Measurement of Liquid Zones and Boundaries in Active Neuron with Pairs of Micro Glass-Electrodes

Yumi Takizawa, Atsushi Fukasawa, and Hiro-aki Takeuchi

***Abstract*—**Electrical measurement of liquid zones and boundaries formed in active neuron is presented. In advance, modelling of an active neuron is shown with three zones and two boundaries. Basic equations are shown to calculate transmission and reflection components for a section with a boundary and two different zones in a transmission line. Then an inhomogeneous transmission line with uniform three zones and two boundaries is considered. Velocity in each zone is given at each zone. A system configuration is then shown for measurement of three zones and two boundaries in an active neuron.

This system is composed of the chirp method for conversion of distance to time-frequency difference with the chirp method and the proposed method for fine resolution of zone potential and boundary reflection in a neuron.

***Keywords*—**Active neuron model, liquid zone and boundary, inhomogeneous transmission line, transmission and reflection components.

I. Introduction

A modeling and analysis of an active neuron has been given by the authors [1-11,15,16]. This model is shown with three zones and two depletion layers for motion of charges in cytoplasm of a neuron. This model was given electro-physically by referring relations of behaviors by unicellular organism and a neuron [12-14]. In spite existence of depletion layers is not proved in experiments, it is expected to be proved in experiments.

A measurement scheme is now given in this paper for measurement of two boundaries in an active neuron using plural glass electrodes inserted in a neuron.

This paper presents fundamental equation to measure first position of a boundary in a section in liquid medium.

This paper then presents a measurement system composed of the Chirp method and proposed scheme with cascading connection. This system is applied to measure electrical behavior in zones and position of boundaries formed in a neuron and *paramecium* of unicellular organism.

The theory and measurement method given in this paper is applied widely to not only a neuron but also other excitatory cells of secretory cell, muscle cell, and neuron.

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II. Electro-Physical Modelling of an Active Neuron

A. Electrical Modeling of Activity of Neuron

$g_0 \sim g_4$ are small glass electrodes to be inserted in a neuron for electrical measurement.

i_d is current through forward diode n_d at the dendrite, and i_a is current through reverse diode n_a at the axon. i_c is current through resistance r_c of the central part. α is current multiplication factor and $\alpha \cdot i_d$ is equivalent current source to the axon.

The directions of n_d and n_a correspond to directions of current i_d and i_a . Current source $\alpha \cdot i_d$ corresponds just to activity of this model.

B. Equivalent Electrical Circuit of Active Neuron

Equivalent electrical circuit of activity and active neuron is shown in Fig. 2 and 3.

The points of d_0, a_0 are outside of membrane. c_0 is a virtual point taken in the central part. r_d and r_a are resistances of forward diode n_d and reverse diode n_a, r_c is the resistance at the central part to outside of a neuron. R_d and R_a are external resistances of synapses s_d and s_a.

$r_d << R_d$ and $r_a << R_a$. r_c is approximately zero.

The capacitances C_d and C_a are caused by the first and second depletion layers respectively. Input and output synapses s_d and s_a.are shown as forward diodes for excitatory synapses (*p*-ions). These synapses work as backward diodes for inhibitory synapses (*n*-ions).

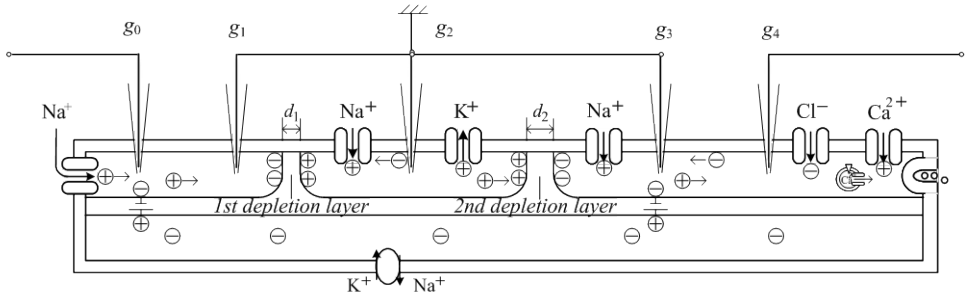

Fig. 1 Electro-physical modelling of an active neuron for positive pulse generation. $g0$ ~ $g5$ are small glass electrodes to be inserted in a neuron for electrical measurement. A pair electrodes in each zone are first inserted.

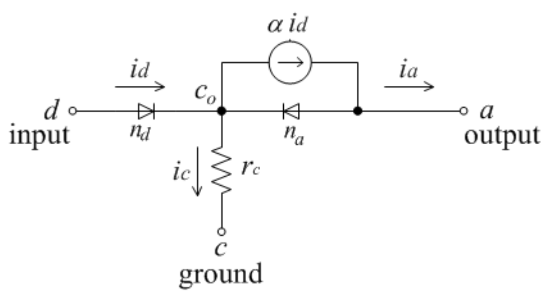

Fig. 2 Electrical modeling of activity of a neuron for positive pulse generation.

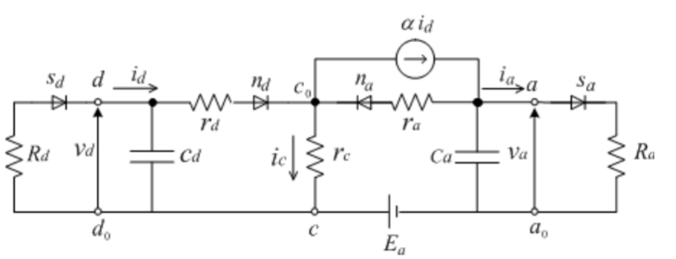

Fig. 3 Electrical modeling of an active neuron for positive pulse generation.

III. Electrical Signal Transmission and Reflection in Liquid Transmission Line

A. Velocity and Transmission Time

Relative dielectric constant $\varepsilon_r(y)$ is assumed depending on position y. The velocity $c(y)$ is given as follows,

$$c(y) = \frac{c_0}{\sqrt{\varepsilon_r(y)}} \quad (1)$$

where, c_0 is the vacum light velocity. Electrical signal trasmission time T is given as follows.

$$T(y) = \int_0^y \frac{\eta}{c(\eta)} d\eta \quad (2)$$

B. Signal Transmission in Discontinuous Medium

An electrical transmission line is shown in Fig. 4.

Small glass electrodes are inserted into the line at points p_k (k = 1, .. , N) along y axis. Section k is deined between points p_{k-1} and p_k, and length of section k is x_k .

It is assumed that a boundary is included in section n, and any boundary is not included in the other sections. p_{Bn} is the boundary position in section n. δ_n is the distance from point p_{n-1}.

The average velocity c_k in the section k is given as;

$$c_k = \frac{x_k}{t_k} \quad (3)$$

where, x_k t_k are distance and passing time in the section k.

The passing time in the section k without boundary is given as;

$$t_k = T_k - T_{k-1} = \frac{x_k}{c_k} \quad (4)$$

The transmission time in the section n including a boundary is given as follows, using the velocities c_{n-1} *and* c_{n+1} at the preceeding and post sections adjacent to the section n.

$$t_n = T_n - T_{n-1} = \frac{\delta_n}{c_{n-1}} + \frac{x_n - \delta_n}{c_{n+1}} \quad (5)$$

$$= \frac{\delta_n\, c_{n+1} + (x_n - \delta_n)\, c_{n-1}}{c_{n-1}\, c_{n+1}} \quad (6)$$

$$= \frac{\delta_n\, (c_{n+1} - c_{n-1}) + x_n\, c_{n-1}}{c_{n-1}\, c_{n+1}} \quad (7)$$

The position of the boundary at y_{Bn} in the section n is given as follows;

$$y_B = y_{n-1} + \delta_n \quad (8)$$

$$\delta_n = \frac{(T_n - T_{n-1})\, c_{n-1}\, c_{n+1} - x_n\, c_{n-1}}{\{c_{n+1} - c_{n-1}\}} \quad (9)$$

$$= \frac{c_{n-1}\, c_{n+1}}{c_{n+1} - c_{n-1}} \left\{ (T_n - T_{n-1}) - \frac{x_n}{c_{n+1}} \right\} \quad (10)$$

C. Measurement of Boundary Positions

Three pairs of glass electodes is considered to be inserted in a cell. By a pair of electrodes ($g0$, $g1$), ($g2$, $g3$), and ($g4$, $g5$) in each zone, uniform velocities are measured at input and output zones without boundary.

$$c_1 = \frac{x_1}{T_1} \quad (11)$$

$$c_3 = \frac{x_3}{T_3 - T_2} \quad (12)$$

$$c_5 = \frac{x_5}{T_5 - T_4} \quad (13)$$

Then the positions of two boundaries enclosing the central part are calculated as;

$$\delta_2 = \frac{c_1\, c_3}{c_3 - c_1} \left\{ (T_2 - T_1) - \frac{x_2}{c_3} \right\} \quad (14)$$

$$\delta_4 = \frac{c_3\, c_5}{c_5 - c_3} \left\{ (T_4 - T_3) - \frac{x_4}{c_5} \right\} \quad (15)$$

The positions p_{B2} and p_{B3} in section 2 and 3 are obtained by substituting Eq (14) and (15) into Eq.(8).

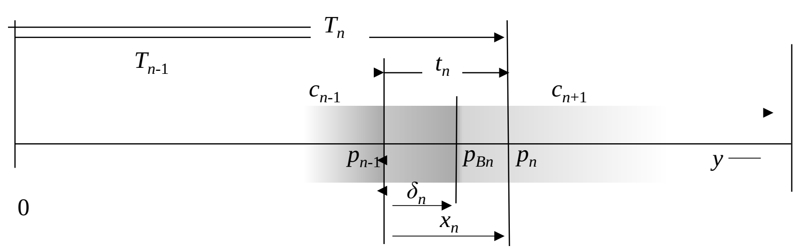

Fig.4 Structure of a section n with a boundary at point p_{Bn}.

IV. Observation of Zones and Boundaries in a Neuron

A. System Configuration

A measurement system is shown in Fig. 5. Which is composed with parts for chirp method and proposed methods. The measurement sample of active neuron is shown above. Three sets of pair electrodes are inserted into individual zones.

Each reflection time $2T_k$ from each electrode is measured by the chirp method. Each position y_B of each boundary is calculated by the proposed method.

B. Transmission Time by the Chirp Method

Each position of glass electrode for reflection is measured by the difference Δf between transmission and reception frequencies.

$$\Delta f = f_t - f_r = 2\alpha T_k \qquad (14)$$

$$\alpha = \{ f_t(\max) - f_t(\min) \} / T_0 \qquad (15)$$

where, f_t , f_r are transmission and reception frequencies. α is the chirp modulation constant defined by f_t (max) and f_t (min). T_0 is time length of a triangle wave for chirp modulation.

Transmission time T_k from reference point g_0 to reflecting point g_k is given by ;

$$T_k = \Delta f / 2\alpha \qquad (16)$$

C. Boundary Position by the Proposed Method

Boundary positions y_{B2} and y_{B4} are calculated by the proposed method using transmission times T_k and section length x_k . The calculation process as follows;

(i) Velocities in sections c_k are calculated by reflection times T_k and section length x_k .
(ii) Boundary section n is taken up by variation of c_k for k. Here, bigger change should be at $c2$ and $c4$.
(iii) The distance δ_{B2} and δ_{B4} is calculated by Eq. (10). Then boundary positions y_{B2} and y_{B4} are calculatobtaned.

When three electrodes are inused, these electrodes are assigned for input, control (ground), and output ports. Input, central, and output potentials are measured for dynamic operation in time-space domain.

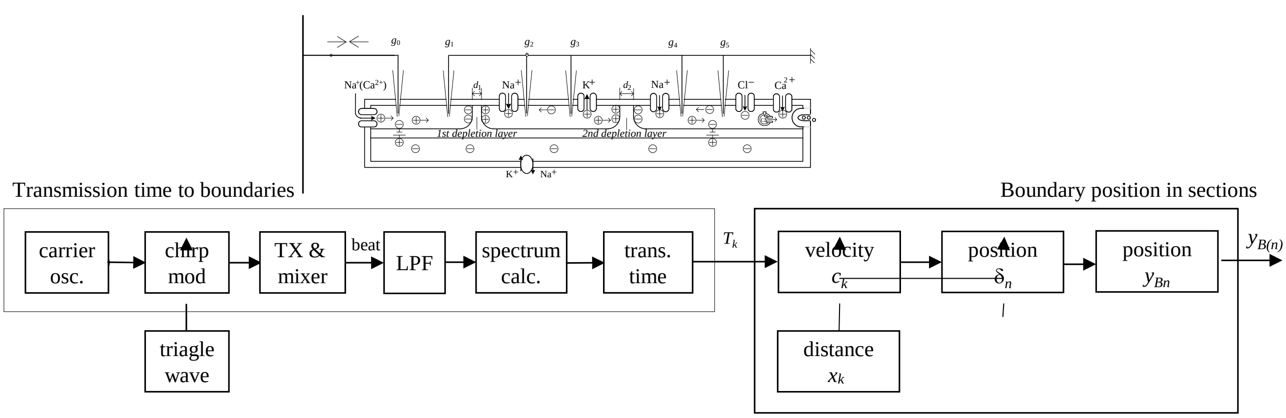

Fig. 5 System configuration of electrical measurement scheme.
Transmission times to boundaries measured by the chirp method.
Positions of boundaries are measured by the proposed method.

V. Electrical Measurement of Zones and Boundaries in Paramecium

Schematic figure of *Paramecium* is shown in Fig. 6. This animal moves backward (downward) for stimulus given at the anterior end. On the contorary, the animal moves forward (upward) for stimulus given at the posterior end.

The function of stimulus reception is regarded as a "swimming receptor cell". And the function of effector for motion of cillia is regarded as a "swimming neuron".

The motion of cillia is driven by increase of density of Ca^{2+} ions inside the cell. It is pointed that the receptor for stimulus depends on the position outside and inside of the cell of the animal. The signal is transmitted along the surface of cytoplasm under the membrane.

Dynamic porcess is found in common between a neuron and *paramecium* except the difference of positive charges. Na^{+} in Fig.2 is replaced by Ca^{2+}. By the way, Ca^{2+} channels at the central part and the entrance of the axon are assumed to be deleted from the electro-physical modelling.

The advantage of paramecium is superior for multiple electrode insertion for testing because of its larger size compared to that of a neuron in brain.

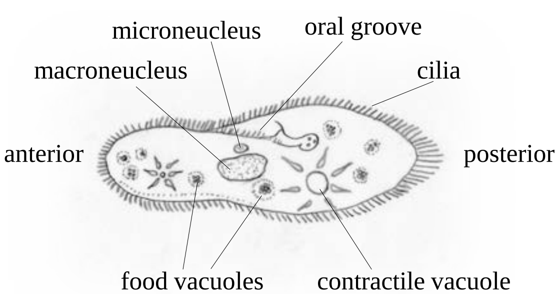

Fig. 6 Unicellular organisms, *Paramecium caudatum*, body length: 250 μm and width: 50 μm, approx., length of cilia: 15 μm, thickness: 0.2μm.

VI. Conclusion

The electrical system was proposed for measurement of potential in zones and positions of boundaries in electrical medium of cytoplasm. Three electrodes are proposed to be inserted in a neuron. This system is essentially obtained by counting transmission and reflection component of signal at zones and boundaries.

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