Electrophysical Generation of Pulse and Plateau Potentials in *Noctiluca*

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Abstract: - This paper presents electrophysical potential generation in *noctiluca*. Dynamic modelling is composed of three electrical zones and two depletion layers (liquid junctions) induced in cytoplasm. Stimulus-sensitive and voltage-dependent ion channels are settled at the membrane around cytopharynx and tentacle. Equivalent circuits of activity are given by an input forward diode and an output reverse diode with current source to drive output resistance. These diodes correspond to the first and the second depletion layers. Typical potential outputs are featured by pulse and plateau with bipolar (positive and negative) potentials defined by Na^+ and Cl^- ion channels driven by the first and the second messengers. Outputs of pulse and plateau with positive and negative potentials are realized by this model.

Key-Words: - *Noctiluca*, electrophysical activity, depletion layer (liquid junction), Na^+ and Cl^- ion channels, pulse and plateau with positive and negative potentials, the first and the second messengers, motions of tentacle.

1 Introduction

Noctiluca is one of the marine unicellular organism flashing in scintillation in sea water. It gathers food and takes it into cytopharynx by tentacle motion. The cell is composed of two membranes. The nuclear and the cytoplasm are in the inner membrane, and it floats and sinks in sea water with large vacuoles in external membrane.

Using glass microelectrode, M. Hisada observed that repetition of negative potential accompanies tentacle bending, 1957[1]. R. Eckert observed that repetition of negative potential accompanies scintillations, 1965[2].

K. Oami, Shibaoka, and Y. Naito presented that negative and positive potentials depend on Cl^- and Na^+ ion channels respectively. These ion channels exist locally at the area close to cytopharynx and tentacle, 1988[3]. And observation of positive pulse (spike) was sure in Ca^{2+} decreased sea water, and ambiguous in natural sea water.

It is pointed that studies of principle of electrophysical operations have never been done. Experimental observation and its interpretation were developed on active potential and current with early model of neurons.

This paper presents that novel approach to activity (excitation) based on dynamic analysis of electric charges (ions) in cytoplasm.

2 Electrophysical Modelling of Positive Potential Generation

2.1 Modelling and operation

Electrophysical modelling is given in Fig. 1.

It is thought that spontaneous input stimulus and output are located at the membrane around cytopharynx and tentacle. Potential pulse and plateau are considered with Na^+ and Cl^- ion channels in receptor driven by the first and the second messengers.

When Na^+ ions are injected the voltage rises up at the pharynx, and this signal drives voltage dependent ion channels and rise the potential at the central part. The potential wall at the first boundary (depletion layer), the potential wall induced at the first depletion layer plays as the forward direction diode.

Na^+ ions drift at the central part and arrive at the second boundary, the second depletion layer induced the boundary, and the potential wall is kept higher because positive ions are not injected anyways. The second depletion layer plays as the reverse diode direction. Once Na^+ ions pass over this higher wall with the effect of thermal energy, energy of Na^+ ions are enhanced.

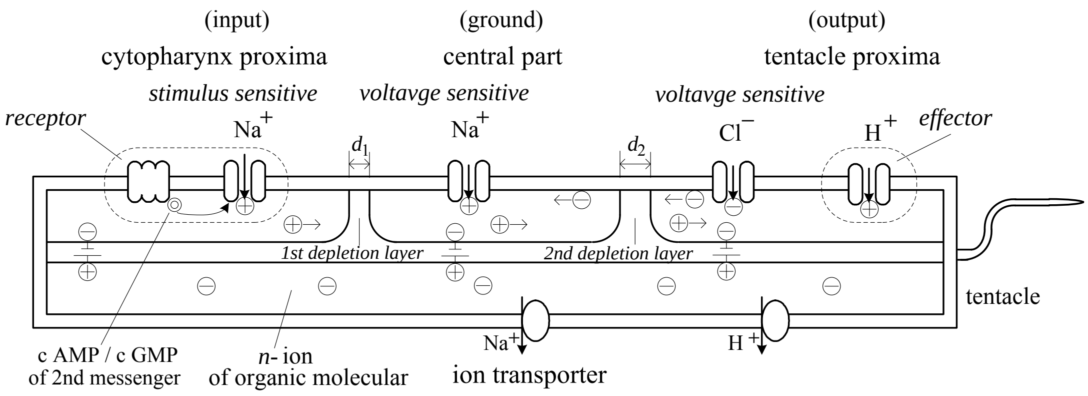


Fig. 1 Electro-physical modelling of *noctiluca* for positive potential generation.
Stimulus (mechano-) sensitive Na^+ channels are at the part of pharynx. Voltage dependent Na^+ channels are settled at the central part between pharynx and tentacle. Effector is defined by proton ion channel. Distribution of ion channels depend on experiments done by [3]. Input ion channels in receptor are driven by the first and the second messengers.

2.2 Equivalent circuit

(1) Electrical modelling of activity

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

Diodes n_p and n_t correspond to the first and the second depletion layers, which are shown as forward and reverse diodes respectively. p, c, and t denote input (pharynx), control, and output (tentacle) ports respectively. c_0 is a virtual point at the central part between the first and the second depletion layers. Most of input current i_p reaches the second depletion layer. Current i_c is lost part of i_p.

α is current multiplication factor. $\alpha \cdot i_p$ is equivalent current source to drive output load.

r_C is the diffusion resistance at the central part, which provides feedback action. The arrows denote equivalent positive current in Fig. 2.

It should be noted that current multiplication function is removed from this model.

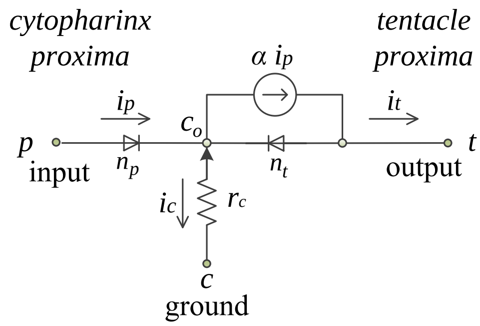


Fig. 2 Electrical modelling of activity for positive potential output. Arrows show positive current.

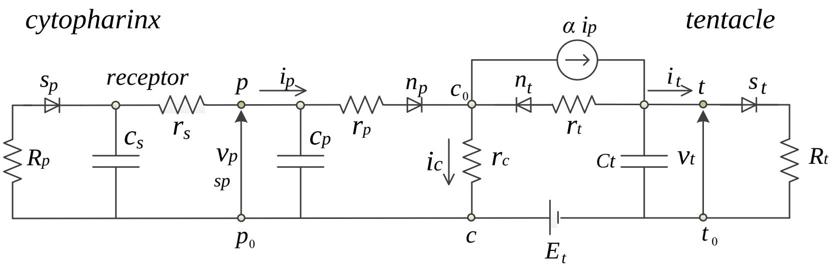


Fig. 3 Electrical modelling for positive potential output.
Input R_p represents equivalent expression of mechanical stimulation.

Electrophysical modelling of an active cell is shown generally in Fig. 3.

Electrophysical activity in the cell is expressed by a section between p - p_0 and t - t_0. Receptor of the cell is expressed by a passive circuit, and the impedances looking outside. The responses without delay (the first messenger) and with delay (the second messenger) are expressed by the components of forward coupling α_{sp} and recurrent component β_{sp}. The effector of the cell is expressed by H^+ channels.

The first and second depletion layers cause capacities C_p and C_t the respectively.

(2) Characteristics as an amplifier

The cell operates as an amplifier with positive feedback. The following analysis is for electrical function corresponding to the section between p - p_0 and t - t_0. Voltage amplification gain G is given as;

$$G = \frac{v_t}{v_p} = \frac{\dfrac{\alpha R_t}{r_p + r_c}}{1 - \dfrac{\alpha R_t}{r_p + r_c} \cdot \dfrac{r_c}{R_t}} = \frac{K}{1 - K\beta} \qquad (1)$$

$$K = \alpha \frac{R_t}{r_p + r_c} \qquad (2)$$

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

where, v_p and v_t 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 $K\beta \geq 1$.

It is remarkable that a certain effect of input stimulus is realized by itself even if input stimulation could not exceed the threshold. It is found in this analysis that this effect is explained by stimulus signal amplification.

(3) Characteristics as a positive potential generator

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

Self-injection oscillation is done by $K\beta \geq 1$. The period of oscillation is calculated based on time-constants for charge and discharge of C_p, r_C, R_t.

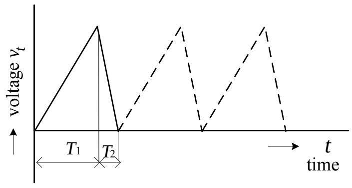


Fig. 4 Duration time of positive potential output. Dotted lines corresponds to multiple pulse generation.

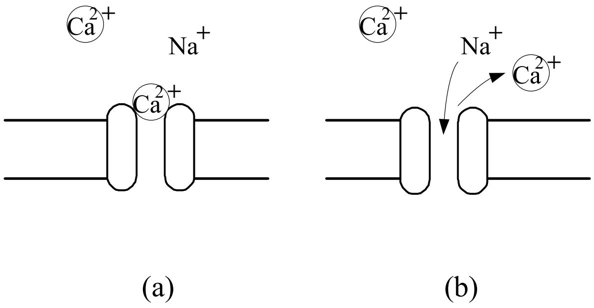


Fig. 5 Operation of Na^+ channel prevented by Ca^{2+}.
(a) Operation in natural sea water.
(b) Operation in Ca decreased artificial sea water.

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

$$T_2 = C_t R_t \qquad (5),$$

where, $R_p + r_p >> r_c$, $r_t = \infty$ are assumed for simplified analysis.

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

$$T = T_1 + T_2$$

$$= C_p \frac{r_c R_t}{r_c + R_t} + C_s\,(r_s + r_c) + C_t R_t \qquad (6).$$

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.

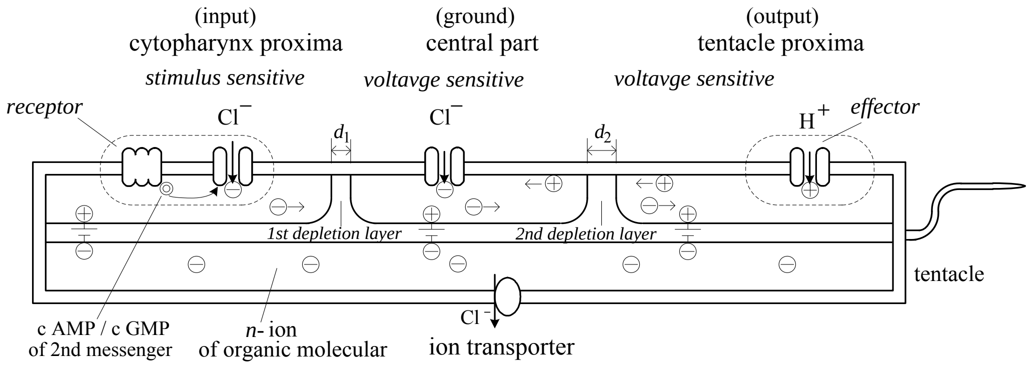


Fig.6 Electro-physical modelling of *noctiluca* for negative generation.

2.3 Ambiguity of positive pulse generation

It is observed that positive pulse is generated certainly in Ca^{2+}-decreased artificial sea water, but ambiguous in natural sea water.

A reasonable model of Na^{+} channel is given in Fig. 5. Ca^{2+} blocks Na^{+} flowing into channels when Ca^{2+} are enough in external liquid (a). Almost all Na^{+} pass as usual ionospheric channels when Ca^{2+} are decreased enough (b). But these types of Na^{+} channels have not been proved in experiments of conventional studies.

3 Electro-Physical Modelling of Negative Potential Generation

Electro-physical modelling is then given for generation of negative plateau. This model is common with the model for positive potential generation except configuration of ion channels.

Electro-physical modelling and the equivalent circuits of negative potential generation are given in Fig. 6, 7 and 8.

In Fig. 6, Cl^{-} is used for negative potential generation. Negative reception potential is induced at input port by injection of Cl^{-} through stimulus-sensitive Cl^{-} channels (the first messenger type), 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, Cl^{-} injection is induced at the central part to reduce the potential difference between two zones.

Duration time of negative potential output is shown in Fig. 9.

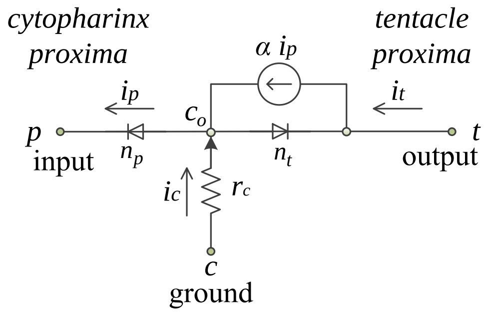


Fig. 7 Equivalent circuit of activity for negative output. Arrows show negative current in the figure.

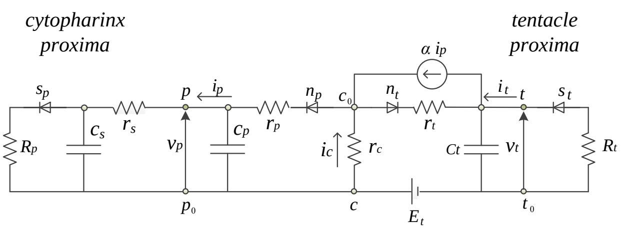


Fig. 8 Equivalent circuit for negative potential output.

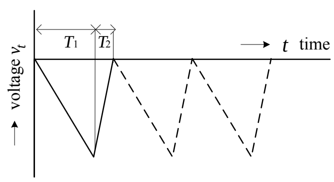
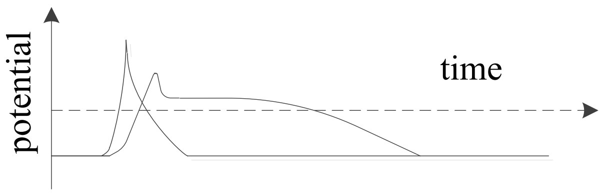


Fig. 9 Duration time of negative potential output. Dotted lines corresponds to multiple pulse generations.

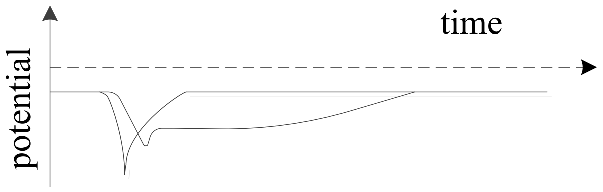
4 Bipolar Potentials in *Noctiluca*

4.1 Modelling of output potential otputs

Expected output potentials are given in Fig. 10 based on t he above schemes. Output potentials in the figure are drawn by superimposing.



(a) Positive potential output



(b) Negative potential output

Fig. 10 Bipolar potential output with short and long time durations.

4.2 Commonality of activity in *noctiluca* and neuron

Recent studies tell that cyclic AMP (adenosine monophosphate) plays an important role in neural cells. This chemical material works to open or to close the gates of ion channels as the second messenger. It takes long time delay to control ion channels caused by chemical production of c-AMP. And this metabolic process continues long time duration. As the results, cell excitation (activity) is featured by plateau compared to pulse by ionospheric ion channels.

It is known that similar responses observed by c-GMP and Ca^{2+} channels as stimulus dependent ion channels.

Bipolar potentials are also observed in neurons of marine animals of aplysia by MacCamann, 1982, and K. Sasaki, et al, 1987 and by M. Shozushima, 1984.

Commonality exists in modelling of generation of positive/negative potential for plateau/pulse signals except kind of ion channels.

5 Conclusion

Electro-physical modelling and equivalent circuit of activity in *nocriluca* were first presented in this paper.

It proved that commonality exists in modelling of *noctiluca* and neuron except the difference in configuration of output signals.

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Appendix

A.1 Early model of cell excitation (activity) and its problem

Conventional studies on active cells were concerned on the effect of membrane "depolarization" and "hyperpolarization" by ion channels which leads "excitation" and "suppression" of cells.

It is pointed that these approaches are provided by the early model for generation of action potential in neurons given by Hodgkin and Huxley.

Fundamental scheme of active operation (amplification feedback) were not presented. But waveform approximation was shown by artificial parameters. Repetitive connection of ion channels distributed on membrane does not correspond to regeneration but feedforward.

It is pointed that amplification with positive feedback of signals are essentially needed for generation of potential output. In this paper, electro-physical modelling is given composed of amplification and feedback functions. This model is applied commonly for positive and negative potential in cells of unicellular and multi-cellular organism.