Propagation of the change in membrane potential by use of the biocell-model

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Supporting Information

The relation between the membrane potential and the membrane current and the propagation of the change in the membrane potential

The membrane potential ($E_{W2\text{-}W1}$) is defined as the potential difference between the inner aqueous phase (W2) and the outer aqueous phase (W1). Here, W1 is regarded as the reference side. Therefore, the positive and the negative currents are attributed to the transport of the cation from W2 to W1 and that from W1 to W2, respectively. Table S1 shows the actual concentrations of K^+ and Na^+ in mammalian skeletal muscle and their calculated $E_{W2\text{-}W1}$ values.[1] When only K^+ can penetrate the cell membrane, the resting potential (–98 mV) is settled by the ratio of the concentration of K^+ in the inner cell to that in the outer cell. If the potential difference is applied between W1 and W2, the relation between $E_{W2\text{-}W1}$ and the membrane current (i) is derived by the Nernst-Planck equation based on the Goldman model, as indicated in Fig. S1 (blue curve). In the present study, we assume that K and Na channels linearly depend on $E_{W2\text{-}W1}$ to simplify. After Na channels begin to open, Na^+ starts to transport from W2 to W1. At that time, the $E_{W2\text{-}W1}$ value changes from the resting potential to the action potential in the positive direction. If only Na channels open, the relation between $E_{W2\text{-}W1}$ and i is shown as red curve. Under the condition, K channel also begin to open and K^+ transports from the inside to the outside. If the hyperpolarization (overshoot) really occurs, the active transport of K^+ from the outside to the inside is caused. After Na channel closed, it seems reasonable to assume that $E_{W2\text{-}W1}$ is more positive than the resting potential since a few Na channels open and the action potential is kept in the vicinity of the local area. Accordingly, it is thought that K^+ transports from the inside to the outside after the closing Na channels and that $E_{W2\text{-}W1}$ goes back to the resting potential.

Table S1 Concentration of K^+ and Na^+ and membrane potentials for mammalian skeletal muscle[1]

Ion	Extracellular concentration/mM	Intracellular concentration/mM	Membrane potential/mV
K^+	4	155	–98
Na^+	145	12	+67

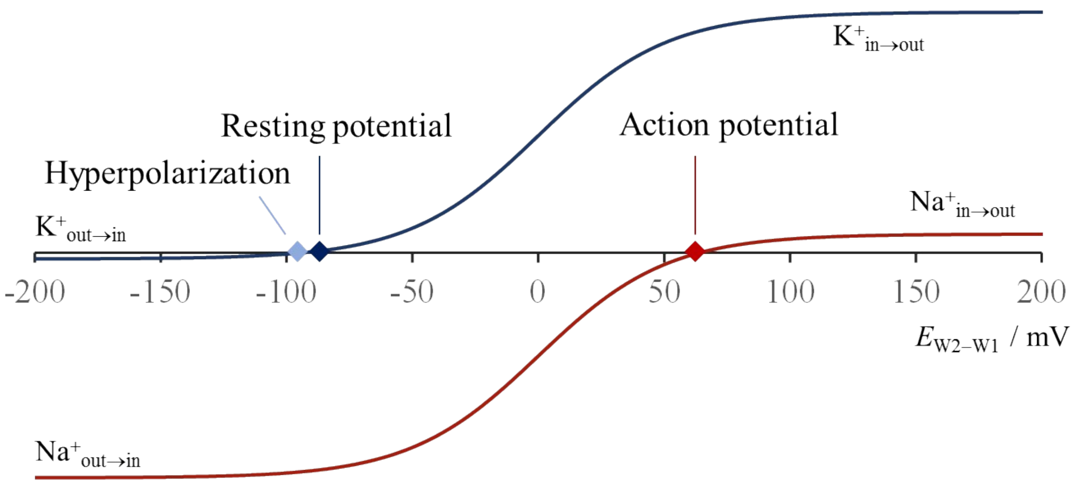

Fig. S1 Imaginary steady-state voltammograms across the membrane between the outer cell (W1) and the inner cell (W2) based on the Nernst-Planck equation and the Goldman assumption. The voltammogram for the transport of K^+ (blue curve) and that for the transport of Na^+ (red curve).

The relation between the circulating current and the propagation of the change in the membrane potential

In the nerve cell, $E_{W2\text{-}W1}$ is usually constant and is determined by the ratio of the K^+ concentration in the inside to that in the outside. The relation between $E_{W2\text{-}W1}$ and the membrane current at a certain site on the axon is illustrated in Fig. S2(A). The $E_{W2\text{-}W1}$ value at this time is defined as the resting potential. When several Na channels begin to open at the site, the current due to the transport of Na^+ appears, as shown in Fig. S2(B). The total current at a given $E_{W2\text{-}W1}$ is equal to the sum of currents in blue and red curves at the same $E_{W2\text{-}W1}$. Since the $E_{W2\text{-}W1}$ value at a zero current changes in the positive direction, $E_{W2\text{-}W1}$ at this site shifts in the positive direction. $E_{W2\text{-}W1}$ moves up to the action potential with an increase in the current due to the transport of Na^+ from W1 to W2, as described in Fig. S2(C). When the difference between the current due to the transport of Na^+ from W1 to W2 and that due to the transport of K^+ from W2 to W1 is maximum, $E_{W2\text{-}W1}$ is regarded as the action potential. After most of Na channels closed and many delayed K channels started to open, $E_{W2\text{-}W1}$ indicates a potential difference between the resting potential and the action potential, as indicated in Fig. S2(D). When all Na channels have closed, the relation between $E_{W2\text{-}W1}$ and i is expressed by blue curve in Fig. S2(E). At this time, the current due to the transport of K^+ from W2 to W1 flows since $E_{W2\text{-}W1}$ is more positive than the resting potential. At last, $E_{W2\text{-}W1}$ goes back to the resting potential.

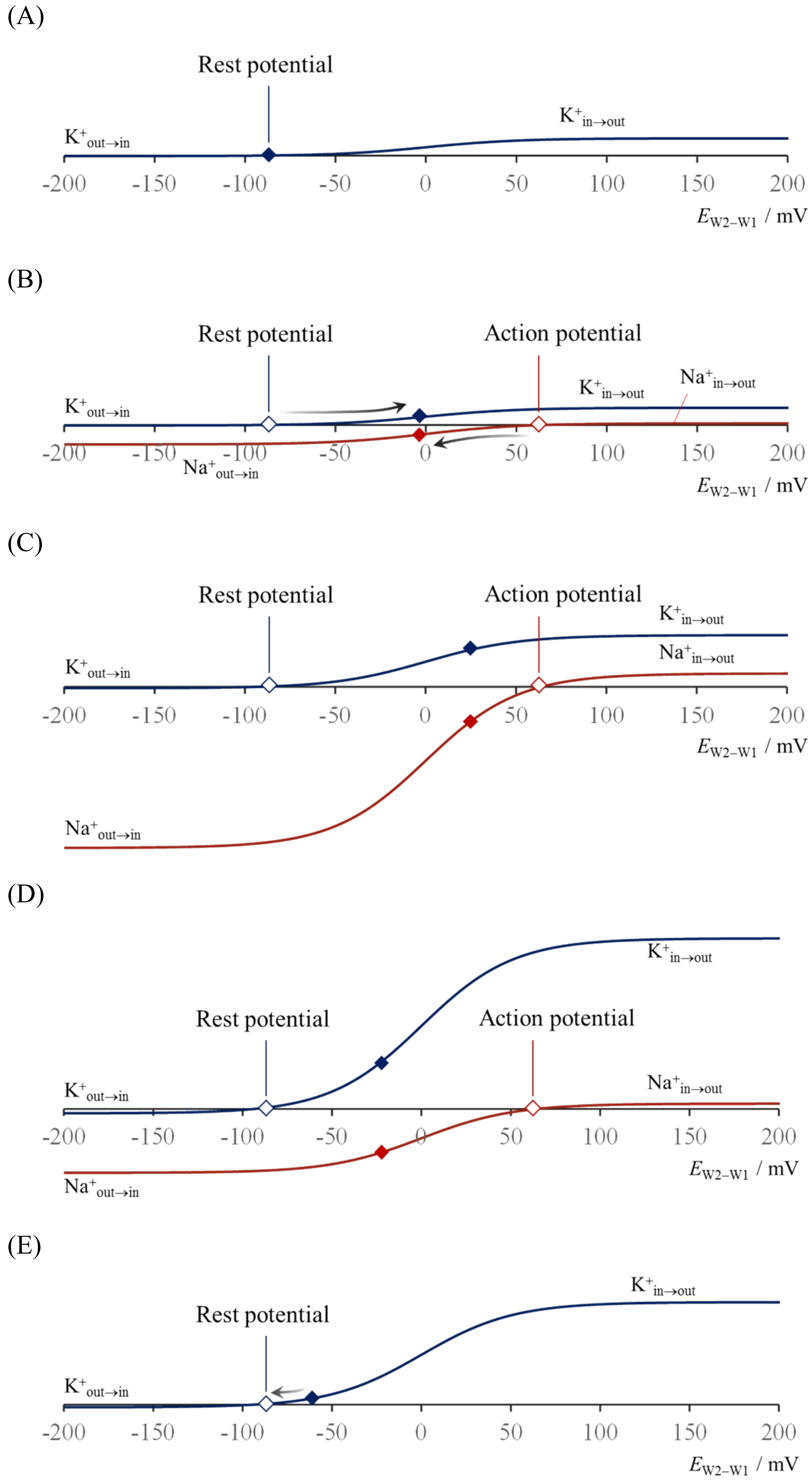

Fig. S2 Imaginary steady-state voltammograms across the membrane between W2 and W2 based on the Nernst-Planck equation and the Goldman assumption. The voltammogram for the transport of K^+ (blue curve) and that for the transport of Na^+ (red curve). (A) Initial condition (the resting potential), (B) the condition after opening several of Na channels, (C) the exciting condition, (D) the condition after closing most of Na channels, (E) the final stage of nervous propagation.

Reference

1. B. Hille, Ion channels of Excitable Membrane, Sinauer Associates, Sunderland, USA, 3rd ed., 2001.