Electrophysical Generation of Pulse and Plateau Potentials in *Paramecium*

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Abstract: - This paper presents electrophysical potential generation in *paramecium* of unicellular organism. Modelling and analysis are done by equivalent electrical circuit in equations. Activity is composed of electrical three zones and two depletion layers induced in the cytoplasm. Analysis was done on space-time dynamic motion of charges (ions). Electrical equivalent circuit of activity and active cell are given. Characteristics analysis is done for amplifier and oscillator. Positive pulse and its variations as negative pulsed, positive plateaus are realised in this modelling.

Key-Words: - *Paramecium*, positive and negative potential generation, positive pulse, swimming directions, Ca^{2+} and K^{+} charges (ions).

1 Introduction

Paramecium is one of the unicellular organisms in limnetic water. Usually it swims slowly by cilia, but it swims forward quickly for stimulation added at back part of the body. Otherwise its swims backward for stimulation added at the front part of body.

Using a glass microelectrode, membrane potential was measured first by T. Kamada, 1934[1]. Electrical potential was between inner and outer surfaces of the membrane. Positive ions passed through membrane more than negative ions.

The relation of the potential polarity and the motion direction was given in experiments by Y. Naitoh and R. Eckert, 1969[2,3]. However the scheme of potential generation was due to the earlier model of positive pulse generation in neurons [4].

This paper gives a unified scheme and equivalent circuits for bipolar (positive and negative) potential generation with C^{2+} and K^{+} ions. Typical output of this modelling is positive pulse. Variations are negative pulse, positive and negative plateaus as its variations.

2 Electrophysical Modelling of Positive Potential Generation

2.1 Modelling and operation

Electrophysical modelling of positive potential generation is given in Fig. 1.

Stimulus-sensitive Ca^{2+} channels are at the front part of body. Voltage-dependent Ca^{2+} channels are assumed at the central part of the body.

For input stimulation at the front part (input), reception potential appears with injection of Ca^{2+} through Ca^{2+} channels, or release from Ca^{2+} vesicles in the cell.

The potential difference is high between input and central zone. But it is reduced by injection of Ca^{2+} at the central part. Ca^{2+} charges pass over the reduced potential wall of the first depletion layer. And Ca^{2+} charges diffuse to the end of the second boundary.

The potential difference is kept high at the second boundary, because any ion channels don't feed positive ions into the output zone. However Ca^{2+} pass over the high potential wall by the thermal energy.

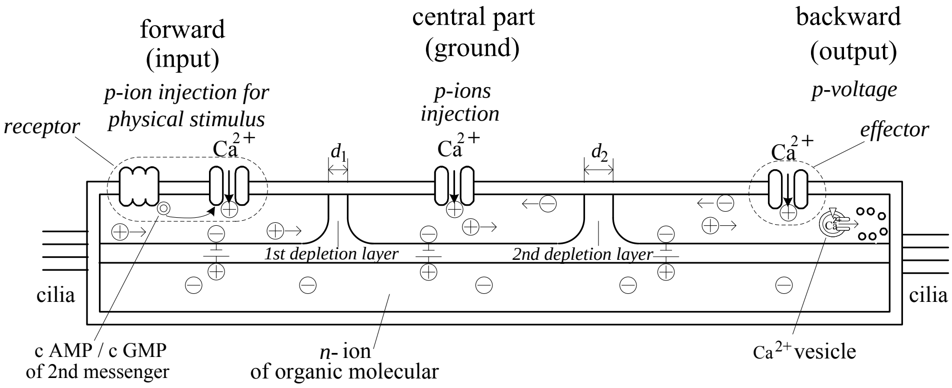


Fig.1 Electrophysical modelling of *paramecium* for positive excitation.

2.2 Equivalent circuit of activity and active cell

(1) Electrical modelling of activity

Electrical modelling of activity for positive potential output is shown in Fig.2.

Input and output diodes n_d, n_a correspond to the first and the second depletion layers, which are shown as forward and reverse direction diodes respectively.

α is current multiplication factor. A part of input i_f is lost to be i_c during diffusion at the central part by reconnection of *p*- and *n*- ions.

$\alpha \cdot i_d$ is equivalent current source flowing output circuit. r_c is the diffusion resistance of *p*-charges through the central part, which provides feedback action.

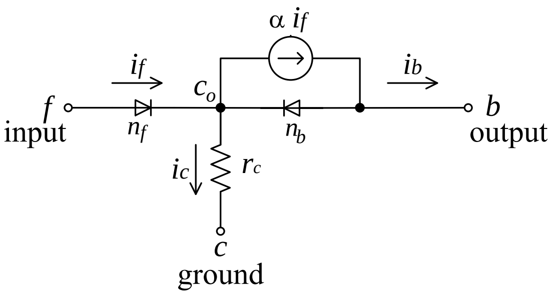


Fig. 2 Electrical modelling of activity of *paramecium* for positive potential output.

(2) Characteristics as an amplifier

Electrical modelling of an active cell is shown in Fig. 3. The points of f_0, b_0 are outside of membrane. c_0 is a virtual point taken in the central part.

r_f and r_b are resistances of forward and reverse diodes n_f and n_b. r_c corresponds to diffusion loss at the central part and brings feedback from output and input circuit.

Resistances m_f and m_b are equivalent expressions of input stimulus and output potential for motion of cilia or chemical secretion.

The capacitances C_f and C_b are caused by the first and second depletion layers respectively. Input and output diodes m_f and m_b.are shown as forward diodes for injection of *p*-ions. These diodes work for ejection of *n*-ions.

Voltage amplification gain *G* is given as;

$$G = \frac{v_b}{v_f} = \frac{\dfrac{\alpha R_b}{r_f + r_c}}{1 - \dfrac{\alpha R_b}{r_f + r_c} \cdot \dfrac{r_c}{R_b}} = \frac{K}{1 - K\beta} \qquad (1)$$

$$K = \alpha \frac{R_b}{r_f + r_c} \qquad (2)$$

$$\beta = \frac{r_c}{R_f} \qquad (3)$$

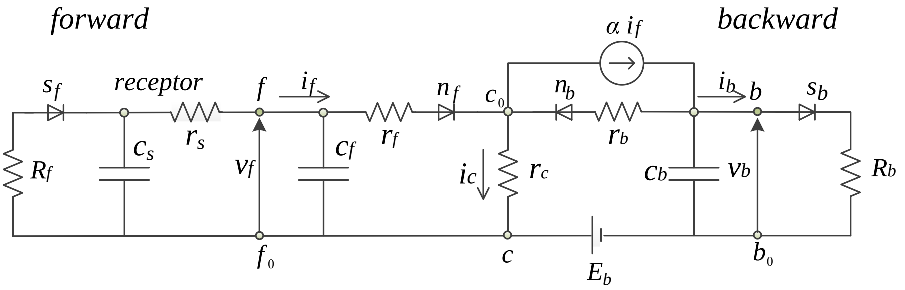


Fig. 3 Electrical modelling for positive potential output including pulse and plateau. Equivalent delay by chemical process for production of the second messenger of c-AMP is written by input circuit *rs Cs*. This circuit is removed for ion channels controlled by the first messenger.

where, v_f and v_b are input (reception potential) and output (action potential) voltages, G, K, β are closed loop gain, open loop gain, and inner feedback ratio respectively. Oscillation condition is given by $K\beta \geq 1$.

In case that $\alpha < 1$, $K\beta \ll 1$. Therefore the cell operates as a voltage amplifier with threshold for input signal with positive inner feedback.

(3) Characteristics as a positive potential generator

The cell operates as an oscillator to generate potential output when the product of open loop gain K and feedback ratio β exceeds 1.

Self-injection oscillation is done by $K\beta \geq 1$.

$$T_1 = C_f \frac{r_c R_b}{r_c + R_b} + C_s\,(\,r_s + r_c\,) \qquad (4)$$

$$T_2 = C_b R_b \qquad (5),$$

where, $R_f + r_f \gg r_c,\ r_b = \infty$
are assumed for simplified analysis.

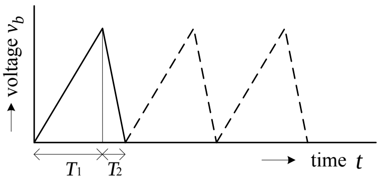


Fig.4 Positive potential voltage output. Dotted lines corresponds to multiple pulse generation.

The period of oscillation T is given as the total time length as following;

$$\begin{aligned} T &= T_1 + T_2 \\ &= C_f \frac{r_c R_b}{r_c + R_b} + C_s\,(\,r_s + r_c\,) + C_b R_b \qquad (6). \end{aligned}$$

The mode of oscillation is astable, because the stable point is less except zero (0) potential.

The cell operates as an astable mode tuned to external injection. Whenever, the phase and the period of original free running oscillator is fluctuating, the oscillator becomes stable by locking to the external signal as shown in Fig. 4.

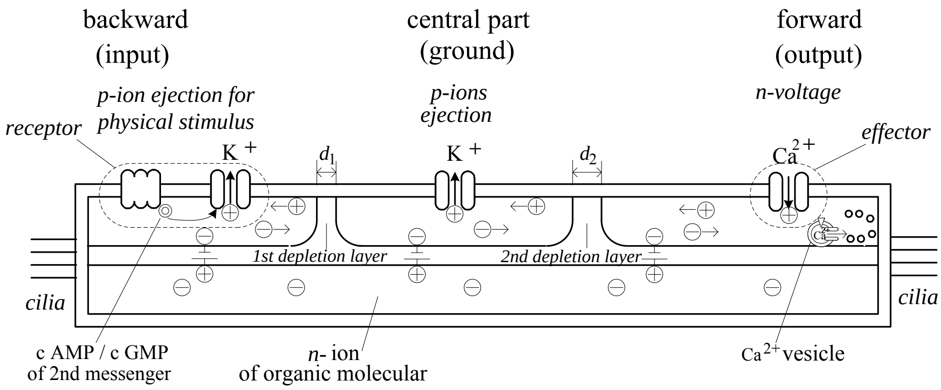


Fig. 5 Electrophysical modelling of *paramecium* for negative excitation.

3 Electrophysical Modelling of Negative Potential Generation

Electrophysical modelling and the equivalent circuits of negative potential generation are given in Fig. 5, 6, and 7.

In Fig. 5, K^+ is used for negative potential generation. Against input mechanical stimulation at the backward part, negative reception potential is induced at input port by ejection of K^+ through mechanosensitive K^+ channels (pulse), or chemical process for production of cyclic AMP as the second messenger mediated by some enzyme from ATP.

When the potential drops down under the resting potential, K^+ ejection is induced at the central part to reduce the potential difference between two zones.

Electrophysically, loss (ejection) of positive charges (K^+) is equivalent to gain (injection) of negative charges. Negative potential generation takes place at the forward part of body. The animal moves forward with twice higher speed than usual swimming, it means the other type of excitation.

It is pointed that negative potential (hyperpolarization) excitation does not mean so called inhibition (suppression) of positive potential excitation.

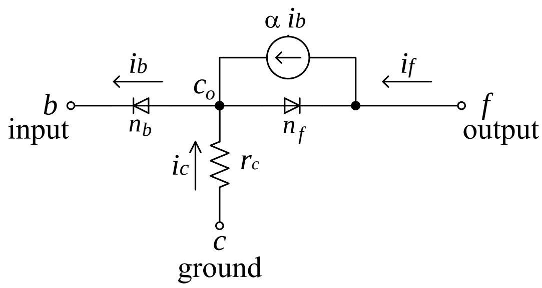


Fig. 6 Equivalent circuit of activity.

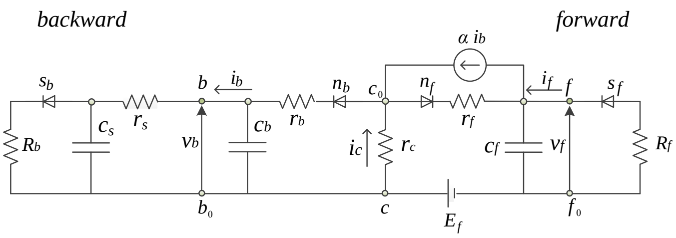
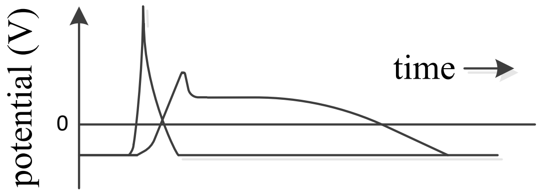
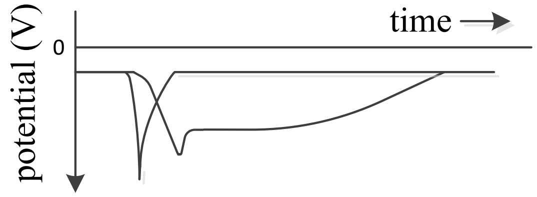


Fig. 7 Equivalent circuit of excitatory cell.



(a) Positive potential waveform



(b) Negative potential waveform

Fig. 8 Output bipolar waveform with short and long time durations.

4 Bipolar Potentials in *Paramecium*

4.1 Modelling of output potential

Typical potential output is positive pulse and plateau as shown in Fig. 8 (a). Negative pulse and plateau are shown in Fig. 8 (b).

It is noted that negative pulse is not always observed steadily. This remind that positive pulse is not always observed in natural sea water[2,13].

4.2 Motion of cilia by bipolar potentials in *paramecium*

It is known that *paramecium* swims by cilia driven by bipolar potentials. It moves backward and forward responding to external stimulus applied at forward and backward parts of the cell respectively. These movements are driven by positive potential (depolarization) and negative potential (hyperpolarization) generated in the cell.

It is also found in experiments that output waveforms are featured by short (pulse) and long (plateau) time durations of continuation, but the role of modulation of waveforms were not known enough, but it is expected that a plateau continues motion, and a pulse enhances action of motions in advance of a plateau. It is also fed that the pulse (spike) happens in short time, and the plateau keeps potentials long time enough for the motion.

5 Commonality of Excitation in *Paramecium* and Neuron

In *paramecium*, injection of Ca^{2+} provides positive potential and ejection of K^+ provides negative potential, and bipolar potentials are used for control of motion of cilia.

Positive (depolarization) and negative (hyper polarization) potential plateau, and positive (depolarization) potential pulse are utilized in *paramecium*, and negative (hyperpolarization) potential pulse is generated under conditions of external and internal kind and density of ions [13].

In neurons, injection of Na^{2+} provides positive potential, and injection of Cl^- provides negative potential. Bipolar potentials are used mainly in for short potential pulses[5-8].

Recent studies inform that cyclic AMP (adenosine monophosphate) plays important roles in neural cells. This chemical material work to open or to close the gates of ion channels as the second messenger. It takes long delay time for chemical process of metabolism. Ca^{2+} works like c-AMP.

Bipolar potentials are used mainly for control of sensing and motor neurons, and for secretion of hormone and neurotransmitter.

This paper proves that similarity exists in principles of generation of plateaus.

6 Conclusion

Unicellular organism of *paramecium* was taken up for study of activity in excitatory cells including neurons in the animal.

Modelling of electrophysical activity was composed of three zones and two depletion layers induced in cytoplasm.

Analysis of electrophysical dynamics of charges (ions) in liquid of cytoplasm was done referred to semiconductor physics.

Analyses of electrical characteristics were done based on electrical circuit theory.

It proved that unified modelling of activity stands among *paramecium* in limnetic water, and *noctiluca* in sea water, and neurons of multicellular animals.

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Appendix

Paramecium is a kind of unicellular organism. A schematic figure is shown in Fig. A-1 for *paramecium ciliophora*.

It swims backward against mechanical stimulus at the front part of body (anterior). This motion is driven by positive action potential generated in a cell.

On the contrary, it swims forward quickly against stimulus at rear part (posterior). This motion is driven by negative action potential.

It is confirmed that mechano-sensitive Ca^{2+} and K^+ channels are distributed on surface of the body, and voltage-sensitive Ca^{2+} and K^+ channels are distributed at somewhere on surface of the body.

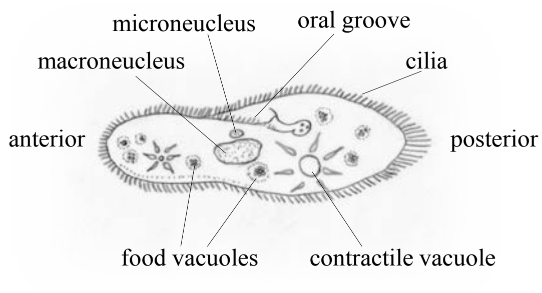

Fig. A-1 *Paramecium ciliophora*.