Unleash the Power Within: Finite Element Modelling of Temporal Interference Stimulation of the Phrenic Nerves

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Intoduction

Mechanical ventilation in the ICU can lead to complications, including ventilator-induced diaphragmatic dysfunction (VIDD), which can result in prolonged hospital stays and increased costs. This project introduces an innovative approach using multiple esophageal electrodes for phrenic nerve stimulation (PNS) to address VIDD. Finite element modeling enhances our comprehension and optimization of stimulation techniques. Esophageal electrodes offer selective stimulation advantages, and Temporal interference stimulation (TIS) shows potential in overcoming conventional limitations. This study evaluates efficient PNS for diaphragm activation while minimizing concurrent stimulation. A comprehensive finite element model, developed with COMSOL Multiphysics®, systematically varies critical parameters to identify the optimal configuration and improve our understanding of TIS electrical field distribution. Simulation results inform effective stimulation protocol design.

Methods

- Electrode Approaches: We explored three electrode placement methods: internal (esophageal), external (transcutaneous cervical), and mixed (esophageal and transcutaneous dipole).
- Simulation Tool: COMSOL Multiphysics® with the AC/DC Module was used to evaluate the impact of these methods on stimulation outcomes.
- Interference Control: Precise interference site control was achieved through current amplitude ratios and electrode positioning.
- Analysis Factors: Factors like stimulation frequency, waveform, and electrode design in this complex system were thoroughly examined.
- Approach Details:
  - *External*: Dipole electrodes were placed on the skin around the neck (see Figure 1).
  - *Internal*: Esophageal placement was done using a custom catheter.
  - *Mixed*: A combination of external and internal placements was employed.
- Electrode-Skin Interface: The skin was modeled as a multi-layer structure with specific electrical properties.
- Parametric Sweep: A time-dependent study with a parametric sweep was conducted, and MATLAB® was used for post-processing.

Results

- Crucial Role of Electrode Placement: The study's results underscore the critical importance of precise electrode placement in steering the external envelope locus during Temporal Interference Stimulation (TIS).
- Envelope Locus Definition: The envelope locus, generated in post-processing, represents the maximum stimulation depth achieved for each parameter setting.
- Impact of Electrode Locations: Variations in electrode locations were found to have a significant impact on control capabilities during TIS. This highlights the potential for fine-tuning stimulation outcomes through precise electrode positioning.
- Effect of Electrode Size: Interestingly, variations in electrode size were observed to have minimal effect on stimulation outcomes, indicating that electrode size may be less critical than placement.
- Non-Invasive Control Potential: The study introduces the exciting potential of controlling the envelope locus without the need to physically relocate electrodes, offering non-invasive control possibilities.
- Optimization for Precision: By optimizing stimulation amplitudes, it becomes possible to activate smaller and more targeted regions, thereby enhancing precision in deep neural stimulation. This outcome holds promise for future applications in neural therapies and interventions.

Discussion and Conculusion

- Electrode Positioning Significance: The study reinforces the importance of precise electrode positioning in controlling the external envelope locus during TIS.
- Model Limitations: It's vital to acknowledge that the current model is simplified and lacks real-world complexity.
- Future Improvements: Future research should focus on enhancing the model's realism by incorporating more anatomical structures and electrical properties, as well as validating results through in vitro and in vivo methods.
- Clinical Considerations: The study highlights the need to account for patient-specific variations to improve the effectiveness and safety of TIS in clinical applications.

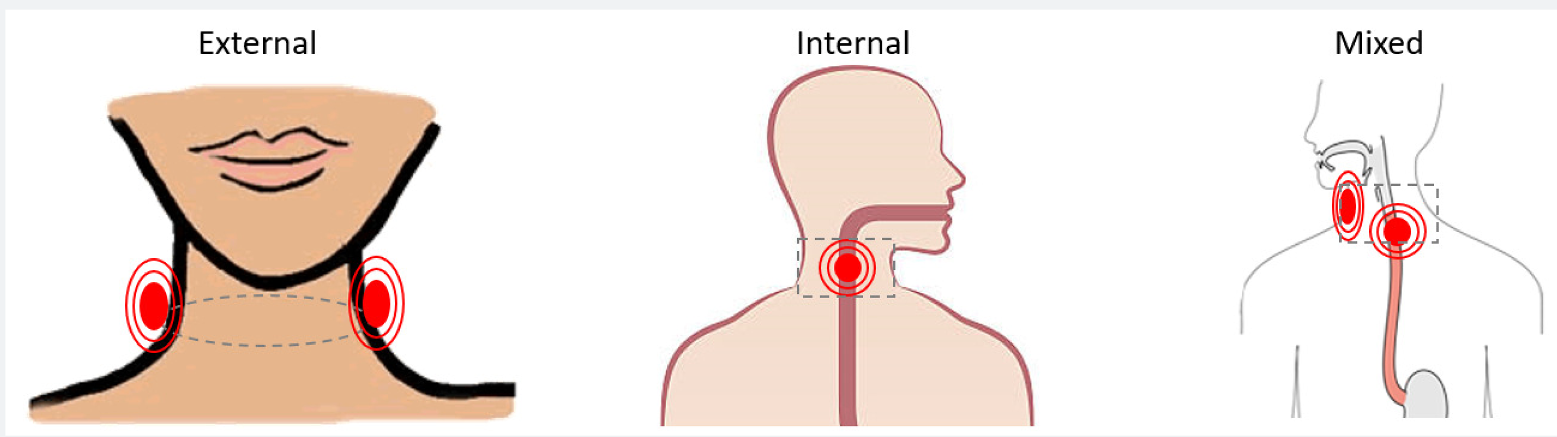

Abbildung 1: Three TIS application forms

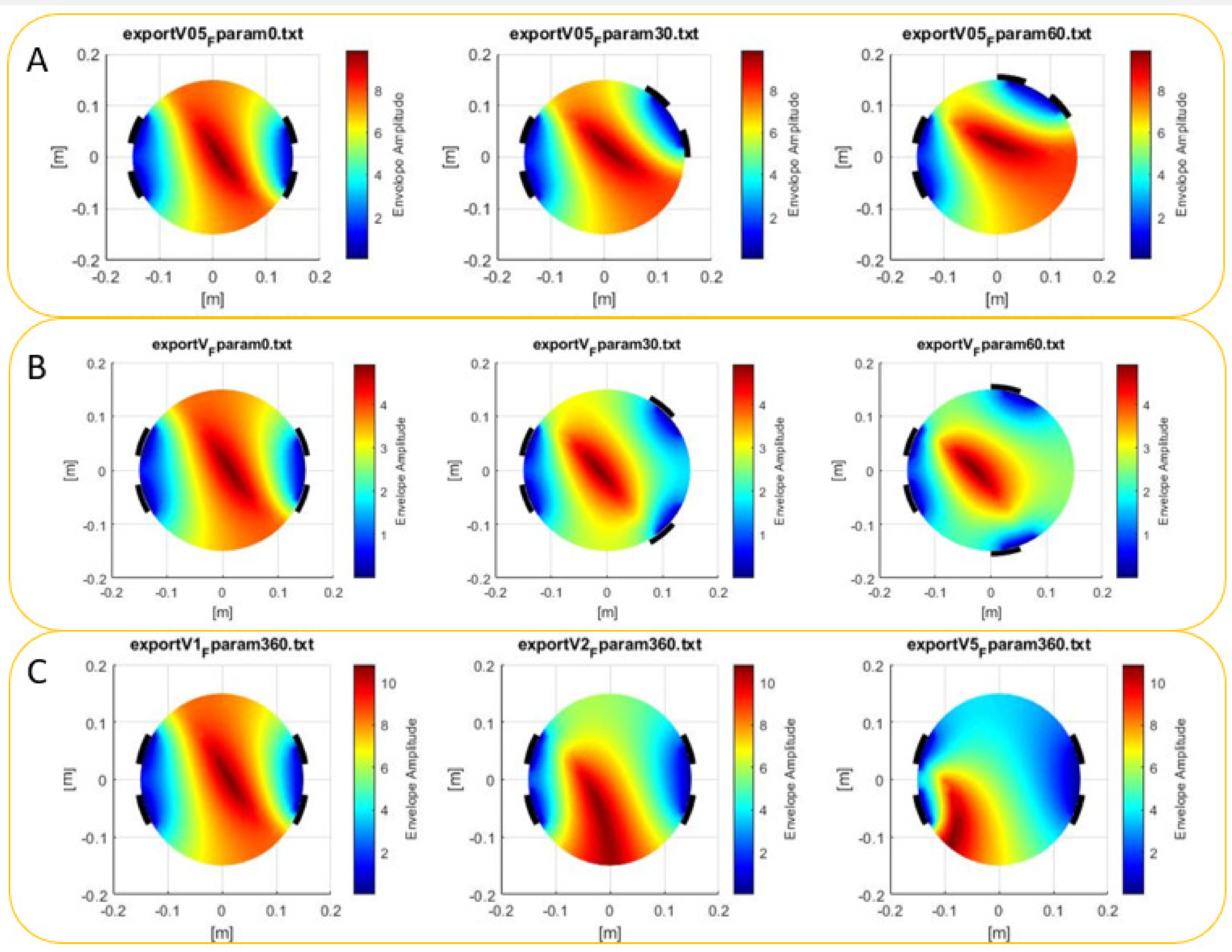

Abbildung 2: Influences of electrode parameters of the right dipole during external approach: A) Rotation, B) Increase of inter-electrode angle, C) Amplitude increase of the right dipole.

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