Simple electronic analogue for teaching on the nerve cell

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Abstract—Two electronic circuits were designed to simulate the electrical properties of a nerve cell: one for the axon membrane and the other for the dendritic and some membranes. The membrane conductances are simulated with field-effect transistors. The circuit designs are explained and many experiments that can be performed by students are described. The circuits were mounted on printed circuit boards and can be easily reproduced. This electronic analogue could be used in a student laboratory to teach the properties of nerve cells.

Keywords—Membrane conductance simulation, Nerve cell analogue, Neurofet

1 Introduction

A FEW years ago an electronic analogue of the squid axon called the Neurofet was introduced by ROY (1972). This analogue circuit used a field-effect transistor (f.e.t.) as the basic element to simulate voltage dependent membrane conductances. One f.e.t. could reproduce the Na+ and another the K+ conductance properties observed in voltage clamp on axon membranes. The original circuit was modified by GULRAJANI and ROBERGE (1976) and used by GULRAJANI, ROBERGE and MATHEIU (1977) to model a burst generating neuron. Also LINKENS and PATTON (1977), and PATTON (1978) used a modified version of the circuit to model the oscillating electrical activity of the gastrointestinal tract.

Since this electronic analogue provides a simple and faithful model to reproduce the electrical activity of excitable cells, it was thought that a general circuit design should be developed with adjustable parameters. Such a design would be flexible enough to permit the simulation of a wide range of excitable membrane characteristics. To complete the simulation of a whole nerve cell, it was necessary to develop another circuit to simulate the action of transmitters on synaptic membranes. The purpose of this paper is to describe these circuit designs and to demonstrate the effects of varying the different membrane parameters responsible for the nerve cell properties.

2 Circuit description

The circuit shown in Fig. 1a simulates a small patch of axon membrane (0.1 mm²). It contains the four basic elements of the equivalent circuit of an axon membrane. Also an access resistance in series with the membrane analogue has been included, to represent the resistance of solutions and electrodes.

The $g_K$ and $g_{Na}$ conductances are simulated each with one f.e.t. whose conductance is controlled by the membrane potential through a feedback network. The basic design of this network is the same as the one proposed previously by ROY (1972) with the addition of a few operational amplifiers to improve the adjustment procedure and the flexibility. With this design, each time constant as well as the gain and the gate polarisations can be changed independently. The circuit is much simpler to adjust and the effects of varying each parameter can be independently observed. The currents in each branch of the analogue can be observed separately during a voltage clamp or an action potential and using a summing amplifier, some or all the currents can be observed in superposition.

The circuit in Fig. 1a has been simplified to provide an axon analogue with fixed parameters (Fig. 1b). This fixed parameter analogue is necessary for nerve network simulation. It can be easily produced in large number and requires only two simple adjustments. A light emitting diode (l.e.d.) was added to this circuit to provide a visual signal when action potentials are appearing.

A second analogue circuit shown on Fig. 2a was developed to simulate the properties of a somatic or dendritic membrane patch at a synapse. The circuit contains three elements in parallel, the capacitance, the leakage conductance with its battery and a transmitter induced conductance $g_t$ with its battery $E_T$. It is possible to simulate an excitatory or an inhibitory transmitter, depending on the value of $E_T$. The circuit simulating the transmitter conductance also uses the f.e.t. as a variable conductance, but in this case the synaptic conductance is not voltage dependent as in
the case of the axon circuit. The input signal usually an
action potential is integrated to simulate the effect of
transmitter emission. Although transmitter emission is
a much more complicated process, the overall result is
approximately equivalent to an integration of the
action potential (LEWIS, 1964). It means that the
amount of transmitter emitted depends on the
amplitude and duration of the membrane potential.

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Fig. 1 (a) Circuit description of the axon analogue A
The upper part gives the membrane equivalent circuit
with its four branches. There are four current
measuring points, $I_C$, $I_I$, $I_K$, and $I_Na$, an input $IN$, an
output $OUT$ and a buffered output $V_s$. The control
circuits of the gate potentials $V_K$ and $V_{Na}$, for each f.e.t.
are given in the lower part of the figure. The output $V_B$
is used as input into $V_K$ and $V_{Na}$.
(b) Description of the simplified circuit A with its
remote connecting plate.