시간간섭자극에서 전극 배치의 효과: 팬텀 모델 및 시뮬레이션 연구

타텟[1], 김현지[1], 김수혁[1], 전예진[1] 박은경[1*]

순천향대학교 의공학과[1]

Effects of electrode placement on temporal interference stimulation: phantom model and simulation study

Thar Htet Nyan[1], Hyunji Kim[1], Suhyeok Kim[1], Yejin Jeon[1], Eunkyoung Park[1*]
Department of Biomedical Engineering, Soonchunhyang University, Korea
*ek.park@sch.ac.kr

Abstract

Temporal Interference Stimulation (TIS) has recently emerged as a promising noninvasive neuromodulation technique that enables selective targeting of deep neural regions through the interference of high-frequency electric fields with small frequency offsets. Despite strong computational evidence of feasibility, experimental validation remains limited, particularly regarding the impact of electrode placement on spatial interference patterns. In this study, we present a systematic investigation of electrode configurations using both phantom experiments and finite-element simulations. A circular saline phantom was constructed and stimulated with two-pair (2000 Hz & 2010 Hz, 3.1 Vpp) and four-pair (1975–2025 Hz, 2975–3025 Hz) waveforms. Voltages were recorded across a dense probe grid and compared directly with COMSOL Multiphysics models under matched conditions. The results demonstrated strong qualitative agreement between phantom and simulation. Two-pair stimulation generated broad diagonal or cross-shaped envelopes depending on electrode orientation, while four-pair stimulation produced multi-lobed, rotationally symmetric interference fields. These findings confirm that electrode placement is the dominant determinant of TIS field distributions, exceeding frequency choice alone. This study establishes phantom–simulation validation as a robust framework for TIS analysis and underscores the importance of optimized electrode geometry for selective neuromodulation.

1. Background

Noninvasive neuromodulation has emerged as a transformative alternative to pharmacological and surgical interventions, offering therapeutic benefits with fewer systemic side effects and reduced risk of complications. Unlike invasive methods, which often require implanted electrodes or drug delivery devices, noninvasive approaches provide the opportunity for repeatable and adjustable treatments tailored to individual patients. Among these, Temporal Interference Stimulation (TIS) has gained significant attention due to its unique mechanism of generating a low-frequency modulation envelope at depth by overlapping two or more high-frequency carriers. This strategy allows targeting of deeper neural structures without directly stimulating superficial tissues at the carrier frequency, thereby improving selectivity [1, 2].

Despite promising computational work, the translation of TIS into experimental and clinical contexts remains limited. One of the critical challenges is the role of electrode placement, which governs the geometry, focality, and intensity of the interference fields. Small variations in placement can shift the region of maximum modulation or broaden the field distribution, potentially reducing the selectivity of stimulation. Most prior studies have relied heavily on finite-element simulations [3], but direct phantom validation of placement effects has been sparse. Establishing this correspondence between simulation and experiment is essential for moving TIS from theoretical feasibility toward robust preclinical and clinical applications [4].

2. Method

2.1 Experimental Setup

A circular phantom was constructed using a 95 mm PLA container filled with 0.9% NaCl solution (conductivity ≈ 1.7 S/m) to approximate tissue electrical properties. The phantom geometry was designed in Autodesk Inventor and 3D-printed in PLA. Rectangular stimulating electrodes (1 × 2 cm) were attached to the phantom surface. Stimulation was delivered in two modes: (i) two-pair configuration with 2000 Hz and 2010 Hz carriers (3.1 Vpp each), and (ii) four-pair configuration with carrier ranges of 1975–2025 Hz and 2975–3025 Hz. Voltages were recorded across 121 probe points arranged in an 11×11 grid (1.25 mm spacing) using a Keysight DSOX1204G oscilloscope. Recorded waveforms were processed to extract peak-to-peak amplitudes of the modulation envelope.

2.2 Simulation Setup

Equivalent electrode placements were modeled in COMSOL Multiphysics 6.3 using the same geometric and electrical parameters as the phantom. The stimulating electrodes (1 × 2 cm) were represented as boundary voltage sources on the phantom surface. The saline domain was assigned conductivity of 1.7 S/m, and sinusoidal voltage sources were applied at the electrodes. Envelope modulation amplitudes were calculated from the simulated electric potential fields and directly compared with phantom measurements for validation of spatial interference patterns.

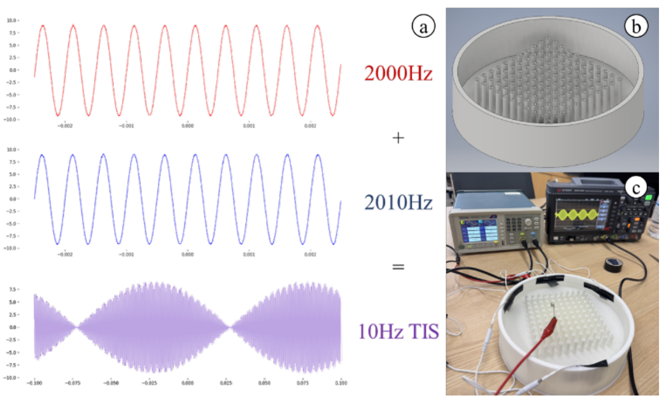

Fig. 1. (a) Principle of Temporal Interference Stimulation (TIS) using 2000 Hz and 2010 Hz carriers to generate a 10 Hz envelope. (b) 3D model of the circular phantom container (c) Experimental phantom setup

3. Result

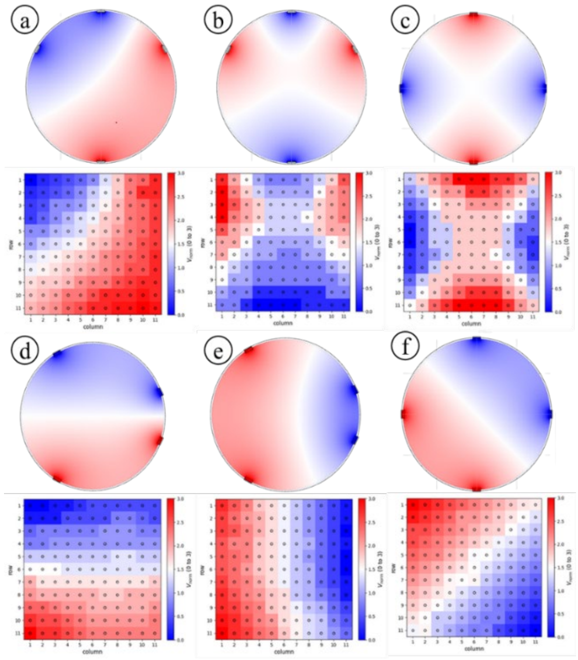

Fig. 2. Interference field distributions with two electrode pairs under different placements. For each case (a–f), COMSOL simulation (top) and experimental phantom measurement (bottom) are shown, demonstrating the influence of electrode orientation on the resulting envelope patterns.

Experimental phantom recordings exhibited strong qualitative agreement with simulation outputs, validating the reliability of finite-element modeling for predicting TIS field distributions. In the two-pair configuration, envelope patterns were highly sensitive to electrode orientation. When electrodes were aligned diagonally, broad gradient fields extended across the phantom, whereas orthogonal placement generated distinct cross-shaped patterns with a more centralized envelope region. These results demonstrate that small changes in electrode positioning can substantially alter the spatial profile of the interference field.

In contrast, the four-pair configuration produced more complex spatial patterns characterized by multiple lobes with partial rotational symmetry. This arrangement provided a wider distribution of interference maxima, suggesting potential for covering larger stimulation regions. However, the increased spatial complexity also reduced focal precision compared to the two-pair setup, indicating a trade-off between selectivity and coverage. Importantly, both phantom measurements and COMSOL simulations consistently reproduced these distinct features, highlighting the predictive power of computational models and confirming the experimental validity of electrode placement effects.

Across all tested placements, electrode geometry was identified as the primary determinant of interference envelope shape and intensity, outweighing the influence of carrier frequency selection. This reinforces the importance of optimized electrode configuration when designing TIS systems for neuromodulation.

4. Discussion

This study systematically evaluated electrode placement effects in Temporal Interference Stimulation by combining phantom experiments with finite-element simulations. Both approaches revealed that electrode geometry is the dominant determinant of interference field distributions, outweighing carrier frequency choice. Two-pair configurations produced more focal and predictable envelopes, whereas four-pair configurations generated broader multi-lobed fields, offering greater coverage but reduced spatial selectivity.

A key limitation of this work is the use of a homogeneous saline phantom, which does not capture the layered conductivity and anisotropy of biological tissues. In addition, only a limited range of electrode separations and orientations was tested. Future studies should expand to anatomically realistic head or pelvic models, incorporate anisotropic tissue conductivities, and explore adaptive electrode arrays for dynamic targeting. Integration with neuronal activation models will also be critical for translating envelope field patterns into predictions of neural response.

In conclusion, phantom–simulation correspondence establishes a robust framework for validating TIS field predictions. Optimized electrode geometry remains the central factor for selective neuromodulation, and multi-pair electrode strategies hold promise for enhancing adaptability in clinical applications.

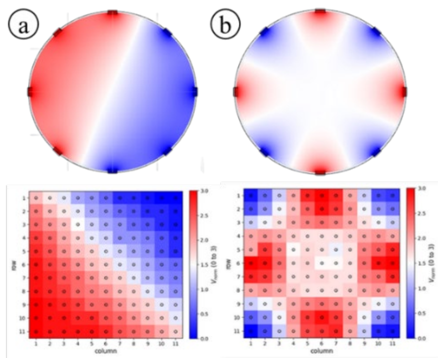

Fig. 3. Interference field patterns with four electrode pairs. (a) COMSOL simulation (top) and experimental phantom measurement (bottom) for diagonal orientation. (b) COMSOL simulation (top) and experimental phantom measurement (bottom) for cross-shaped orientation.

5. Acknowledgement

This work was supported by grants from the National Research Foundation of Korea (NRF), funded by the Korean government (Ministry of Science and ICT, MSIT) (RS-2022-NR070502 and RS-2023-00220534), and from the Korea Health Technology R&D Project through the Korea Health Industry Development Institute (KHIDI), funded by the Ministry of Health and Welfare, Republic of Korea (RS-2025-02273012).

6.Reference

[1] N. Grossman, D. Bono, N. Dedic, S. B. Kodandaramaiah, A. Rudenko, H. Suk, A. M. Cassará, E. Neufeld, L. Kuster, T. Tsai, et al., “Noninvasive deep brain stimulation via temporally interfering electric fields,” Cell, vol. 169, no. 6, pp. 1029–1041, 2017.

[2] E. Mirzakhalili, B. Barra, M. Capogrosso, and S. F. Lempka, “Biophysics of temporal interference stimulation,” Cell Systems, vol. 11, no. 6, pp. 557–572, 2020.

[3] I. R. Violante, K. Alania, A. M. Cassarà, E. Neufeld, J. Grossman, G. A. Mashour, et al., “Non-invasive temporal interference electrical stimulation of the human hippocampus,” Nature Neuroscience, vol. 26, pp. 1101–1112, 2023.

[4] J. Lee, E. Park, W. Kang, Y. Kim, and K. S. Lee, “An efficient noninvasive neuromodulation modality for overactive bladder using time interfering current method,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 28, no. 11, pp. 2410–2418, 2020.