for both optimal and suboptimal tripolar Laplacian estimates higher linear combination coefficients (6 and 16 respectively) correspond to the difference between the potentials on the middle ring and the central disc (equal to the smaller Laplacian estimate) as opposed to lower estimation coefficient (-1) corresponding to the difference between the potentials on the outer ring and the central disc (equal to the larger Laplacian estimate). As for the effect of different frequency bands on average coherence, the last three rows of Table 2 suggest that coherence is higher in lower frequency bands. It appears that lower frequency components are more similar in the signals sensed by the middle and outer ring poles and more different for components of higher frequency. Further investigation is needed to determine whether this is due to physical aspects related to wave propagation at different frequencies, to signal-to-noise ratio that that might be poorer at higher frequencies, or to physiological considerations and interpretation of the activity for each of these frequency bands.

Consistency between zero lag and maximum cross-correlations for all comparison pairs in Table 1 means that there was no substantial time delay between different data channels. Same would have likely been true for [14] if segments were normalized for both cross-correlation calculations like it was done in this study and not just for the maximum one like it was done in [14].

Boxplots in Figs. 2 and 3 demonstrate consistency between the human subjects in terms of maximum cross-correlation and average full spectrum coherence for the case of optimal versus suboptimal tEEG as the most relevant one to the purpose of this study (except for maximum cross-correlation for human subject 4 that appears to be higher than those corresponding to the rest of the subjects). This suggests that most of the variation in the data might be intra-subject (i.e. between 10s signal segments for individual subjects) as opposed to inter-subject. However, there is greater variation in the last three rows of Tables 1 and 2 that could potentially be inter-subject and further investigation is needed for conclusive proof.

V. Conclusions

While the obtained results suggest that suboptimal tripolar Laplacian estimation coefficients may be sufficient, the real limitation is the t-Lead geometry itself which still corresponds to over 4 times the median Laplacian estimation errors compared to the optimal tripolar concentric ring electrode configuration [13]. Future work directions include but are not limited to assessing nonlinear synchrony measures and parameters that are less influenced by volume conduction effect such as the imaginary part of the coherence or phase lag index [19] as well as assessing the effects of suboptimal coefficients and/or suboptimal CRE configurations on different biomarkers from bioelectric signals not only in EEG based applications, but also in electrocardiogram [20] or electromyogram (for example, swallowing [21], uterine [22] or respiratory [23] muscles) based ones.

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