Assessing the importance of optimal Laplacian estimation coefficients for commercially available concentric ring electrodes on human data and via finite element method modeling

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Introduction

- Concentric ring electrodes (CREs) are wearable and noninvasive electrophysiological measurement sensors that have found numerous applications in various studies.
- Previous studies on CREs have used negligible dimensions model (Fig. 1) and proposed ways to improve the accuracy of surface Laplacian estimation resulting in realistic finite dimensions model (Fig. 2) that optimized coefficients for the second spatial derivative estimate obtained via CREs.

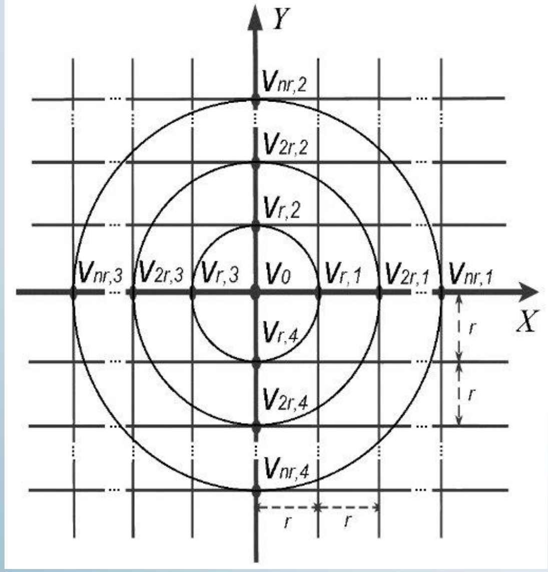


Figure 1. Negligible dimensions model of a CRE from.

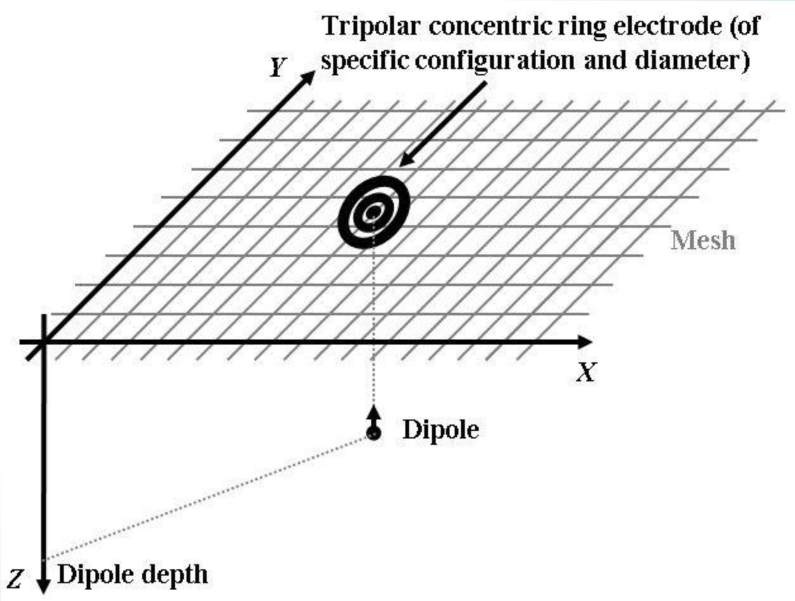


Figure 2. Schematic of the finite element method (FEM) model used to maximize the accuracy of Laplacian estimation.

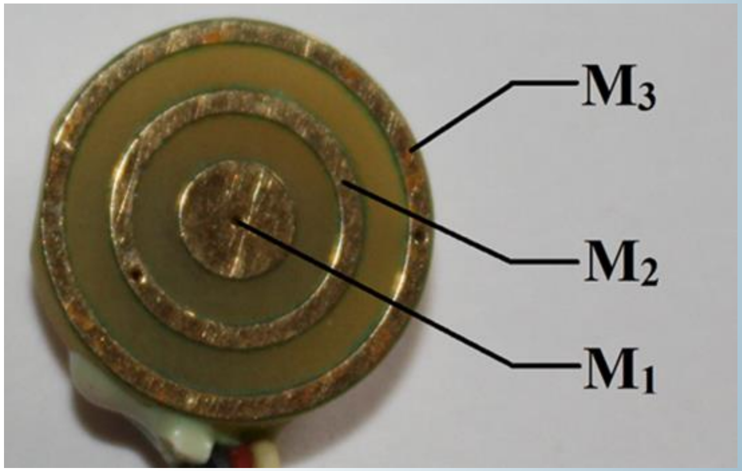
Introduction

- The Laplacian is the second spatial derivative of the surface potential.
- This provides higher spatial resolution.
- The Laplacian can be estimated through arrays of single pole electrodes.
- Only CREs allow estimating the Laplacian at each electrode.
- This presentation will include different examples of surface Laplacian estimates.

Introduction

- t-Lead is a commercially available tripolar CRE that is produced by CREmedical Corp (Kingston, RI). Recently optimal coefficients (6,-1) for t-Lead have been found to be different from the currently used suboptimal coefficients (16,-1), which can impact the diagnostic value of the estimated Laplacian signal [1]. The purpose of this thesis was to quantify the difference between suboptimal and optimal coefficients.

Figure 3. t-Lead electrodes from CREmedical (https://cremedical.com/product-2-2/).



[illegible] Tripolar CRE with the same dimensions as t-Lead electrodes from CREmedical and labeled monopolar signals/recording surfaces: central disc (M1), middle ring (M2), and outer ring (M3).

[1] Makeyev O. et al., 9th ECSA (2022)

Introduction

- The SAS study aimed to apply linear time and frequency domain signal synchrony measures to human electroencephalogram (EEG) data to assess the difference due to current and optimal coefficients. The results provided insights into the impact of using optimal coefficients on Laplacian estimation accuracy [1].

- The ISBI study was two-fold. First, we assessed how well finite element method (FEM) modeling estimates Laplacian potential using suboptimal verses optimal coefficients. Second, we analyzed the nonlinear synchrony measure between EEG Laplacian estimates using both coefficients to compare with previously obtained linear synchrony measures [2].

[1] Benally, A. et al., IEEE SAS (2024)
[2] Benally, A. et al., IEEE ISBI (2025)

Methods on signal recording

- The EEG dataset for this study was adopted from Oleks’ studies [1], [2].
- Six healthy human subjects (ages 24-40, one female). The subjects were instructed to remain motionless and seated in a chair to reduce artifacts due to movement. The EEG data was recorded using a gUSB amplifier with normalized unit gain (g.tec medical engineering GmbH, Schiedlberg, Austria) at 1200 samples per second for a total duration of 1730s.
- The data was band-pass filtered (0.1-100Hz) and recorded 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 (Fig. 5).

Fig. 5 t-Interface pre-amplifiers from CREmedical (https://cremedical.com/product-2-2/).

[1] Makeyev O. et al., IEEE SPMB (2013)
[2] Makeyev O. et al., IEEE NEBEC (2014)

Methods on signal analysis

- Neuronal signal synchrony measures were applied to six pairs of signals in both the time and frequency domains including all combinations of optimal and suboptimal tripolar (tEEG) as well as larger and smaller bipolar (bEEG) Laplacian estimates.

$$\text{tEEG (suboptimal)} = 16\cdot(\text{M2} - \text{M1}) - 1\cdot(\text{M3} - \text{M1}) \tag{1}$$

$$\text{tEEG (optimal)} = 6\cdot(\text{M2} - \text{M1}) - 1\cdot(\text{M3} - \text{M1}) \tag{2}$$

$$\text{bEEG (smaller)} = \text{M2} - \text{M1} \tag{3}$$

$$\text{bEEG (larger)} = \text{M3} - \text{M1} \tag{4}$$

- Cross-correlation coefficients were calculated at lag zero as well as at the optimal lag to account for any time delay between signals.
- 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 pairwise comparisons were averaged using the full spectrum as well as individual frequency bands (delta, theta, alpha, beta, and gamma).

Methods on signal analysis (cont.)

- To quantify the mutual dependence between the signals, the normalized mutual information (NMI) was utilized.
- Using Shannon entropy, mutual information was computed using (5) for the two probability distributions signals and their joint probability distributions based on the histograms.
- The results were then normalized to fall within range of 0 to 1.
- NMI was used with four different normalization approaches (minimum, maximum, arithmetic, and geometric) to compare all combinations.
- MATLAB implementation of NMI was adopted from [1].

$$MI(X;Y) = \sum_{x_i y_j} P_{X,Y}(x_i, y_j) log_2 \frac{P_{X,Y}(x_i, y_j)}{P_X(x_i) P_Y(y_j)} \qquad (5)$$

[1] J. M. Mira-Tomás et al., CASEIB (2022)

Methods using FEM modeling

- FEM model has been adopted Oleks' studies [1,2].
- Evaluate the Laplacian and its estimates at various mesh points for electrode diameter ranging from 0.5 to 5 cm.
- FEM modeling was used to compare the performance of two realistic finite dimensions model of the t-Lead electrodes (Fig 6A and 6B), the dimensions were scaled to the size of the 9 intervals. To derive the suboptimal coefficients for them, additional electrode configuration was considered with a ratio of median radii of 1 to 2 (Fig. 6C).
- To assess the accuracy of the Laplacian estimation the relative error and the normalized maximum error was computed for different electrode diameters using (6) and (7).
    - The smaller the errors, the more accurate the estimation.

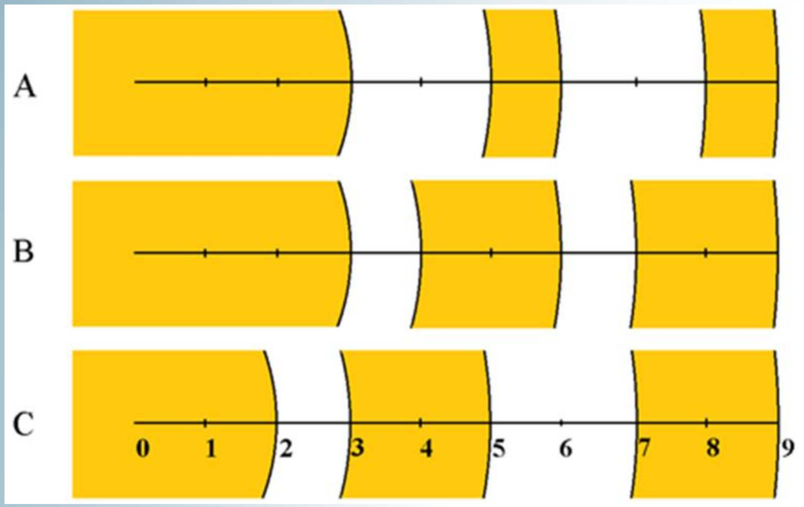


Figure 6. Three finite dimension
Corresponding to: two approxima
t-Lead dimensions (panes A and B)
configuration with one to two ratio
of median ring radii (panel C).

$$\text{Relative error}^i = \sqrt{\frac{\sum(\Delta v - \Delta^i v)^2}{\sum(\Delta v)^2}} \qquad (6)$$

$$\text{Normalized maximum error}^i = \frac{\max\left|\Delta v - \Delta^i v\right|}{\max\left|\Delta v\right|} \qquad (7)$$

[1] Makeyev O. et al., 9th ECSA (2022)
[2] Makeyev O. et al., SAS (2022)

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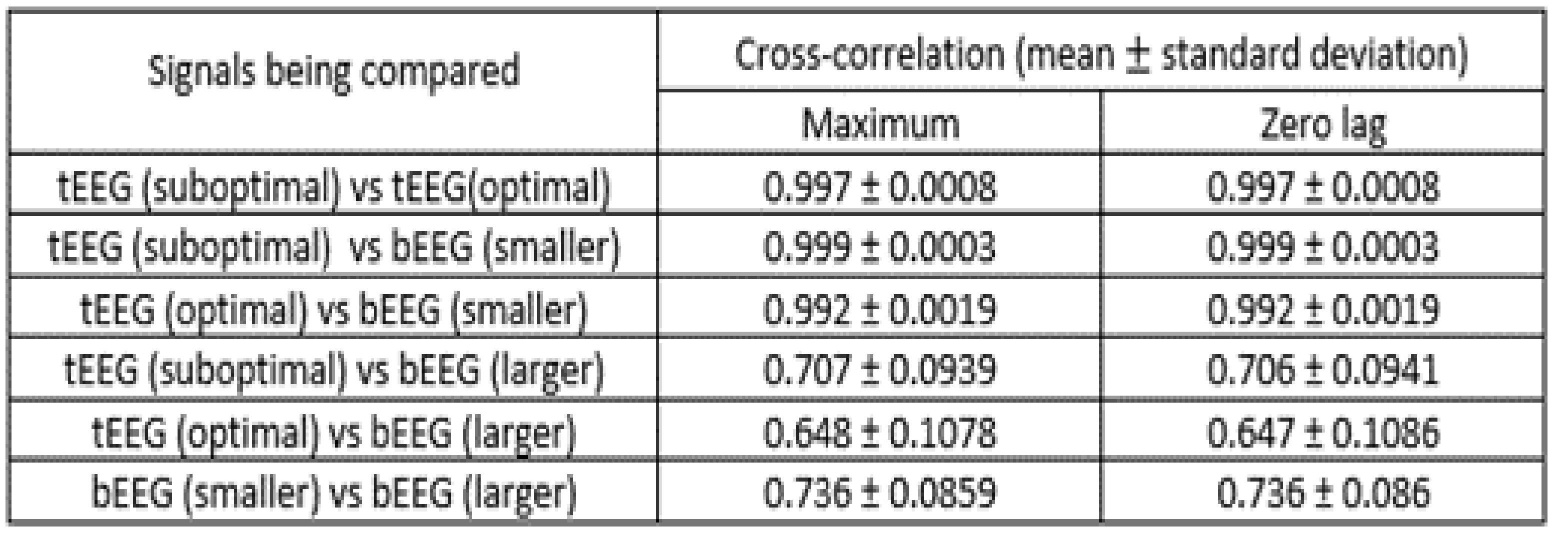
Results on EEG data

- Three signal synchrony measures were obtained for all pairwise comparisons.
- The maximum and zero lag cross-correlation are presented in Table 1.

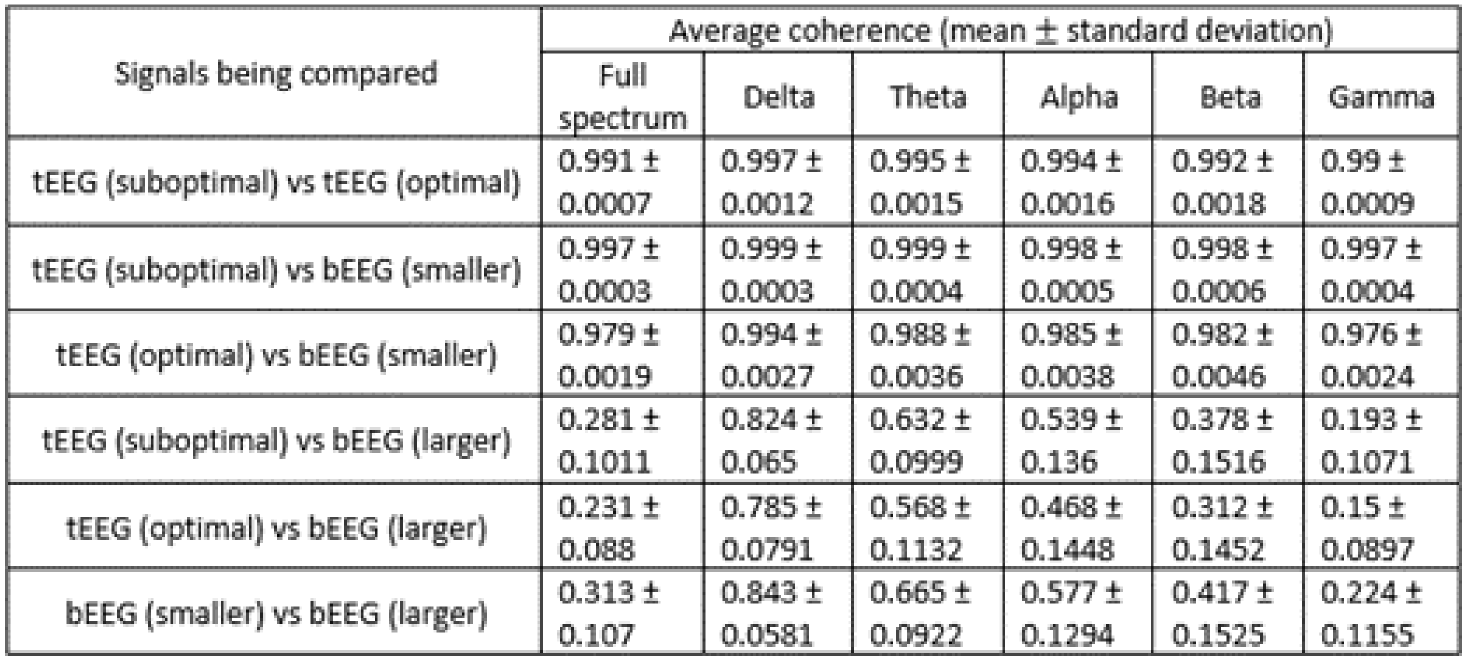


Signals being compared	Cross-correlation (mean ± standard deviation)	
	Maximum	Zero lag
tEEG (suboptimal) vs tEEG(optimal)	0.997 ± 0.0008	0.997 ± 0.0008
tEEG (suboptimal) vs bEEG (smaller)	0.999 ± 0.0003	0.999 ± 0.0003
tEEG (optimal) vs bEEG (smaller)	0.992 ± 0.0019	0.992 ± 0.0019
tEEG (suboptimal) vs 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 1. Two signal synchrony measures [illegible] on) calculated to compare six pairs of Laplacian estimate signals.

Results on EEG data (cont.)

- The average coherence across the full spectrum as well as for individual frequency bands are presented in Table 2.



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

TABLE 2. Average cohere [illegible] pairs of Laplacian estimate signals.

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FEM results

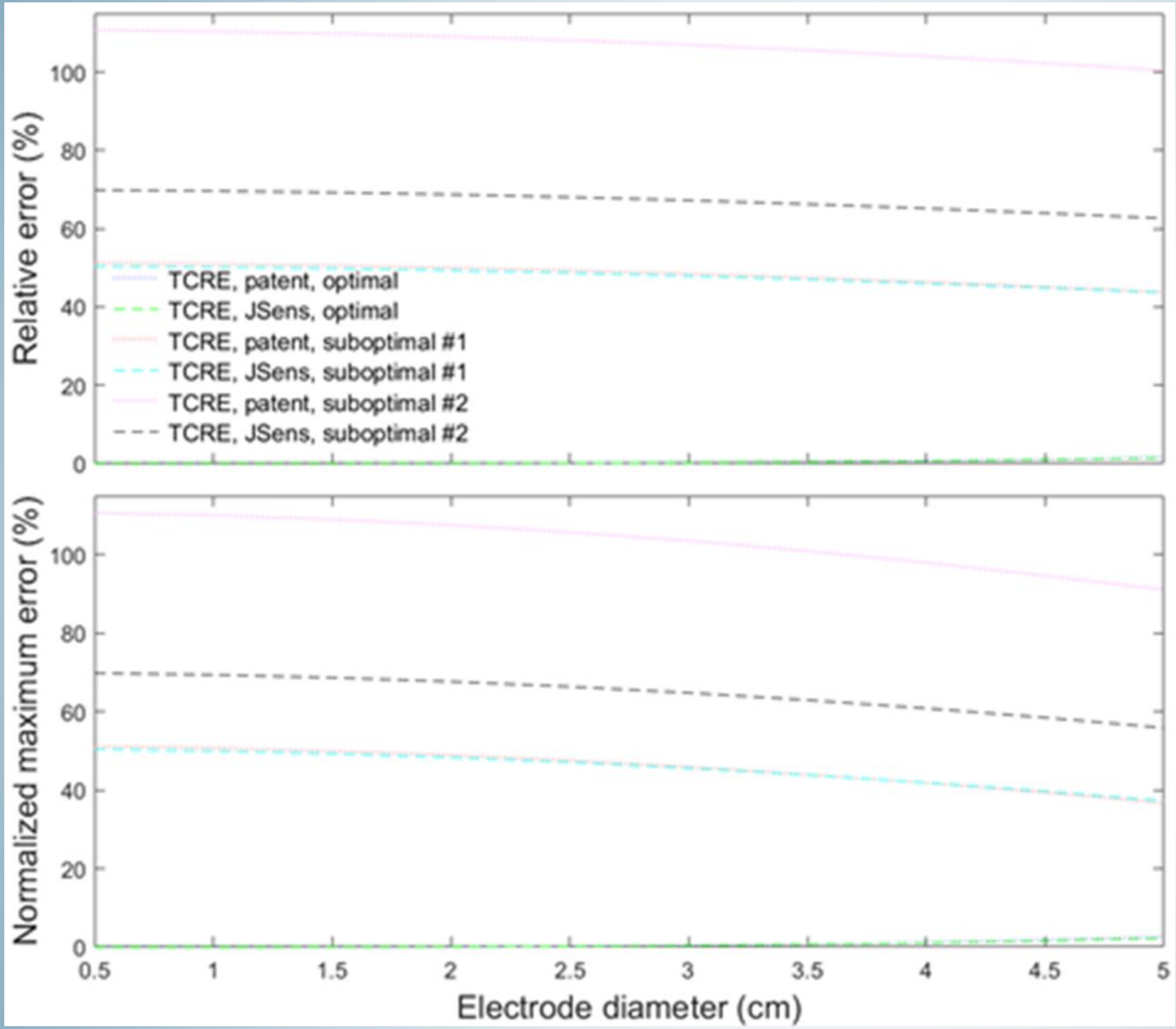
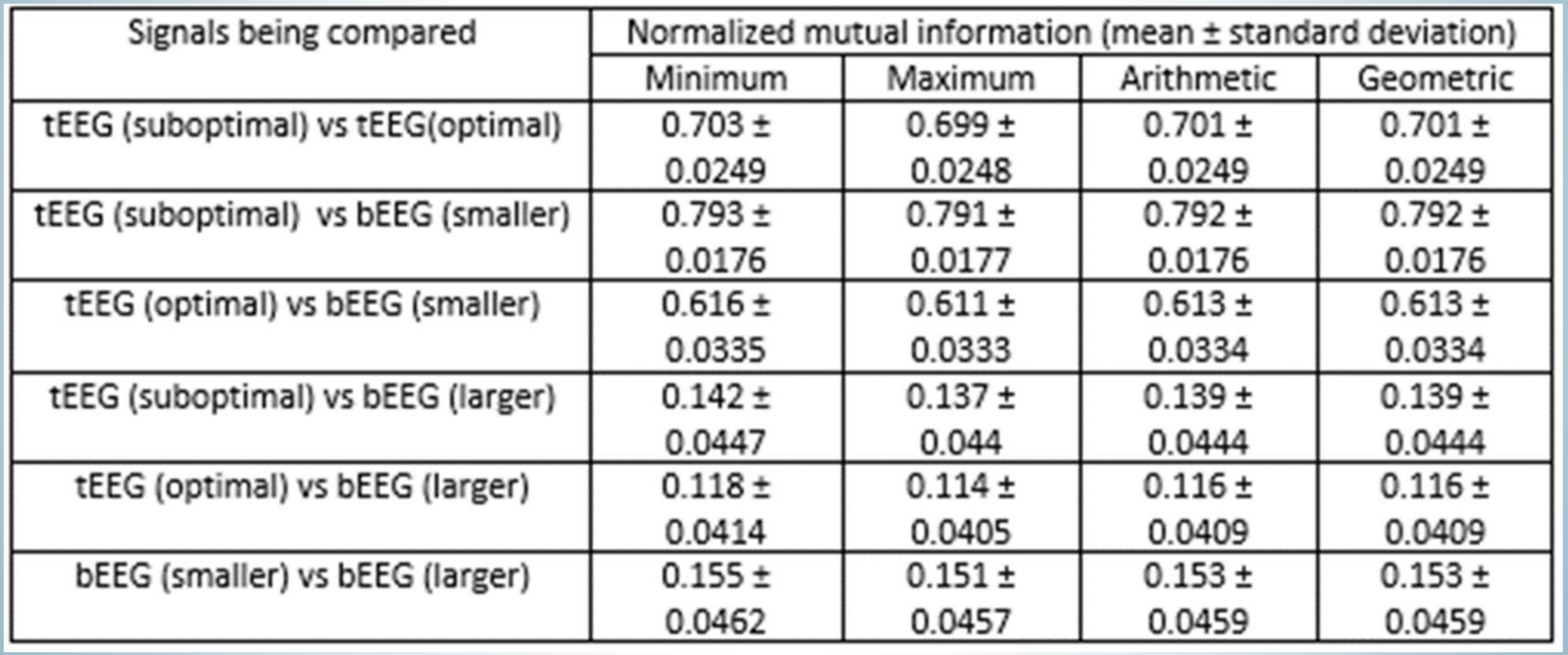


Figure 7. Relative (top panel) and normalized maximum (bottom panel) errors of surface Laplacian estimation corresponding to two tripolar concentric ring electrode configurations approximating t-Lead dimensions with three sets of coefficients for each including the optimal and two suboptimal ones respectively.

[1] Benally A. et al., ERN (2024)

Results on EEG data (cont.)

- The NMI values for all six pairs of signals to compare the four different normalized approaches are presented in Table 3.



Signals being compared	Normalized mutual information (mean ± standard deviation)			
	Minimum	Maximum	Arithmetic	Geometric
tEEG (suboptimal) vs tEEG(optimal)	0.703 ± 0.0249	0.699 ± 0.0248	0.701 ± 0.0249	0.701 ± 0.0249
tEEG (suboptimal) vs bEEG (smaller)	0.793 ± 0.0176	0.791 ± 0.0177	0.792 ± 0.0176	0.792 ± 0.0176
tEEG (optimal) vs bEEG (smaller)	0.616 ± 0.0335	0.611 ± 0.0333	0.613 ± 0.0334	0.613 ± 0.0334
tEEG (suboptimal) vs bEEG (larger)	0.142 ± 0.0447	0.137 ± 0.044	0.139 ± 0.0444	0.139 ± 0.0444
tEEG (optimal) vs bEEG (larger)	0.118 ± 0.0414	0.114 ± 0.0405	0.116 ± 0.0409	0.116 ± 0.0409
bEEG (smaller) vs bEEG (larger)	0.155 ± 0.0462	0.151 ± 0.0457	0.153 ± 0.0459	0.153 ± 0.0459

TABLE 3.Six pairwise comparisons using four different approaches of normalized mutual information (minimum, maximum, arithmetic and geometric).

Discussion of EEG results

- Very high signal synchrony between tripolar Laplacian estimates for compared signals tEEG (suboptimal vs. optimal) in Tables 1 and 2 initially indicated that the differences due to different coefficients may not be significant.
- Lower cross-correlation and average coherence values for larger bipolar Laplacian estimate (rows 4-6) in Tables 1 and 2 are consistent with prior results on Laplacian estimation accuracy.
- Larger bipolar estimate corresponding to the lowest Laplacian estimation accuracy is likely the reason why it corresponds to lower synchrony with other, higher accuracy Laplacian estimates.
- High cross-correlation (0.7-0.9) between bipolar Laplacian estimate for compared signals bEEG (smaller vs. larger) suggests some differences in sensed activity due to the larger distance from the central disc.

Discussion of FEM and NMI results

- Obtained preliminary FEM modeling results (Fig. 4) indicate median ratio of relative errors corresponding to suboptimal over optimal coefficients for two approximating t-Lead electrodes to range between 479 and 644 times.
- Respective ratio of normalized maximum errors ranges from 278 to 375 times.
- The final FEM results were published in the ISBI paper bringing ratios down somewhat.
- The NMI results suggest that the optimal versus suboptimal tEEG coefficients produced very different signals, indicating that t-Lead users are experiencing suboptimal signal quality.
- The NMI of 0.7 between optimal and suboptimal tEEG implies they share limited information, whereas NMI 0.79 between suboptimal tEEG and smaller bEEG indicates greater shared information.
- NMI results are consistent across four normalization methods for all six signal comparisons, supporting the robustness of the findings.

Conclusions

- The ISBI NMI results confirm the FEM findings with human data, indicating that the difference between optimal and suboptimal coefficients leads to significantly different tEEG signals, suggesting that current t-Lead users may be potentially experiencing suboptimal signal quality.
- The use of suboptimal coefficients in the Laplacian estimation of the Laplacian potential worsens the estimation accuracy and significantly impacts the information involving real life data like human EEG.
- Thanks to this study, companies (like CREmedical) that produce preamplifiers (like t-Interface) may see the benefit to modify their devices using the optimal Laplacian estimation coefficients like (6,-1) in case of t-Lead.

Conclusions cont.

- Future work
  - My master's thesis is nearing completion; however, there are still some results that have yet to be presented. Later this month, I will be presenting findings involving intra- and inter-subject variability at the Tribal Research Symposium in Alexandria, VA, marking my fourth visit there.
  - Additionally, my research will continue through collaboration with Sheldon Chee, who will be applying the same methods to a different research project revolving around emulation using the same human data that Dr. Boudria collected [1].
  - While I am passionate about pursing a career as a clinical laboratory scientist, I am also considering applying for a faculty position here at Diné College. I am currently undecided about my pathway but I do know that I need to explore each direction and will determine which best aligns with my long term goals. Regardless of my decision, I am committed to continuing my professional development and providing meaningful contributions to my community and my people.

[1] Chee, S. et al., IEEE ISBI (2025)

Thank you!

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Comments and Questions?