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PROTEIN POLARIZATION INDUCED BLOCH WAVES IN AXONAL FIBRES

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Abstract. *The major problem of cognitive neuroscience is to understand how and to what extent our behavioural processes are governed by the workings of brain and nervous systems. To understand the subjective mental processes in a meaningful and quantitative way a new level of description is needed. Of late a trend has emerged to study different forms of cognition in terms of their neural-oscillation correlates. Questions have been raised whether the combined and synchronous actions of neurons and its constituents can explain the underlying mechanism of cognition. A theoretical perspective on neural oscillations at multi-scale level would indeed be important. Oscillations are of very much functional significance when we talk about large scale phenomena. It has been argued before that technique familiar in the study of transmission line can be used to analyze large-scale spontaneous dynamics of cortex yielding Bloch waves. The Bloch waves could be treated as a continuum in dynamic responses of discrete cells where the continuity would arise from the Bloch concept. An electro-dynamical cable theory of protein polarization in dendrites gives travelling wave solutions. In this paper we are investigating the protein polarization induced Bloch waves in axonal fibres.*

1. INTRODUCTION

The aim of this paper is to understand and explore mechanisms of biological rhythms and the role of neural oscillations and synchrony in information processing.

Repetitive or rhythmic neural activity called Neural Oscillation is reflected in the central nervous system. Localized mechanisms in individual neurons or interactions between them cause oscillatory activity in multiple ways [1-5]. Membrane potential or rhythmic patterns of action potentials generate oscillatory activation of post synaptic neurons. Electroencephalogram (EEG) reflects synchronized activity of many neurons causing macroscopic oscillations. Feedback connections between the neurons cause group oscillatory activity that result in the synchronization of their firing patterns at a different frequency. Delta(1-4 Hz), theta(4-8 Hz),alpha(8-12 Hz),beta(13-30 Hz),gamma(30-100 Hz)are examples of macroscopic neural oscillations.

Of late, the generation of oscillations and their roles has been gaining momentum in the field of neurodynamics. Oscillatory activity is believed to play a key role in processing neural information. A collective interpretation though absent numerous ongoing research upholds the active role of neural oscillations which are observed at different levels [6-8].

Among the most common activity patterns in the brain are spatiotemporally organized waves. Experimentalists are able to observe these activity patterns whether in response of numerous individual neurons and in the ensemble response of the neural circuit. An interdisciplinary approach based on physical and mathematical sciences can contribute greatly to our comprehension of the brain-dynamics by making explicit the method by which wave-like activity emerges from neuronal activity [9-11].

High neural interconnectivity and strong computing capabilities in a cell result from intricate structures like neuronal dendritic trees. W. Rall in the 1950’s was the path breaker when he started studying the function of dendritic structures in theoretical neuroscience. A new detailed outlook towards study of dendrites is possible because of advancement in experimental techniques. The existing view of neural information processing continues to be based on mainly passive properties of the membrane drawn from the implementation of linear cable theory to dendrites. However, nonlinear models have been suggested to adjust new experimental proof [12-13]. Owing to the protein polarization producing intracellular capacitive effects passive dendrites devoid of voltage-gated ion channels, if modeled as linear cables can become active. In an ohmic cable this is depicted by capacitive charge equalization and dispersion of continuous polarization charge densities. As because free charge density decays with the Maxwell’s time-constant previous results showed the predominant effect of the intracellular capacitive current owing to inactive membranes, happens with sub-millisecond precision rather than at the quite slower membrane time-constant. Due to protein polarization the impact of the axial capacitance in the circuit produces a lengthier effect with the signal descending at a much slower time-scale [14-15].

Aur & Jog[16] had opined that reducing neuronal activity to electrical propagation in cables cannot function as a standardized model of computation by neurons since it's an oversimplification. Intricate processes that take place within the neuronal membrane, dendrite, soma or axons cannot be taken into consideration by moving charges. That these structures function simply as conductors without involving additional mechanisms to aid information processing is quite unlikely. Poznanski & Cacha [15] have considered "*protein polarization as a mechanism by way of passive dendrites becoming active by treating the dipolar core as a conductor of current based on the assumption that interactions between individual moving charges can be treated as a homogeneous intracellular medium of constant conductivity and permittivity in space and time*".

2. Modeling and calculations

We are modelling the active dendrite as a periodic transmission line as shown in the figure 1. The T unit comprises of the impedances and admittances of the axon and membranes. The pi part has been introduced to make the passive membrane a protein polarized active one with the distributed backward-wave transmission line having the feedback and coupling terms through Z_b and Y_d . This is a modified form of a transmission line model used earlier[17-20] where the theory of wave propagation in periodic structures and Bloch's theorem have been used in connection with neuroscience yielding the voltage and current Bloch waves which can be found in terms of the different resistances, capacitances and frequency.

The properties of transmission structure can be obtained considering the properties of its unit cells which are repeated to form a cascade.

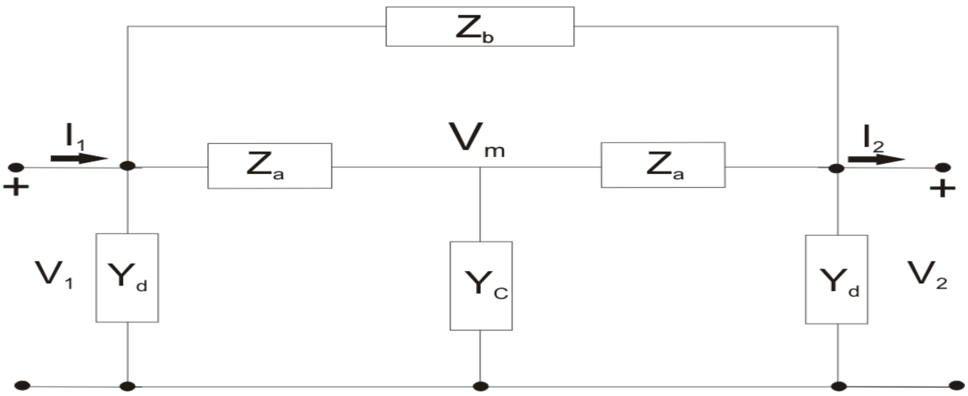

Figure 1: Unit Cell

We have

$$\begin{pmatrix} n \\ I_n \end{pmatrix} = \begin{pmatrix} A & B \\ C & A \end{pmatrix} \begin{pmatrix} n+1 \\ I_{n+1} \end{pmatrix} \quad (1)$$

Also

$$\begin{pmatrix} {}_{n} \\ I_n \end{pmatrix} = e^{i\gamma_u P} \begin{pmatrix} {}_{n+1} \\ I_{n+1} \end{pmatrix} \tag{2}$$

Eqs. (1) and (2) give

$$\begin{pmatrix} A - e^{i\gamma_u P} & B \\ C & A - e^{i\gamma_u P} \end{pmatrix} \begin{pmatrix} {}_{n+1} \\ I_{n+1} \end{pmatrix} = 0 \tag{3}$$

This is homogeneous system of equations. Non-trivial solution exists if $\left(A - e^{i\gamma_u P}\right)^2 - BC = 0$.

Also given that $$e^{i\gamma_u P} = A \pm i\sqrt{1 - A^2} \tag{4}$$

This implies $$A^2 - BC = 1 \tag{5}$$

The non-trivial solution in this case will be:

$${}_{n+1} = K\ (say) \tag{6}$$

and

$$I_{n+1} = \frac{e^{i\gamma_u P} - A}{B}\ {}_{n+1} = \frac{\pm i\sqrt{1 - A^2}}{B} K$$

And hence

$$I_n = e^{i\gamma_u P} \frac{e^{i\gamma_u P} - A}{B}\ {}_{n+1} = (A \pm i\sqrt{1 - A^2}) \frac{\pm i\sqrt{1 - A^2}}{B} K \tag{7}$$

$${}_{n} = \left(A \pm i\sqrt{1 - A^2}\right)\ {}_{n+1} = \left(A \mp \sqrt{BC}\right)\ {}_{n+1} \tag{8}$$

Further

$$A = D = \frac{\{z_b + z_a(2 + y_c z_b + 2y_d z_b) + z_a^2(y_c + y_c y_d z_b)\}}{(2z_a + y_c z_a^2 + z_b)} = \frac{2z_a z_b z_c + z_b z_c z_d + 2z_a z_c z_d + 2z_a z_b z_d + z_a^2 z_d + z_a^2 z_b}{z_d(2z_a z_c + z_a^2 + z_b z_c)} \tag{9}$$

$$B = \frac{\{z_a z_b(2 + y_c z_a)\}}{(2z_a + y_c z_a^2 + z_b)} = \frac{z_a z_b(2z_c + z_a)}{2z_a z_c + z_a^2 + z_b z_c} \tag{10}$$

$$C = \frac{\{y_c + 2y_d + y_c y_d z_a\}(z_b + z_a(2 + y_d z_b))}{(2z_a + y_c z_a^2 + z_b)} = \frac{(z_d + 2z_c + z_a)(z_b z_d + 2z_a z_d + z_a z_b)}{z_d^2(2z_a z_c + z_a^2 + z_b z_c)} \tag{11}$$

where

$$z_a = R_a + \left(\frac{1}{jwc_a}\right) \tag{12}$$
$$z_b = R_b + \left(\frac{1}{jwc_b}\right)$$

and (13)

$$y_c = \frac{1}{z_c} = \left(\frac{1}{R_m + \frac{1}{jwc_m}}\right),$$
$$y_d = \frac{1}{z_d} = \left(\frac{1}{R_d + \frac{1}{jwc_d}}\right),$$

Substituting for z_a, z_b, z_c and z_d in Eqs. (9-11) and solving, we obtain

Numerator (B)=$\{\boldsymbol{z_a z_b(2z_c + z_a)}\}$ (14)

$$= \left(R_a + \frac{1}{jwc_a}\right)\left(R_b + \frac{1}{jwc_b}\right)\left[2\left(R_m + \frac{1}{jwc_m}\right) + R_a + \frac{1}{jwc_a}\right]$$
$$= \left[\left\{\left(R_aR_b - \frac{1}{w^2c_ac_b}\right)(2R_m + R_a) - \left(\frac{R_a}{wc_b} + \frac{R_b}{wc_a}\right)\left(\frac{2}{wc_m} + \frac{1}{wc_a}\right)\right\} - j\left\{\left(\frac{R_a}{wc_b} + \frac{R_b}{wc_a}\right)(2R_m + R_a) + \left(R_aR_b - \frac{1}{w^2c_ac_b}\right)\left(\frac{2}{wc_m} + \frac{1}{wc_a}\right)\right\}\right]$$

Denominator(B)= $(\boldsymbol{2z_a z_c + z_a^2 + z_b z_c})$ (15)

$$= (2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2} - j\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right)$$

Numerator (C)=$\{\boldsymbol{2z_c + z_d + z_a}\}(\boldsymbol{z_b z_d + 2z_a z_d + z_a z_b})$ (16)

$$= \left\{(R_a + R_d + 2R_m)\left(R_bR_d + 2R_aR_d + R_aR_b - \frac{1}{w^2c_ac_b} - \frac{1}{w^2c_bc_d} - \frac{2}{w^2c_ac_d}\right) - \left(\frac{1}{wc_a} + \frac{1}{wc_d} + \frac{2}{wc_m}\right)\left(\frac{R_b}{wc_a} + \frac{R_a}{wc_b} + \frac{R_d}{wc_b} + \frac{R_d}{wc_a} + \frac{R_b + 2R_a}{wc_d}\right)\right\} - j\left\{(R_a + R_d + 2R_m)\left(\frac{R_b}{wc_a} + \frac{R_a}{wc_b} + \frac{R_d}{wc_b} + \frac{R_d}{wc_a} + \frac{R_b + 2R_a}{wc_d}\right) + \left(\frac{1}{wc_a} + \frac{1}{wc_d} + \frac{2}{wc_m}\right)\left(R_bR_d + 2R_aR_d + R_aR_b - \frac{1}{w^2c_ac_b} - \frac{1}{w^2c_bc_d} - \frac{2}{w^2c_ac_d}\right)\right\}$$

Denominator(C)= $\boldsymbol{z_d^2(2z_a z_c + z_a^2 + z_b z_c)}$ (17)

$$= \left(R_d - \frac{j}{wc_d}\right)^2 \Bigg\{(2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2} - j\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right)\Bigg\}$$

$$= \left(R_d^2 - \frac{1}{w^2c_d^2}\right)\Bigg\{(2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2}\Bigg\} - \frac{2R_d}{wc_d}\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right) - j\Bigg\{\frac{2R_d}{wc_d}\left((2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2}\right) + \left(R_d^2 - \frac{1}{w^2c_d^2}\right)\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right)\Bigg\}$$

$$Numerator(A) = (\boldsymbol{z_bz_cz_d} + \boldsymbol{z_a}(\boldsymbol{2z_cz_d} + \boldsymbol{z_dz_b} + \boldsymbol{2z_cz_b}) + \boldsymbol{z_a^2}(\boldsymbol{z_d} + \boldsymbol{z_b}) \tag{18}$$

$$= \left(R_mR_d - \frac{1}{w^2c_mc_d}\right)(R_b + 2R_a) + \left(2R_aR_b - \frac{2}{w^2c_ac_b}\right)(R_d + R_m) + \left(R_a^2 - \frac{1}{w^2c_a^2}\right)(R_b + R_d) - \left(\left(\frac{R_d}{wc_m} + \frac{R_m}{wc_d}\right)\left(\frac{2}{wc_a} + \frac{1}{wc_b}\right) + \left(\frac{R_b}{wc_a} + \frac{R_a}{wc_b}\right)\left(\frac{1}{wc_m} + \frac{1}{wc_d}\right) + \frac{2R_a}{wc_a}\left(\frac{1}{wc_d} + \frac{1}{wc_b}\right)\right) j\Bigg[\left(\frac{R_d}{wc_m} + \frac{R_m}{wc_d}\right)(R_b + 2R_a) + \left(R_mR_d - \frac{1}{w^2c_mc_d}\right)\left(\frac{2}{wc_a} + \frac{1}{wc_b}\right) + \left(2R_aR_b - \frac{2}{w^2c_ac_b}\right)\left(\frac{1}{wc_m} + \frac{1}{wc_d}\right) + (R_d + R_m)\left(\frac{R_b}{wc_a} + \frac{R_a}{wc_b}\right) + \frac{2R_a}{wc_a}(R_b + R_d) + \left(R_a^2 - \frac{1}{w^2c_a^2}\right)\left(\frac{1}{wc_d} + \frac{1}{wc_b}\right)\Bigg]$$

$$Denominator(A) = \boldsymbol{z_d}(\boldsymbol{2z_az_c} + \boldsymbol{z_a^2} + \boldsymbol{z_bz_c}) \tag{19}$$

$$= \left(R_d - \frac{j}{wc_d}\right)\Bigg\{(2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2} - j\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right)\Bigg\}$$

$$= R_d\left\{(2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2}\right\} - \frac{1}{wc_d}\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right) - j\left\{\frac{1}{wc_d}\left((2R_a + R_b)R_m + R_a^2 - \frac{2}{w^2c_ac_m} - \frac{1}{w^2c_bc_m} - \frac{1}{w^2c_a^2}\right) + R_d\left(\frac{2R_m}{wc_a} + \frac{R_m}{wc_b} + \frac{2R_a}{wc_a} + \frac{2R_a + R_b}{wc_m}\right)\right\}$$

3. CONCLUSION

Cortical waves are produced by nonlocal synaptic couplings. We have modeled an active dendrite introducing a distributed backward-wave transmission line concept to take into account the voltage dependent non-linear capacitor-voltage characteristics arising due to protein polarization.

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