An analog neuron emulator for education and testing of neurophysiological instruments

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ABSTRACT

An electronic circuit has been developed to emulate the passive and active electrical properties of a neuron. The emulator outputs a voltage that represents the membrane potential of a neuron. The output port has impedance comparable to typical impedance of an intracellular microelectrode. The output voltage can be modulated by current stimuli via an input port. Without input stimuli, the emulator outputs the resting membrane potential, which is adjustable within the range of -30 to -100 mV. When the membrane potential is depolarized and exceeds a preset threshold, the emulator generates a train of impulses, which represents the firing of action potentials. Adaptation in the spiking response during depolarization and after-hyperpolarization are also represented. Figure 3 shows microelectrode recordings of a series of progressive depolarization in the LPD1 neuron of the left pedal ganglion of the pond snail, *Lymnaea stagnalis* (top) and outputs of the neuron emulator in response to the same stimuli (bottom). The emulator also interacts with neurophysiological instruments such as a voltage clamp amplifier. The areas of application of this neuron emulator include testing of neurophysiological measurement/control instruments and education in electrophysiology.

INTRODUCTION

In developing an electrophysiology course at the University of Rhode Island, it was necessary to incorporate an electrical engineering design project to satisfy biomedical engineering curriculum requirements. It became increasingly clear that performing the dissection of the common pond snail, *Lymnaea Stagnalis,* to record action potentials from the cerebral ganglia was not a simple task. Since it is a primary goal of an engineer to obtain and analyze data, it was proposed to develop a circuit that would emulate the action potential of a neuron. Using *L. Stagnalis* as a reference, we developed an electrical model of the characteristics of a neuron, i.e., ion exchange (current), resting potential (resistance and capacitance), and action potential (voltage response to current across resistance). The circuit responds to various adjustable inputs by generating a pulse train in a manner similar to the spontaneous action potential train produced by *L. Stagnalis.*

DESIGN

As shown by the functional block diagram in figure 1, the membrane potential generation circuit is enclosed between input and output resistance/capacitance circuits, which provide the necessary resistance and capacitance properties of a neuron membrane. The membrane potential signal consists of three parts: resting potential, resistance potential, and firing action potential. The input current is converted to voltage to control the firing frequency of the oscillator. The on/off of the oscillator is controlled by the comparator and the threshold reference to mimic the depolarization threshold behavior of neurons. The oscillator can produce the required action potential spikes, which, after incorporating the adaptation control and after-hyperpolarization signal, is fed to shaping filter to give out a train of pulses of the similar shape as real action potential spikes [1]. The block of Adjustable Gain is designed to simulate the resistance response of the neuron to current input.

This circuit is designed with consideration of general uses, so most parts of the device are designed as adjustable. As a result, by adjusting the potentiometers, this device can emulate a large range of neuron species.

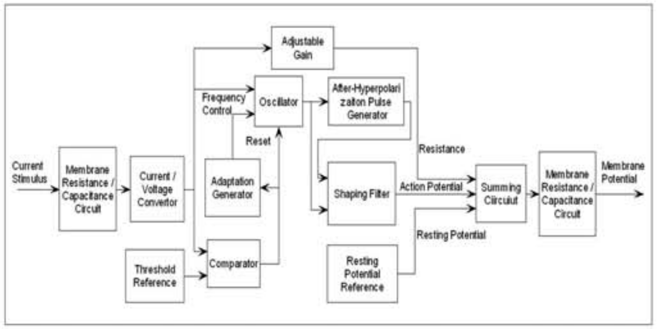


Figure 1. Configuration Diagram of the Active Circuit Neuron Model

EXPERIMENTAL TESTING RESULTS

Figure 2 summarizes the experimental testing results on the neuron emulator, as compared to the experimental results obtained from a biological neuron. The membrane and action potentials, in response to gradual steps of depolarization (top panel), were recorded by used a glass micropipette electrode in the parietal neuron RPD1 of the right parietal ganglion of the pond snail (*Lymaea stagnalis*) [2]. The current stimuli for the depolarization steps were provided by a voltage-clamp amplifier (GeneClamp 500, Axon Instrument) with the clamp feedback turned off. The neuron emulator was adjusted to emulate the cellular parameters of the biological neuron, i.e. membrane potential, resting potential, etc., and generated very similar results (middle panel). When the clamp feedback was turned on, the neuron emulator responded to the voltage-clamp amplifier (bottom panel). The feedback currents from the voltage clamp successfully cancelled out the action potential spikes generated by the neuron emulator, which demonstrates the remarkable similarity between the emulator and the neuron.

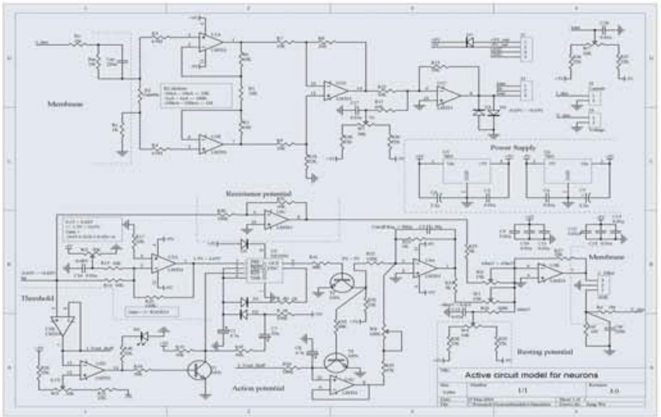
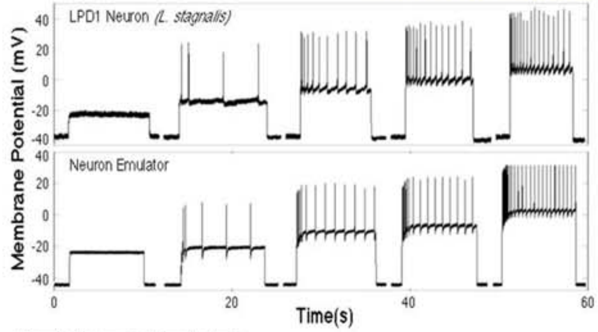


Figure 2. The circuit schematic of the Neuron Emulator



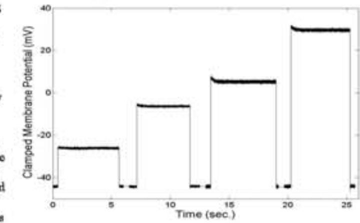


Figure 3. <u>Top:</u> experimental results showing gradual depolarization steps and the action potentials recorded by use of an intracellular microelectrode in a neuron in the parietal ganglion of the pond snail (*Lymnaea stagnalis*). **<u>Middle:</u>** the corresponding membrane and action potentials generated by stimulating the neuron emulator. The parameters in the emulator were tuned to represent the biological neuron shown in the top panel. **<u>Right:</u>** voltage clamp results on the neuron emulator. A voltage clamp amplifier (GeneClamp 500, Axon Instrument) was used to clamp the neuron emulator at various voltage step and eliminate to action potentials with current feedback.

Figure 4. The neuron emulator performs real-time, interactive simulation of a neuron in terms of the following: 1) electrode and membrane resistance and capacitance for both current input and voltage output ports (figure 4) , 2) membrane resting potential when input current is zero, 3) firing of action potentials above a depolarization current threshold, 4) adaptation of the spiking response (figure 5), 5) hyper-polarization following each spike, and 6) response to voltage clamping.

CONCLUSION

The neuron emulator presented hereinabove realizes a circuit which is easy and economical to build, yet capable of emulating the electrical properties of neurons. These properties include, but are not limited to, input/output impedance, resting potential and action potential responding to current stimulus. The testing experiments showed excellent resemblance between the emulated potential waveform and the actual membrane potential waveform, in addition to displaying the correct response to such biological instrumentation as the voltage clamp. Potential applications for this device span the fields of biological instrumentation development and training, as well as electrophysiology education.

REFERENCES

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