

Varying the Time Delay of an Action Potential Elicited with a Neural-Electronic Stimulator

Robert B. Szlavik, Frank Jenkins

Center for Biomedical Engineering and Rehabilitation Science, Louisiana Tech University, USA

Abstract - There have been various theoretical and experimental studies presented in the literature that focus on interfacing neurons with discrete electronic devices such as transistors. It has also been demonstrated experimentally that neural-electronic devices can be used to elicit action potentials in a target neuron in close proximity to the neural-electronic stimulator. The time delay between stimulus and the onset of the neural action potential can be varied by varying the pulse amplitude and width generated by the neural-electronic stimulator (transistor).

Keywords – Neural-electronics, neural engineering

I. INTRODUCTION

It has been demonstrated experimentally by Weis and Fromherz, as well as Vassanelli and Fromherz, that a detectable signal can be conducted from a neuron *in vitro* to a silicon transistor [1] [2]. Nerve cell excitation using a semiconductor based electronic device has been demonstrated by Fromherz and Stett [3]. Direct interface and subsequent signal conduction between individual neurons and single transistors would, if practically achievable in an *in vivo* environment, have the potential of providing a solution to many of the localization issues associated with conventional non-specific field based functional electrical stimulation (FES) techniques.

In motor nerve stimulation applications, it is desirable to recruit different populations of motor units at different times. A temporally staggered recruitment of motor units would help to mitigate rapid fatigue of the musculature observed in many FES regimes. The ability to easily vary the time delay between the stimulus and the onset of the action potential could be utilized in motor nerve stimulation applications where it is desirable to vary the recruitment time of different motor nerve fibers in the nerve trunk and consequently motor units. It is demonstrated in this study that the relatively simple approach of modulating the neural-electronic stimulator (transistor) drain potential pulse amplitude could be used to vary the time delay between the stimulus onset and the peak of the action potential. Since it has been demonstrated through simulation studies that stimulus pulse width is expected to change the recruitment profile of nerve fibers [4], the impact of variations in the transistor drain potential pulse width is also investigated.

II. METHODOLOGY

The modeling approach adopted in this study is analogous to the approach taken in Szlavik [5]. The physical parameters related to the membrane and the transistor are shown in Table 1., along with the definition of the circuit components.

TABLE I
LIST OF THE VARIABLES AND PHYSICAL AS WELL AS GEOMETRIC PARAMETERS THAT WERE USED IN THE EQUIVALENT CIRCUIT MODEL

a_j	Interface and nerve cell radius	10 (μm)
d_j	Nerve cell transistor seal distance	10 (nm)
L	Length of the nerve cell	40 (μm)
A_ψ	Free membrane region area	$\pi r_j^2 + 2\pi r_j L$ (cm^2)
A_P	Interfaced membrane region area	πr_j^2 (cm^2)
T	Temperature	6.3 ($^\circ\text{C}$)
ρ_I	Extracellular environment resistivity	15 ($\text{k}\Omega\text{cm}$)
c_{JG}	Gate oxide capacitance per unit area	0.3 ($\mu\text{F}/\text{cm}^2$)
c_{Na}^o	Extracellular sodium ion concentration	0.491 (mol/L)
c_{Na}^i	Intracellular sodium ion concentration	0.05 (mol/L)
c_{K}^o	Extracellular potassium ion concentration	0.02011 (mol/L)
c_{K}^i	Intracellular potassium ion concentration	0.400 (mol/L)
G_{Na}^M	Maximum sodium conductance per unit area	0.120 (S/ cm^2)
G_K^M	Maximum potassium conductance per unit area	0.036(S/ cm^2)
m	Hodgkin Huxley first order kinetic variable[6]	
h	Hodgkin Huxley first order kinetic variable[6]	
n	Hodgkin Huxley first order kinetic variable[6]	
Ψ_{Na}	Free membrane region sodium conductance	(S)
Ψ_K	Free membrane region potassium conductance	(S)
P_{Na}	Interfaced membrane region sodium conductance	(S)
P_K	Interfaced membrane region potassium conductance	(S)
R_J	Interface junction seal resistance [1]	$\rho_I / (5\pi r_j)$ (Ω)
C_M	Membrane capacitance per unit area	4.0 ($\mu\text{F}/\text{cm}^2$)
C_ψ	Free membrane region capacitance	(F)
C_P	Interfaced membrane region capacitance	(F)
C_{JG}	Gate oxide capacitance	$c_{JG}\pi r_j^2$ (F)
V_{Na}	Sodium ionic (Nernst) potential	(V)
V_K	Potassium ionic (Nernst) potential	(V)
v_I	Intracellular potential	(V)
v_J	Interface junction potential	(V)
v_M	Interface region transmembrane potential	(V)
v_D	Drain Potential	(V)
R_D	Drain Resistance	1.0(k Ω)
V_{to}	Transistor turn on potential	1.5 (V)
K	Transistor K parameter	1.0 (mA/V ²)
V_{DD}	Transistor drain DC bias	10 (V)

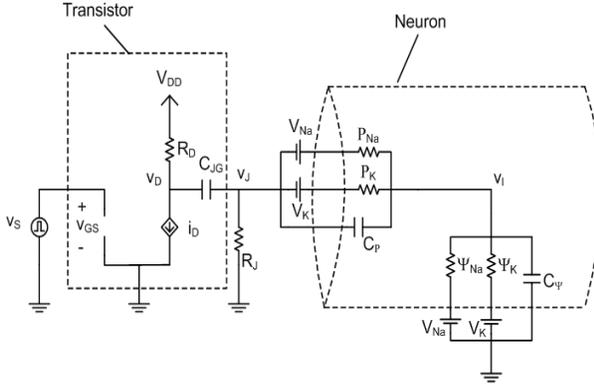


Fig. 1. Non-linear equivalent circuit model of the neural-electronic stimulator. The equivalent circuit component values are calculated using the physical parameters and formulas shown in Table 1.

The non-linear equivalent circuit that incorporates the non-linear properties of the membrane is shown in Fig. 1. This model was developed by dividing the membrane into a region that is interfaced with the electronic device, represented by the P labeled circuit components, and a free region of the membrane, represented by the Ψ labeled circuit components [1;7] as per (1).

$$\begin{aligned} \Psi_{Na} &= A_{\Psi} G_{Na}^M m^3 h \\ \Psi_K &= A_{\Psi} G_K^M n^4 \\ P_{Na} &= A_P G_{Na}^M m^3 h \\ P_K &= A_P G_K^M n^4 \end{aligned} \quad (1)$$

Fig 1. illustrates that the overall simulation circuit is divided into two parts consisting of an equivalent circuit that models the transistor and a lumped parameter equivalent circuit model of the neuron. Consistent with this modeling approach is the assumption that the specific neuron used can be considered a small cell [6].

The coupled ordinary differential equations (2), (3) and (4), were written in terms of the intracellular potential v_I , the transmembrane potential v_M across the region of the membrane interfaced with the transistor gate $v_M = v_I - v_J$, and the drain potential v_D .

$$\frac{v_D}{R_D} - \frac{V_{DD}}{R_D} + i_D + C_{JG} \frac{dv_D}{dt} + C_{JG} \frac{dv_M}{dt} - C_{JG} \frac{dv_I}{dt} = 0 \quad (2)$$

$$C_{JG} \frac{dv_I}{dt} - C_{JG} \frac{dv_M}{dt} - C_{JG} \frac{dv_D}{dt} + \frac{v_I}{R_J} - \frac{v_M}{R_J} + \quad (3)$$

$$P_{Na} V_{Na} - P_{Na} v_M + P_K V_K - P_K v_M - C_P \frac{dv_M}{dt} = 0$$

$$\Psi_{Na} v_I - \Psi_{Na} V_{Na} + \Psi_K v_I - \Psi_K V_K + C_{\Psi} \frac{dv_I}{dt} + \quad (4)$$

$$P_{Na} v_M - P_{Na} V_{Na} + P_K v_M - P_K V_K + C_P \frac{dv_M}{dt} = 0$$

The transistor used in the simulation study was assumed to be an insulated gate field effect n-channel enhancement mode device with parameters as shown in Table 1. Since the device is assumed to be operated exclusively in the active region, the drain current is governed by (5).

$$i_D = K(v_{GS} - V_{to})^2 \quad (5)$$

An inverted transistor gate stimulus pulse v_S was used where the DC bias value was adjusted to vary the height of the non-inverted pulse that occurs at the transistor drain when the gate to source voltage and consequently the drain current was turned off (ie. $v_{GS} = 0$ V). The DC bias on the transistor drain did not impact the neuron because of the blocking capacitance C_{JG} associated with the insulated gate of the transistor. Due to the DC bias, the topology and stimulation regime investigated is not optimal from the perspective of power consumption related issues.

A multistep ordinary differential equation solver for stiff problems was used to solve the initial value problem associated with the non-linear system of ordinary differential equations.

III. RESULTS

The impact of the stimulus pulse amplitude at the drain of the transistor on the time delay between the onset of the stimulus and the peak of the intracellular action potential was investigated. The effect of variations in the stimulus pulse width was also investigated. Fig 2. illustrates the impact on variation in drain pulse amplitude on the time course of the intracellular action potential. The graph of Fig. 3 illustrates the effects of variations in both stimulus drain pulse amplitude as well as pulse width on the action potential delay time.

Simulation results illustrate that there is a decreased in delay time associated with an increase in the stimulus pulse amplitude. This can be seen from Fig. 2, where the time course of the action potentials is shown.

REFERENCES

- [1] Weis, R. and Fromherz, P., "Frequency dependent signal transfer in neuron transistors," *Physical Review E*, vol. 55, no. 1, pp. 877-889, Jan.1997.
- [2] Vassanelli, S. and Fromherz, P., "Transistor records of excitable neurons from rat brain," *Applied Physics A*, vol. 66 pp. 459-463, 1998.
- [3] Fromherz, P. and Stett, A., "Silicon-neuron junction: capacitive stimulation of an individual neuron on a silicon chip," *Physical Review Letters*, vol. 75, no. 8, pp. 1670-1673, 1995.
- [4] Szlavik, R. B. and de Bruin, H., "The effect of stimulus current pulse width on nerve fiber size recruitment patterns," *Medical Engineering & Physics*, vol. 21 pp. 507-515, Sept.1999.
- [5] Szlavik, R. B., "Strategies for improving neural signal detection using a neural-electronic interface," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 11, no. 1, pp. 1-8, Mar.2003.
- [6] Weiss, T. F., *Cellular Biophysics* Cambridge: MIT Press, 1996.
- [7] Fromherz, P., "Extracellular recording with transistors and the distribution of ionic conductances in a cell membrane," *Eur Biophys J*, vol. 28 pp. 254-258, 1999.

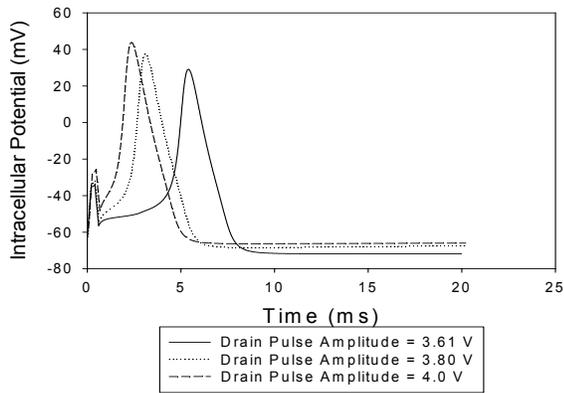


Fig. 2. Graph showing the intracellular action potentials for different values of drain pulse amplitude. The stimulus pulse with was 200 μ s.

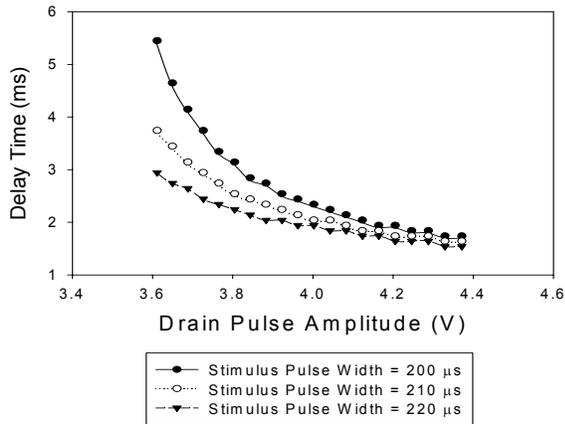


Fig. 3. Graph showing delay time between stimulus onset and the peak of the intracellular action potential as a function of the drain pulse amplitude.

IV. DISCUSSION

The simulations demonstrate that a decrease in the stimulus pulse amplitude as well as stimulus pulse width can result in a three fold increase in the time delay between the initiation of the stimulus pulse and the onset of the intracellular action potential peak. The impact of stimulus amplitude variation observed with our model is consistent with other studies presented in the literature that utilize alternate models of the neural-electronic stimulator [3].