Neural stimulation safety and energy efficiency: Waveform analysis and validation

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Abstract

Energy efficiency and safety are key issues to accurately stimulate neural tissues. A novel waveform has lately been proposed: the rising exponential waveform; nevertheless, no experimentation has been done using an active model of the membrane in order to validate these results. This paper proposes this analysis using several types of waveforms. The total power consumption, taking into consideration the electrode-tissues interface impedance and neural tissues properties, is presented as a function of the waveform type and pulse width. Finally, a method to identify proper pulse current reversal is proposed. The rising exponential waveform is validated to be the energy-optimal and safer type of waveform.

1. INTRODUCTION

In order to safely and accurately stimulate neural tissues, both nerve tissue properties and electrode-tissues interface (ETI) must be considered. Most implanted devices are powered by an inductive link or are battery powered which makes energy efficiency an important criterion for choosing a stimulation waveform. Jezernik and Morari determined an energy-optimal waveform, the rising exponential, for the activation of nerve fibres [1], and Lazziri et al [2] presented and validated an ETI model, but no comparisons is available with other waveforms than the square one, nor with dynamic model. On the other hand, guidelines for safe stimulation of neural tissues were presented by Merill et al [3] but no methods have been proposed to identify the exact stimulation parameters of current reversal. In this paper, a comparative study with other waveforms over a Hodgkin-Huxley (HH) model [4] is proposed. Also, a global model of the system that includes two ETIs and one nerve is used to visualize the power consumption of stimulation. Finally, the total amounts of net charges injected by the stimulation is verified in order to identify the safest type of waveform. In addition, we propose an extended analysis of the ETI model presented in [2] all together with additional considerations from electrochemical phenomena are reported [5].

2. METHODS

The validation of results from [1] will be performed with a dynamic model of the membrane to calculate the current threshold and energy dissipation of the stimulation. It is important to make distinction between the energy dissipated in tissues and the power consumption of the stimulator. Hence, to analyze the real power consumption of a single stimulation site with stimulator design in mind, one must consider the impedance of the global system including ETIs. Finally current reversal and safety consideration will be analyzed.

2.1 Waveform analysis

In order to simplify the analysis, only the stimulating phase of a single pulse is considered for the calculation of current threshold and the comparison between waveforms. Current reversal will be studied afterward. As reported in [1] the reference for analysis will be the rising exponential waveform since it is believed to be the optimal waveform for the stimulation of neural tissues. The square waveform, as in [1], will also be studied. As Fourier’s theory suggests, all functions can be expressed as a summation of sinusoidal functions. We will be studying sinusoid functions (half and quarter of a sinusoid cycle and a function containing the two first harmonics of the square waveform). In addition, a hyperbolic sinusoid function will be analyzed.

2.2 Threshold and energy in tissues

Energy was calculated using a standard relation; energy is the integral of the power.
The tissues membrane potential is used for the calculation of the energy as in [1]. Since we are studying subthreshold phenomena by trying to bring the membrane potential, using a standard HH model [4], from rest to threshold potential, liminal current will be calculated as a function of pulse width. Energy calculations will be expressed as a function of the pulse width (stimulation duration). However, the calculated energy in tissues cannot be considered as the electronic power consumption of the stimulation for a single pulse, see 2.3.

2.3 Total power consumption

Very often, energy dissipated in ETI is not considered for the calculation of the energy-optimal waveform for the stimulation of neural tissues. However, the power consumption as a function of the stimulation waveform can be calculated. Neural tissue impedance will be considered as in [2] and be $R_\infty$. Bipolar stimulation will be considered as well so that we can consider both ETIs to be of the same impedance. This real power consumption of stimulation is given by Eq. (2).

$$
E_{\text{stim}} = \int_{t_0}^{t_\text{rise}} \left[ 2v_{\text{ext}}(t) + v_{\text{stim}}(t) \right] i_{\text{ext}}(t) \, dt \quad (2)
$$

2.4 Safe stimulation and current reversal

In order to achieve a safe level of stimulation, one must limit the total charge injection needed to raise the membrane potential from rest to threshold; specifically, faradaic charge transfer must be limited [3]. Faradaic charge transfer, as opposed to capacitive charge transfer, occurs when electrons are released from the electrodes and reduction processes happen. By reducing these processes, safer stimulation can be achieved. Reduced product concentration variations can be calculated at the stimulation site by Eq. (1) as shown in [5].

$$
C_R(t) = \int_{-\infty}^{\infty} \frac{i_f(t-\tau)}{nFA\sqrt{D_R\pi\tau}} \, d\tau \quad (1)
$$

where n is the stoichiometric number of electrons involved in the reaction, $F$ is the faraday constant, $A$ the area, $D_R$ the diffusion coefficient of reduced products and if the faradaic current. ETI model can be use to evaluate faradaic current $i_f(t)$ of Eq. (1). The model used in this paper comes from [2]. The capacitive branch is represented by the double layer impedance and the faradaic branch is modeled by the charge transfer resistance and the Warburg impedance (mass transfer). ETI parameter values have been evaluated in [2] as functions of the stimulating current amplitude and will be used in this work; a nominal value of 10 µA is used.

Since all irreversible reactions cannot be avoided, the second phase of the stimulation pulse, known as current reversal, is used. This phase of the stimulation is important to 1) oxidize products that have been created by reduction while stimulating neural tissues and 2) bring the potential of the electrode back to its resting potential. In order to realize these processes, one must calculate the proper current reversal waveform. Eq. (1) should be used to bring the reduced product concentration back to zero after the stimulating phase so that ionic concentrations are back to their initial stage and the Nerst potential is the resting one. The optimal current reversal waveform can be calculated knowing that its properties imply that it recovers most of the reduction products in the minimum time without changing the threshold current.

3. RESULTS

3.1 Energy in tissues

Energy relations have been obtained for every waveform specified in section 2.1. Current thresholds as functions of pulse width were calculated using an HH model. Results are presented as ratios over rising exponential waveform in function of the pulse width (Figure 1).
Variations are due to the deviation of the ionic channel impedance, and peaks (saturations) can be assumed to be the effect of the rheobase current; therefore we can identify the presence of action potentials and membrane depolarization for large pulse width.

3.2 Total power consumption
Current thresholds were calculated as in Section 3.1. Total power consumption per pulse curves are presented in Figure 2 as ratios over rising exponential.

3.3 Reduced product concentration
Results presented are the reduced product concentration at the end of the stimulating phase in Figure 2. Each waveform as a function of the liminal stimulation duration (pulse width) is compared to exponential waveform results.

From Figure 3, we conclude that the rising exponential waveform is energy-optimal for the stimulating phase, but will also minimize the total energy needed for current reversal. Of important note is that slight variation in tissue properties results in significantly different optimal waveform. These parameters vary between stimulation sites and this adds to the complexity of the stimulator design and usage.

In conclusion, this paper confirms the assumption that the rising exponential is, in general, the most optimal and safest waveform among those that have been studied. The results presented in this paper regarding ETI were obtained with constant ETI parameters. However, Authors in [2] show that these parameters vary with the stimulation current amplitude. Rising exponential and hyperbolic sinusoid amplitude can quickly grow which means an increase in the ETI impedance and in energy dissipation. Extensive work should be done to consider these deviations.

References

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