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Improving Precision of Computational Electromagnetics for Transcranial Stimulation

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Abstract— Transcranial current stimulation (tCS) is an emerging non-invasive electrical brain stimulation technique that is currently undergoing extensive investigation and clinical trials to improve the diagnosis and treatment of neurological disorders. Prior to implementing any intervention, physicists rely on numerical simulations to accurately target the brain region involved with the specific disease. Improving targeting is therefore a matter of importance that extensively relies on numerical modeling. The impact of tCS also benefits from numerical methods, using neuronal activity modeling to predict the effect and understand the interaction with the *in situ* electric field. This work addresses the current methods used as well as new emerging methods.

Keywords—Electrical brain stimulation, non-invasive brain modulation, quasi-static approximation, electrical properties variability.

I. INTRODUCTION

Transcranial current stimulation (tCS), sometimes referred to as transcranial electrical stimulation, is a powerful non-invasive brain stimulation (NIBS) technique that involves the application of electrical current through two or more electrodes to induce a stimulating Electric field (EF) in targeted brain regions. The current can be either direct (tDCS) or alternating (tACS), which are supposedly involving different mechanisms [1]. The advantages of tCS include its cost and portability, especially compared to other NIBS such as transcranial magnetic stimulation (TMS). In addition, tCS has demonstrated a wide range of possible applications in improving cognitive function, both in healthy subjects [2] and in patients suffering from neurological disorders such as Parkinson's disease [3], stroke [4], and depression [5]. Consequently, tCS holds significant promise as a therapeutic tool, but significant challenges remain in terms of deepening our understanding of underlying mechanism and improving focality to stimulate only targeted brain region(s).

To investigate tCS mechanisms, extensive work has been previously done to hypothesize how tCS could have an effect at the single neuron level [1], [6]. It can be studied *in vivo* [7] or *in silico* with a computational model of neurons to understand which parameter is discriminant in tCS effects which could provide insights into optimal stimulation parameters to modulate specific neurons and oscillations.

Improving tCS focality has been done by designing smaller electrodes and increasing the number of stimulating electrodes [8]. However, the associated optimization process relies on the use of numerical methods to predict the induced EF. This prior knowledge needs to be precise and general to be applicable.

Therefore, the present contribution aims to overview the numerical aspects of tCS, and more generally electromagnetic brain stimulation, and to discuss about possible new techniques using higher frequencies.

II. NEURONAL MODELING

To predict the impact of EF on neurons, one can simulate fully reconstructed neurons with a driving force and examine their entrainment relative to the stimulation waveform. This approach was used to study the effect of 10-Hz tACS in [9] using multiple neuron types to study which neurons are the most responsive to this particular setup. However, it is important to consider the whole electroencephalography (EEG) spectrum, which spans from 0 to 100 Hz, since it reflects all the main neuronal frequency bands (e.g., alpha). Consequently, a broader range needs to be investigated with more diversity in considered inhibitory cells (only L4 basket cells considered previously), to study the frequency preference of cell groups for a better stimulation design and specificity.

III. ELECTRIC FIELD MODELING

Electric field modeling is an important part of tCS research, since it is a pre-requisite on the design of tCS protocols. Multiple software are used to design the stimulation protocol knowing the stimulation target. Reconstructed anatomy can be obtained with magnetic resonance imaging and tissue segmentation, to attribute the associated electrical properties essential to EF calculations. However, only conductivity is currently considered since low frequencies are typically considered for stimulation (typically within the extremely low-frequency range, < 300 Hz), and therefore relative permittivity is neglected, which could lead to errors in both magnitude and phase at these frequencies but also for higher frequencies now considered where the quasi-static approximation can lead to errors in EF calculations [10].

IV. HIGHER FREQUENCY POSSIBILITIES

Higher frequencies are being considered using interfering signals to either 1) target deeper regions inaccessible by conventional tCS using sinusoidal interfering currents, known as transcranial temporal interference stimulation (tTIS) [11], or 2) reduce off-target stimulation using short pulses distributed to result in a constant current at the target, known as intersectional short-pulse electrical stimulation [12]. This increase in stimulation frequency should be accompanied by appropriate EF modeling [10] but also requires investigating how these frequencies can interact with neurons. This has been partly addressed for tTIS with computational models showing that neuronal membrane can demodulate the amplitude of the lower-frequency signal [13]. However, even higher frequencies are under investigation, using radio frequency signals and antennae to deliver tTIS [14]. This technique could enable better targeting due to the wavelength reduction, which could be the size of the stimulation spot. However, extensive work on the feasibility of such

stimulation needs to be conducted with *in vivo* measurement as a validation step.

V. CONCLUSION

Transcranial current stimulation advances were accompanied by the utilization of numerical methods to predict the generated EF, but also to enhance our understanding of how its interaction with single neurons. However, those techniques can still be improved using novel waveforms and protocols, as well as deepening our insights on tCS-induced electric field interaction with neurons to design innovative waveforms.

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