Linear and nonlinear signal synchrony measures to assess salt bridge shorting and conventional disc electrode emulation via tripolar concentric ring electrode on human electroencephalogram data

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INTRODUCTION: CREs/t-Leads

- Concentric ring electrodes (CREs) are noninvasive sensors designed to progress electrophysiological measurements by directly approximating the surface Laplacian (second spatial derivative of potential). By its design of having a central disc with one or more concentric rings, CREs provide better spatial resolution and less noise, compared to conventional disc electrodes (CDEs, Figure 1B).
- Tripolar concentric ring electrodes (TCREs, Figure 1A) are CRE configurations, comprising of three concentric conductive elements: a center disc, a middle ring, and an outer ring.
- A specific commercial implementation of TCRE sensors, called t-Leads (CREmedical, Kingston, RI), are utilized for specialized high-fidelity recordings, functioning to cancel out distant noise and to focus on localized activity (e.g. cortical).
- *In summary, t-Leads apply TCRE technology to provide a high-resolution, low-noise alternative to CDE, acting as a highly focused "spatial filter."*

Figure 1. Laboratory sensor equipment includes tripolar concentric ring electrode (A) and conventional disc electrode (B).

INTRODUCTION: eEEG

- In electrophysiology, the emulation of CDE (called eEEG) via TCRE is a biomedical engineering technique simulating the performance of traditional CDEs to obtain both high-spatial-resolution, Laplacian signals and traditional potentials simultaneously from the exact same location. Essentially, eEEG with TCREs is approximating CDEs with another electrode, or in this case with a recording surface of the outer ring a TCRE, or eEEG.
- It uses signal processing techniques to approximate the performance of physical concentric rings by combining signals from a central disc and one or more rings to calculate the surface Laplacian, rather than measuring surface potential like CDEs. Its simultaneous recordings are advantageous in that eEEG allows for comparing measurements without needing two separate recording systems.
- Presently, eEEG is currently used widely in numerous recent t-Lead-based studies, ranging from sleep monitoring to brain computer interface.

INTRODUCTION: Salt bridge shorting

- In galvanic/electrochemical cells, a salt bridge maintains electrical neutrality while separating two half-cells, thereby facilitating ionic flow without liquid mixing. Shorting occurs when this separation fails, allowing direct ionic communication.
- With electrophysiology, salt bridge shorting occurs when a conductive path unintentionally connects two separate electrolyte solutions. This interrupts potential measurements by creating a direct pathway.
- With TCREs, salt bridge shorting refers to unintended electric conduction between concentric rings due to conductive electrolyte bridging via electrode gels/paste or bodily fluids. This creates a low-resistance path between concentric rings and masking true potential differences. This results in identical signals from different recording surfaces, hence compromising Laplacian signal estimation accuracy.

INTRODUCTION: Goals of First-Author Papers

- Chapter 2: In the first paper, signal synchrony between emulated CDE values versus outer ring of TCREs values are analyzed using normalized mutual information (NMI) to demonstrate that emulation of CDE with outer ring of TCRE (eEEG) is not as effective as previously believed.
- Chapter 3: In the second paper, the middle ring and central disc of TCREs are assessed as better emulations of CDE by finding their cross-correlation, coherence, and NMI values, in hopes of being an alternative option to Paper #1.
- Chapter 4: In the third paper, we use prior data from Papers #1 and #2 as a baseline to examine the possibility of salt bridge shorting between recording surfaces of t-Lead TCREs.

CHAPTER TWO: METHODOLOGY

- In applied statistics and linear signal processing, there are two fundamental, complementary analyses, called time-domain synchrony (cross-correlation) and frequency-domain synchrony (coherence), that are used to interpret data.
- Time-domain analysis focuses on how signals evolve with time and phase alignment, while frequency-domain analysis assesses strength of association at specific spectral components by decomposing signals into constituent sinusoidal components to evaluate synchrony.
- Since time-domain (cross-correlation) analysis measures synchrony between two signals as a function of time displacement (lag) and frequency-domain (coherence) analysis measures the extent to which one signal is related to another at specific frequencies, both scaled to 0 to 1 range.
- Limitation of **linear synchrony**: By assuming that relationships between signals is proportional, linear synchrony measures can miss more complex (nonlinear) dependencies.

CHAPTER TWO: METHODOLOGY

- While linear synchrony focuses on proportional relationships via cross-correlation and coherence, **nonlinear synchrony** measures similarity between signals via dependencies between complex systems.
- With nonlinear synchrony, mutual information is a measure from Information Theory on how much information two signals share, indicating how much knowing one variable reduces uncertainty about the other based on Shannon entropy, which can grow indefinitely. So, normalization of mutual information, or NMI, would bind this dependency from a 0 (totally independent) to 1 (highly dependent) range – becoming scaled to be comparable to linear synchrony measures.
- The premise of this chapter, is to answer a fundamental question: Can the outer ring of TCRE (eEEG) and shorted TCRE truly replicate CDE signals, not just linearly but in a fully informational context using NMI?

CHAPTER TWO: METHODOLOGY

- Methodology focuses on both phantom model and human EEG datasets to compare signals between outer ring of TCRE (eEEG) only, shorted TCRE (or combined surfaces of outer ring, middle ring, and central disc), and the standard CDE in this first paper.
- Phantom model data: The three said electrodes were tested and covered in conductive paste. The physical arrangement include placing TCRE (eEEG) and shorted TCRE on a copper plate (cathode), and positioning both 2-mm away from a centrally-placed, small circular copper disc (anode) as vertices of equilateral triangle.
- Human EEG data: Participants include 6 healthy subjects (ages 24-40, one female) sitting motionless to reduce movement artifacts. Set up includes placing said electrodes on 10-20 EEG system, focusing on P4 (parietal) region with right mastoid as reference.

CHAPTER TWO: RESULTS

- When comparing signals between the outer ring of a TCRE versus CDE and between the TCRE with shorted recording surfaces versus CDE using different normalization approaches (geometric, arithmetic, maximum, and minimum), the obtained values for NMI measure on **phantom model data** are presented in Table 1.

Signals being compared	Normalized mutual information (mean ± standard deviation)			
	geometric	arithmetic	maximum	minimum
Outer ring versus disc electrode	0.679 ± 0.0348	0.679 ± 0.0348	0.675 ± 0.0355	0.683 ± 0.0341
Shorted TCRE versus disc electrode	0.634 ± 0.0268	0.634 ± 0.0268	0.629 ± 0.0279	0.64 ± 0.0257

Table 1. Signal comparison using NMI with four different normalization approaches on phantom model data.

CHAPTER TWO: RESULTS

- When comparing signal synchrony measures between the outer ring of a TCRE versus CDE using the different normalization approaches of geometric, arithmetic, maximum, and minimum, the obtained values for NMI measure on **human EEG data** are presented in Table 2.

Signals being compared	Normalized mutual information (mean ± standard deviation)			
	geometric	arithmetic	maximum	minimum
Outer ring versus disc electrode	0.652 ± 0.0742	0.652 ± 0.0743	0.649 ± 0.0752	0.654 ± 0.0733

Table 2. Signal comparison using NMI with four different normalization approaches on human EEG data.

CHAPTER TWO: DISCUSSION

- By integrating nonlinear NMI measures, results from phantom model data show that outer ring of TCRE (eEEG) is less similar to CDEs than previously thought, based on linear synchrony measures of cross-correlation and coherence from prior research.
- Despite eEEG outperforming shorted TCRE, this paper implies the mean NMI values from the outer ring of TCRE may not be as effective as an emulation of CDE as previously suggested.
- This leads for future work to focus on exploring alternative TCRE methods as options, specifically middle ring and central disc, in comparing their performance as CDE emulators against the aforementioned results of the outer ring of TCREs.
- This paper was presented at the 2025 IEEE International Symposium on Biomedical Imaging in Houston, Texas.

CHAPTER THREE: METHODOLOGY

- Methodology revisits only the human EEG dataset from Chapter 2, comparing signal pairs between middle ring versus CDE and between central disc versus CDE. The middle ring and central disc signals were not collected originally in phantom model dataset therefore it is not assessed in this second paper.
- Additionally, this methodology acknowledges that direct recordings for signal comparisons between middle ring versus CDE and between central disc versus CDE were not monitored in human EEG dataset, setting the premise of the paper by highlighting the indirect algebraic calculations implemented for differentiating between idyllic, theoretical measures of brain activity (i.e. signal) and actual measurements from recording system (i.e. channel).

CHAPTER THREE: METHODOLOGY

- When distinguishing between signals and channels, it is important to remember the components of TCRE design. For outer ring, middle ring, and central disc, each component has its own true signal, denoted as x^{OR}, x^{MR}, and x^{CD}, respectively. This dataset includes three channels (X, Y, and Z) among others.
- A signal indicates true activity in the brain at specific electrode surfaces – what is being measured. A channel refers to the recorded combinations of signals – what is actually recorded.
- When considering x^{OR} as a pure signal, the key idea is to reconstruct missing signals mathematically, using three channels (Equations 1-3), for central disc (x^{CD}, Equation 4) and middle ring (x^{MR}, Equation 5) as they were not directly measured. All resulting signals were scaled to zero mean and unit standard deviation, for consistency and direct comparability with each other.

$$X = x^{OR} \quad (1)$$

$$Y = x^{MR} - x^{CD} \quad (2)$$

$$Z = x^{OR} - x^{CD} \quad (3)$$

$$x^{CD} = X - Z = x^{OR} - (x^{OR} - x^{CD}) \quad (4)$$

$$x^{MR} = Y + (X - Z) =$$
$$= x^{MR} - x^{CD} + [x^{OR} - (x^{OR} - x^{CD})] \quad (5)$$

CHAPTER THREE: RESULTS

- In both signal comparison pairs between middle ring versus CDE and between central disc versus CDE, the obtained values for cross-correlation assessing for potential time delays include comparing signals between zero lag and maximum (or optimal lag) on human EEG data, and are presented in Table 3.

Cross-Correlation	**Signal Comparison Pairs (mean ± standard deviation)**	
	Middle ring versus conventional disc electrode	***Central disc versus conventional disc electrode***
Zero lag	0.984 ± 0.012	0.986 ± 0.01
Maximum	0.984 ± 0.012	0.986 ± 0.01

Table 3. Signal comparison using cross-correlation with zero and optimal lag on human EEG data.

CHAPTER THREE: RESULTS

- In both signal comparison pairs between middle ring versus CDE and between central disc versus CDE, the obtained values for coherence assessing frequency content (i.e. rhythm or speed of signal) compare signals using different spectral frequency bands (full spectrum, delta, theta, alpha, beta, and gamma) on human EEG data, and are presented in Table 4.

Coherence	**Signal Comparison Pairs (mean ± standard deviation)**	
	Middle ring versus conventional disc electrode	***Central disc versus conventional disc electrode***
Full Spectrum	0.969 ± 0.0245	0.979 ± 0.0164
Delta	0.941 ± 0.0557	0.958 ± 0.0169
Theta	0.951 ± 0.0517	0.975 ± 0.0126
Alpha	0.977 ± 0.0127	0.984 ± 0.0113
Beta	0.976 ± 0.0206	0.985 ± 0.0124
Gamma	0.969 ± 0.0263	0.978 ± 0.0195

Table 4. Signal comparison using coherence with spectral frequency bands on human EEG data.

CHAPTER THREE: RESULTS

- In both signal comparison pairs between middle ring versus CDE and between central disc versus CDE, the obtained NMI values using different normalization approaches (geometric, arithmetic, maximum, and minimum) on human EEG data are presented in Table 5.

Normalized Mutual Information	**Signal Comparison Pairs (mean ± standard deviation)**	
	Middle ring versus conventional disc electrode	***Central disc versus conventional disc electrode***
Geometric	0.589 ± 0.0997	0.587 ± 0.0725
Arithmetic	0.589 ± 0.0997	0.587 ± 0.0725
Maximum	0.586 ± 0.1003	0.584 ± 0.0735
Minimum	0.592 ± 0.0992	0.59 ± 0.0714

Table 5. Signal comparison using normalized mutual information with different normalization approaches on human EEG data.

CHAPTER THREE: DISCUSSION

- While finding a suitable alternative for emulation of CDEs via outer ring of TCRE (eEEG), there were several key findings from the results:
  - With cross-correlation, this study resulted in signals closely matching overall, ensuing middle ring and central disc to being very similar to CDE. Additionally, there were no time lags between signals to be found, so there was no delay as all electrodes were receiving brain activity at the same time.
  - With coherence, albeit there is consistency across all frequency bands between middle ring- and central disc- versus CDE – suggesting similar electrode behavior across different types of signal activity – the slightly lower coherence values show less similarity in frequency content.
  - With NMI checking how much information two signals share, this study shows less similarity compared to ~0.65 NMI value (in Chapter 2). This means both middle ring and central disc share less information with CDE than the outer ring, making them not quite as equivalent and slightly worst at reproducing full informational content.

CHAPTER THREE: DISCUSSION

- From the resulting key findings, we are able to further our presumptions and specify our interpretations in this study:
  - There is an agreement of consistency with middle ring and central disc signals among the different analysis methods of cross-correlation, coherence, and NMI overall with Paper #1 and prior research – consistency with earlier research strengthens confidence in the findings of this paper.
  - However, albeit middle ring and central disc signals show consistency, they remain as slightly less accurate alternatives, compared to the current best option. They are close alternatives, but their small performance gaps can be meaningful.
- Interesting nuances: As a side note, the results show that central disc is a better option based on both linear synchronies (cross-correlation and coherence), while middle ring is the better option based on nonlinear synchrony – warranting future work for deeper understanding.

CHAPTER FOUR: RESULTS

- For signal comparisons between outer ring versus middle ring, middle ring versus central disc, and outer ring versus central disc, the obtained cross-correlation values, including compared signals between zero lag and maximum (or optimal lag), on human EEG data are shown in Table 6.

Cross-Correlation	**Signal Comparison Pairs (mean ± standard deviation)**		
	Outer ring versus middle ring	***Middle ring versus central disc***	***Outer ring versus central disc***
Zero lag	0.996 ± 0.0033	0.994 ± 0.0063	0.995 ± 0.0031
Maximum	0.996 ± 0.0033	0.994 ± 0.0063	0.995 ± 0.0031

Table 6. Three signal comparisons using cross-correlation with zero and optimal lag on human EEG data.

CHAPTER FOUR: RESULTS

- For signal comparsions between outer ring versus middle ring, middle ring versus central disc, and outer ring versus central disc, the obtained coherence values, including average spectral values for full spectrum delta, theta, alpha, beta, and gamma, on human EEG data are shown in Table 7.

Coherence	**Signal Comparison Pairs (mean ± standard deviation)**		
	Outer ring versus middle ring	***Middle ring versus central disc***	***Outer ring versus central disc***
Full Spectrum	0.991 ± 0.0072	0.992 ± 0.0098	0.995 ± 0.004
Delta	0.987 ± 0.013	0.974 ± 0.0296	0.987 ± 0.0031
Theta	0.986 ± 0.0122	0.981 ± 0.0293	0.992 ± 0.0035
Alpha	0.993 ± 0.0036	0.993 ± 0.0064	0.996 ± 0.0025
Beta	0.993 ± 0.0064	0.993 ± 0.0095	0.996 ± 0.0036
Gamma	0.991 ± 0.0079	0.993 ± 0.0089	0.995 ± 0.0046

Table 7. Three signal comparisons using coherence with spectral frequency bands on human EEG data.

CHAPTER FOUR: RESULTS

- For signal comparisons between outer ring versus middle ring, middle ring versus central disc, and outer ring versus central disc, the obtained NMI values, using geometric, arithmetic, maximum, and minimum normalization approaches, on human EEG are shown in Table 8.

Normalized Mutual Information	**Signal Comparison Pairs (mean ± standard deviation)**		
	Outer ring versus middle ring	***Middle ring versus central disc***	***Outer ring versus central disc***
Geometric	0.713 ± 0.0723	0.673 ± 0.0855	0.683 ± 0.0549
Arithmetic	0.713 ± 0.0723	0.673 ± 0.0855	0.683 ± 0.0549
Maximum	0.712 ± 0.0725	0.67 ± 0.0859	0.68 ± 0.055
Minimum	0.715 ± 0.0721	0.675 ± 0.0851	0.685 ± 0.055

Table 8. Three signal comparisons using normalized mutual information with normalization approaches on human EEG data.

CHAPTER FOUR: DISCUSSION

- Emulation of CDE (eEEG) via outer ring of TCRE is not directly related to this point of the thesis. Instead, the eEEG data gathered in Chapter 2 led to viable alternatives for Chapter 3. To strengthen the argument in Chapter 4, we are simply using these eEEG results as a baseline comparison for short bridge shorting in comparing signals from the same TCRE (e.g. outer ring versus middle ring, middle ring versus central disc, and outer ring versus central disc).
- Like Chapter 3, there are several key findings from the results in Chapter 4, and are as follows:
  - With cross-correlation, high similarities are seen between all three signal comparisons. For each signal comparison, there are no differences between maximum and zero lag, signifying no timing delay between the different components of the same TCRE.
  - With coherence, high similarities are seen between all three signal comparisons. The resulting consistency among frequency bands confirm absence of outliers.
  - With NMI, the similar values from all four approaches state confidence in low similarities, often interpreting as signal comparisons being related but meaningfully different.
- If salt bridge shorting were to occur, then signals would be identical by values being recorded as exactly 1. Because the signals are not perfectly identical, this paper shows no salt bridge shorting for this t-Lead electrode geometry on this dataset.

CONCLUSION

- In Chapter 2, this paper demonstrates that while the outer ring of TCRE may show similarity to CDEs, the nonlinear synchrony measure of NMI indicates it as a lesser effective emulation of CDE than previously thought. This suggests the need to assess other TCRE components for better emulation.
- In Chapter 3, when assessing for alternatives to emulated CDE via TCREs, this paper demonstrates that middle ring and central disc are promising options but not superior.
- In Chapter 4, the assessment of possible salt bridge shorting found that signal comparisons within the components of a TCRE (like t-Leads) have high but not perfect similarities, and thus are not identical. This proves both salt bridge shorting not occurring and each TCRE recording surface functioning as an independent recording electrode.

CONCLUSION

- With research, the future work based on this thesis initially suggests two routes, and they are:
  - Advancing this research with collecting larger datasets, both human and phantom (ballistic gelatin) datasets, and indigenizing current research.
  - Going beyond this research presently, I am involved in both optimizing CRE design and assessing Artificial Intelligence innovation potential with regard to CREs.
- Regarding my educational and career pathways, my thesis journey solidifies my endeavors in becoming an research professor at a TCU. I view my Master of Science in Biology as a milestone in finding a PhD program with interdisciplinary approaches in biology, chemistry, and mathematics. At a TCU, this approach will allow me to reach the abstract minds of indigenous STEM students by teaching the academic value of each discipline while acknowledging an indigenous perspective – valuing students' knowledge and value systems. Needless to say, I am prone to an accelerated pace, so an idyllic pathway would be teaching students and working towards my Ph.D. simultaneously.

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T’áá ííyisí axhéhee’ nitsáágo!

Thank you!

Questions?