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# Theoretically modeling oscillations and waves (EEG and MEG signals) of the brain neuronal fluids and extracellular fluids, using plasma hydrodynamics

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## Abstract

***Introduction:*** *Ionic oscillations and waves of the brain neurons are mostly analyzed and recorded by* EEG (electroencephalography*) and (or) MEG (*magnetoencephalography). In principle EEG and MEG signals arise from the same neuronal sources. The traditional models of EEG and MEG do not involve natural excitations and attenuations, encodings (decodings), displacement currents of the brain neuronal electromagnetic signals, nor active pumps and passive channels of biological ions. Besides, we have not found any published research at an ionic level to theoretically describe the mechanisms how oscillations and waves of the brain neuronal fluids and extracellular fluids are excited, attenuated and maintained in the both natural and forced modes.

**Methods and Results:** We introduce the plasma physics into brain theory; based on plasma hydrodynamic equations and published data of the brain or neuron sciences and molecular biology, at an ionic level, we model the mechanisms of the complete procedures of excitations, attenuations, propagations (oscillations and waves) of the brain neuronal fluids and extracellular fluids in the both natural and forced modes; our models include active pumps and passive channels of biological ions. Moreover, we also elucidate frequency and amplitude modulations (encodings), displacement currents, as well as effective values of the alternating electric current densities, electric and magnetic fields and voltages, based on the modeling results of the brain neuronal and extracellular plasma waves (oscillations).

**Conclusion:** Our modeling results are qualitatively consistent with the published data of brain neuroscience as well as EEG and MEG.

**Keywords:** Brain neuron; Plasma hydrodynamics; Natural and forced waves and oscillations; EEG and MEG; Frequencies and amplitudes; Encodings and modulations

## 1. Introduction

*Ionic oscillations and waves of the brain neurons are mostly analyzed and recorded by* EEG (electroencephalography*) and (or) MEG (*magnetoencephalography).

In principle EEG and MEG signals arise from the same neuronal sources, typically postsynaptic currents from apical dendrites of pyramidal. Both EEG and MEG revealed the millisecond spatiotemporal dynamics of visual processing with largely equivalent results. However, EEG and MEG have systematic differences in sampling neural activity [1]. In this paper, our theoretic models are based on the both published EEG and MEG data.

Estimating the neuronal sources that generated a given potential map at the scalp surface requires the solution of an inverse problem. Historically, two different possible directions have been investigated in order to solve this inverse problem and find the generators of a given scalp activity. At one direction, distributed models are based on the linear

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theory in conjunction with mathematical and/or biophysical a priori constraints are more likely to be used [2]. At another direction, the so-called dipole localization models assume that only a limited number of generators are active over a period of time; these generators are typically modeled as equivalent current dipoles (ECD) [2-5].

The traditional models of the distributed and dipole localization do not involve natural excitations and attenuations, encodings (decodings), displacement currents of the brain neuronal electromagnetic signals, nor biological active pumps and passive channels of biological ions.

In studies of brain theory, we investigated the mechanisms of Alzheimer's diseases [6] and the brain thinking [7].

The neuronal signal transmission along the neuron axons (or dendrites) were modeled as electrical (and magnetic) circuits, and the information propagation and processing in the neurons are modeled as the electric (and magnetic) fields. [6-7].

*However, we have not found any published research at an ionic level to theoretically describe the mechanisms how oscillations and waves of the brain neuronal fluids and extracellular fluids are excited, attenuated and maintained in the both natural and forced modes.*

*To help* data analysis and diagnosis more accurately in clinic as well as to understand more deeply information-rich EEG (electroencephalography*) and MEG (*magnetoencephalography) by obtaining more complete electromagnetic signals of the brain neurons, *in this paper, we introduce the plasma physics into brain theory; based on plasma hydrodynamic equations and published data of the* brain or neuron sciences and molecular biology*, at an ionic level, we model the mechanisms of the complete procedures of* excitations, attenuations, *propagations (oscillations and waves) of the brain neuronal fluids and extracellular fluids in the both natural and forced modes; our models include* active pumps and passive channels of biological ions.

Moreover, in this study, we also elucidate frequency and amplitude modulations (encodings), displacement currents, as well as effective values of the alternating electric current densities, electric and magnetic fields and voltages, based on the modeling results of the brain neuronal and extracellular plasma waves (oscillations).

## 2. Methods

*In this study, our models are based on theories of the hydrodynamics and plasma physics [8-12] (and waves [13]), as well as published data of the brain or neuron sciences [14-23] and molecular biology [24].*

## 3. Models

We consider the brain neuronal fluids and extracellular fluids as quasi plasmas of physics and liquids; moving K+, Na+, Ca2+, Mg2+, Cl- and other micro ions [24] as sources of electric current densities that produce dynamic electric fields; other macro ions are quasi stationary; the ions are ionic fluids; polarized $H_2O$ as neutral fluids that either stay around the static ions or move with the dynamic ions. [6-7, 11-12]

To obtain theoretical analytic solutions of the intra and extra cellular fluids' oscillations, attenuations and waves, we apply the plasma hydrodynamic equation to model the fluids' movements. The equations are identical or similar for the intra and extra cellular fluids.

### 3.1. The plasma hydrodynamic equation of the brain neuron fluids

*The spontaneous (natural) oscillations and waves of the brain (such as* pyramidal*) neuron plasma are instantaneous and short-lived, they attenuate soon after initiating; the continuous and periodic oscillations and waves of the brain neuron plasma are forced (driven) by external* electrochemical *powers that are mostly provided by biological active pump ATP and ionic channels just like that in cardiovascular system [11-12].*

If the ions in a plasma are displaced from their equilibrium positions, electric fields will be built up in such a direction as to restore the neutrality of the plasma by pulling the ions back to their original positions. (Figure 1 (a) and (b)) Because of their inertia, the ions will overshoot and oscillate around their equilibrium positions with a characteristic frequency known as the plasma frequency, [8-9] if the attenuating force is smaller than the restoring force.

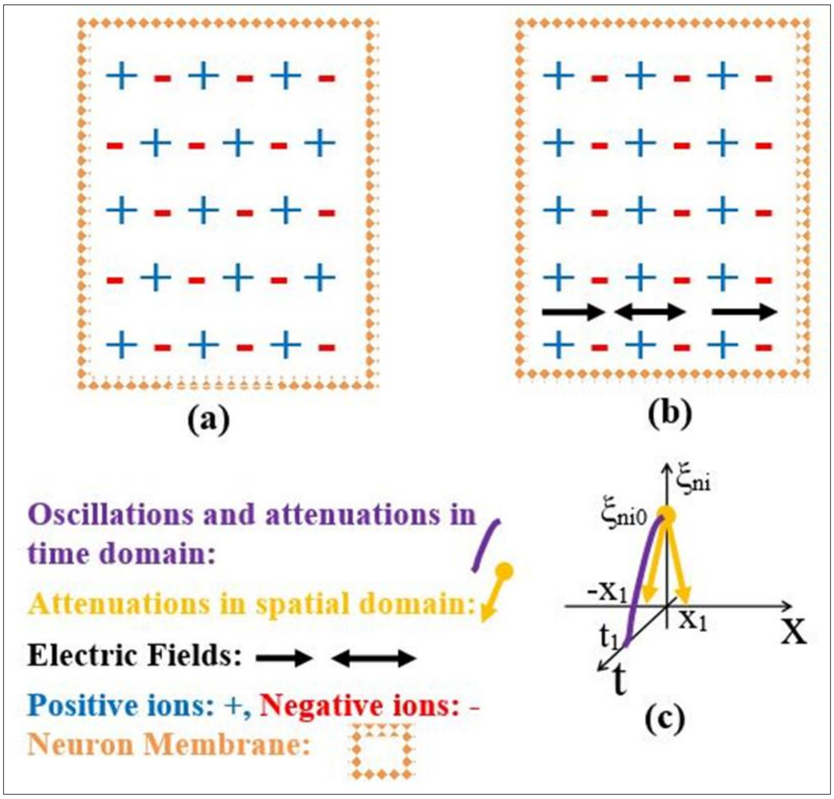


**Figure 1** Modeling initiation mechanisms of natural oscillations of quasi (physics and liquid) plasma in a brain neuron (such as a pyramidal neuron): (a) undisturbed and (b) disturbed plasma; (c) $\xi_{ni}$ denotes the departure of the equilibrium position of the ion, the temporal oscillation is over (or critical or under) damped and the spatial variation is linearly and sharply going down to zero without any oscillation (see the text). The cellular ions are mostly K+, $HCO_3^-$, $PO_4^{3-}$, nucleic acids, metabolites carrying phosphate and carboxyl groups; the extracellular ions are mostly Na+ and Cl- (not shown); the neutral molecules are mostly polarized $H_2O$ (not shown). The draw is in two dimensions and not to scale. See the text

Equation 1 is a longitudinal hydrodynamic equation (convective or total derivative) of the plasma and describes the momentum transfer of the (physics and liquid) plasma ions (species i, the subscript) in one temporal and three spatial dimensions [8-9,11-13]:

$$n_i m_i(d\mathbf{v}_i/dt) = n_i m_i[\partial\mathbf{v}_i/\partial t + (\mathbf{v}_i\cdot\nabla)\mathbf{v}_i] = n_i q_i[\mathbf{E} + \mathbf{v}_i\times\boldsymbol{\mu}\mathbf{H}] - \nabla\cdot\mathbf{P}_i - n_i m_i\mathbf{v}_i\nu_i \quad (1)$$

where, ·, ∇ and × respectively denote operators of scalar product, differential gradient and cross product; velocity **v**, electric and magnetic fields **E** and **H** are vectors; magnetic permeability **μ** and fluid pressure **P** are tenors; ν is a mean or effective collision frequency (Ohm's law and damping factor related, the damping attenuation can be compensated by external driving power, such as ATP pumps); mass m is a sum of masses of the ion itself and the neutral molecular $H_2O$ [13]; n is the particle density; q is the ion effective charge.

In theory, we can obtain the solutions of equation (1) by resolving a self-consistent set of fields and motions [8,13].

The different ionic streams (flows) are usually in different time orders rather than in the same time [14-23]. This is a very complicated topic of multiple ion streams [8-12]. To obtain simple and elegant analytic solutions, we have to perform some approximations.

To estimate oscillations or waves of the brain neuron plasma, we mostly use K+, Na+, Ca2+, Cl- concentrations or densities, based on molecule biology data [24]. For instances, let densities for K+ be $n_K$, the correspondent effect (combination) mass be $m_K = m_{K+} + m_{H2O}$. Based on equation (1), the longitudinal hydrodynamic equation for plasma K+ is,

$$n_K m_K(d\mathbf{v}_K/dt) = n_K m_K[\partial\mathbf{v}_K/\partial t + (\mathbf{v}_K\cdot\nabla)\mathbf{v}_K] = n_K q_K[\mathbf{E} + \mathbf{v}_K\times\boldsymbol{\mu}\mathbf{H}] - \nabla\cdot\mathbf{P}_K - n_K m_K\mathbf{v}_K\nu_K \quad (2)$$

where, letter K denotes ion K+. We can obtain the plasma hydrodynamic equations for other ion species by replacing letter K with the other correspondent letters in equation (2).

### 3.2. The plasma natural oscillations and attenuations of the brain neuron fluids

Equations 1 and 2 can be transformed to three oscillation (vibration) equations respectively in x, y and z directions in a Cartesian coordinate system, or in r, φ and x directions in a cylindrical coordinate system, or in r, φ and θ directions in a spherical coordinate system.

Let ξ be the longitudinal departure of the equilibrium positions of the ion K+ in x coordinate (in a Cartesian coordinate system) (Figure 1 (a, b)), we neglect the magnetic field H because it is very week comparing the electric field [21-22], we also neglect $\mathbf{v}_{Ky}\cdot\nabla_y\mathbf{v}_{Kx} + \mathbf{v}_{Kz}\cdot\nabla_z\mathbf{v}_{Kx}$, assuming they are trivial compared with $\mathbf{v}_{Kx}\cdot\nabla_x\mathbf{v}_{Kx}$. Therefore, we approximately get a simplified one spatial dimensional scalar longitudinal hydrodynamic equation of the plasma K+ based on equation (2),

$$n_K m_K\{\partial(\partial\xi_K/\partial t)/\partial t + [(\partial\xi_K/\partial t)(\partial/\partial x)](\partial\xi_K/\partial t)\} = n_K q_K E_x - (\partial/\partial x)P_K - n_K m_K(\partial\xi_K/\partial t)\nu_K \quad \ldots\ldots\ldots\ldots(3)$$

Where, $\nabla\cdot\mathbf{P}$ is replaced by the gradient of a scalar pressure, $\nabla_x p = (\partial/\partial x)P_K$ [8].

Therefore, after separating the inner and external electric fields, from equation (3) we obtain,

$$n_K m_K\{\partial^2\xi_K/\partial t^2+[(\partial\xi_K/\partial t)(\partial/\partial x)](\partial\xi_K/\partial t)\} + n_K m_K(\partial\xi_K/\partial t)\nu_K+ (n_K q_K)^2\xi_K/\varepsilon_x+(\partial/\partial x)P_{Kx}$$

$$= n_K q_K E_{ex} \ldots\ldots\ldots\ldots (4)$$

Where, the subscript e denotes the externally produced, ε denotes an electric permittivity, the term $(n_K q_K)^2\xi_K/\varepsilon_x$ is produced by the inner disturbed electric field (Figure 1) and $\mathbf{E_{ex}}$ continually and periodically drives ion streams (Figures 2, 3) [8-9, 11-13].

From equation (4), we obtain the homogeneous equation of the natural oscillations and (or) waves without external forces, it is approximately,

$$n_K m_K\{\partial^2\xi_K/\partial t^2+[(\partial\xi_K/\partial t)(\partial/\partial x)](\partial\xi_K/\partial t)\} + n_K m_K(\partial\xi_K/\partial t)\nu_K+ (n_K q_K)^2\xi_K/\varepsilon_x+(\partial/\partial x)P_{Kx}$$

$$= 0 \ldots\ldots\ldots\ldots (5)$$

After neglecting trivial term $(\partial/\partial x)P_{Kx}$ [8,12] in equation (5), we get,

$$n_K m_K\partial^2\xi_K/\partial t^2 + n_K m_K(\partial\xi_K/\partial t)\nu_K+ (n_K q_K)^2\xi_K/\varepsilon_x = - n_K m_K[(\partial\xi_K/\partial t)(\partial/\partial x)](\partial\xi_K/\partial t) \ldots\ldots\ldots\ldots (6)$$

Let equation (6) approximately equal to 0 [8, 12], and assume $\xi_K(x,t) = X_K(x)T_K(t)$, $\partial X_K(x)/\partial x \neq 0$, $\partial T_K(t)/\partial t \neq 0$, and

$$[\partial X_K(x)/\partial x][\partial T_K(t)/\partial t]^2 \approx 0 \ldots\ldots\ldots\ldots (7)$$

$$\partial X_K(x)/\partial x = dX_K(x)/dx = - X_{nK0}/|x_1| \ldots\ldots\ldots\ldots (8)$$

Equation (8) is the homogeneous equation in space domain. See Figure 1 (c), the solution of equation (8) is,

$$X_{nKx} = X_{nK0}[1 - |x|/|x_1|],\ |x| \leq |x_1| \quad \ldots\ldots\ldots\ldots (9)$$

where $X_{nK0}$ is a constant complex amplitude, it is involved in a phase and it is based on boundary or initial conditions.

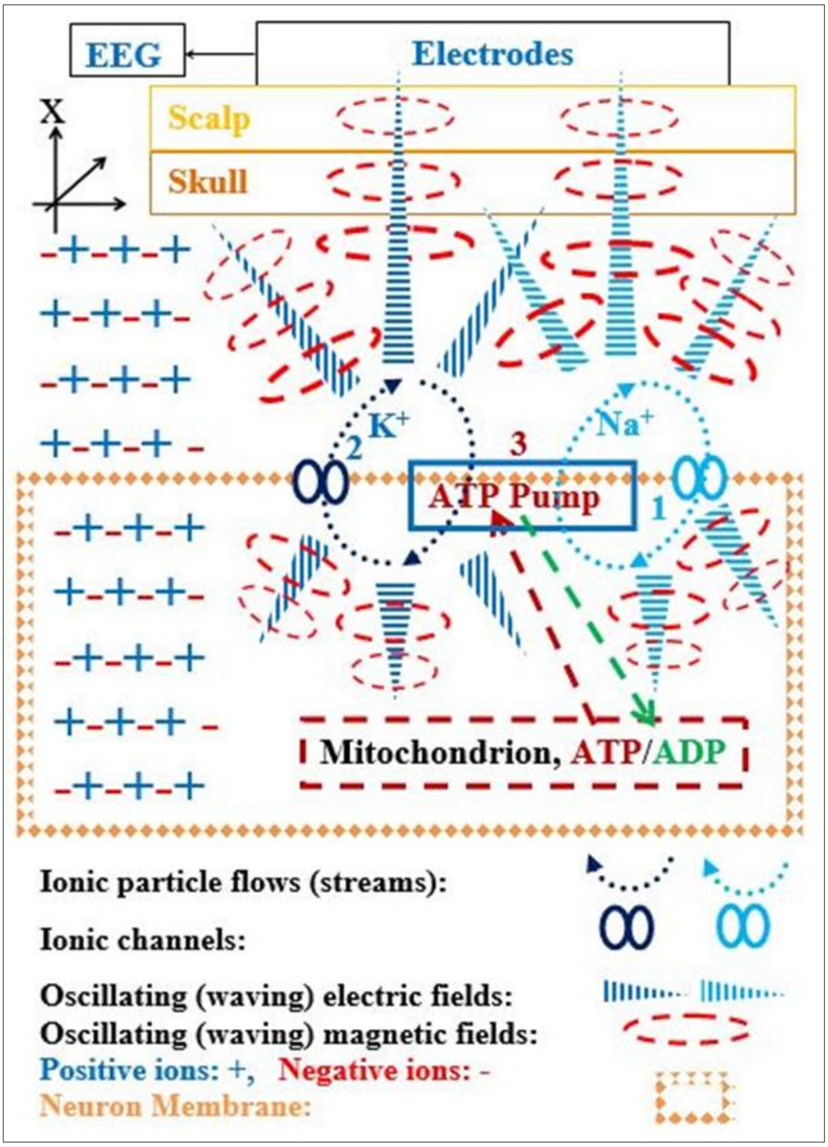


**Figure 2** Sampling neural activity of EEG [14-24]. Periodical K+ and Na+ inputs and outputs across the cellular membranes not only economically generate the alternating currents locally, but also economically transmit the alternating (± bidirectional) electric and magnetic fields (the wider (thicker) the lines, the stronger the fields), voltages and currents over long distances in the brain (pyramidal) neurons, neural networks and other physiological systems. Numbers 1, 2 and 3 represent the events' orders of the ionic particle flows during the period in time domain. Other pumps and ions are not shown for simplification. The draw is in two dimensions and not to scale. See the text and Figure 1

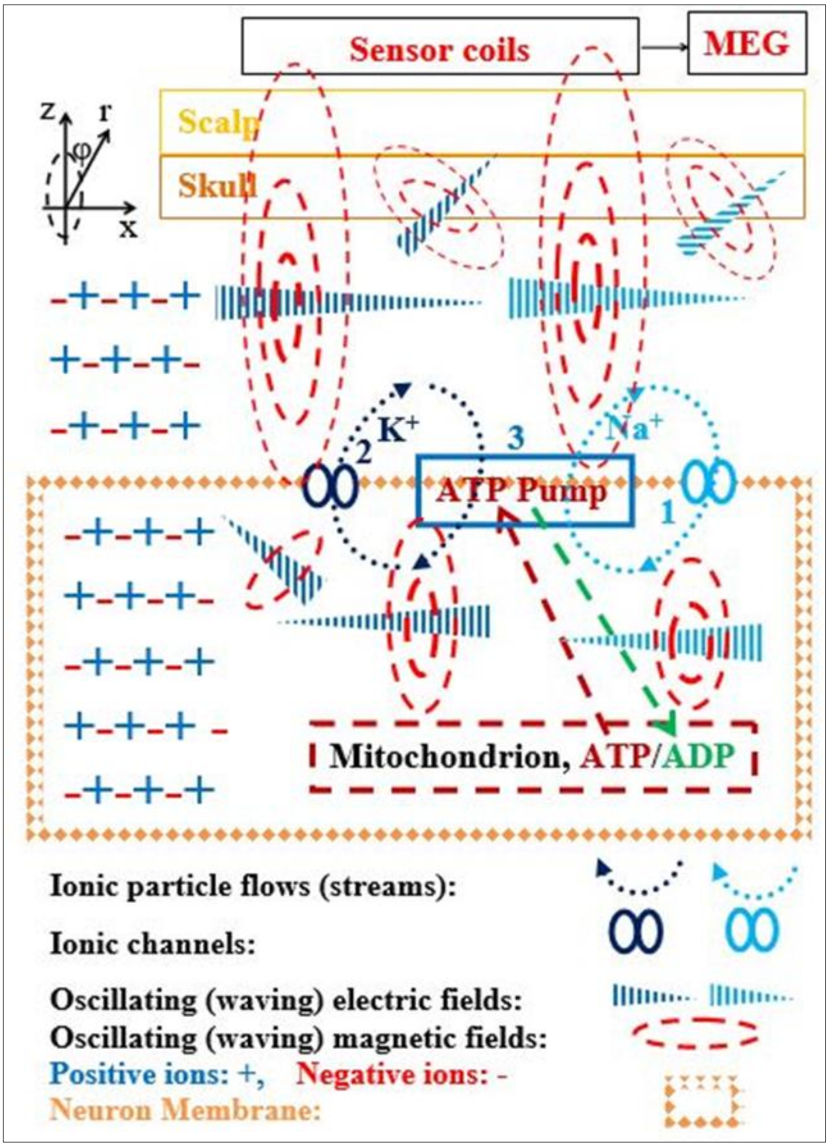


**Figure 3** Sampling neural activity of MEG [27, 28]: MEG signals are stronger than that in Figure 2. The draw is in two dimensions and not to scale. See the text and Figures 1, 2

From equations (6 - 7), we obtain the homogeneous equation of the natural oscillation in time domain [12],

$$n_K m_K d^2T_K(t)/\partial t^2 + n_K m_K (dT_K(t)/dt)\nu_K + (n_K q_K)^2 T_K(t)/\varepsilon_x = 0 \text{............ (10)}$$

The solution of equation (10) is (see Figure 1 (c)),

$$T_{nKt} = T_{nK0}\exp(-\Gamma_{nK}t + i\omega_{nK}t) \text{ ............ (11)}$$

Where $T_{nK0}$ is a constant complex amplitude, it is involved in a phase and it is based on initial conditions; $\Gamma_{nK}$ *(=* $\nu_K/2$) *is the natural attenuation coefficient.* The solution represents natural, transitory and under (critical or over) damped oscillations (Figure 1 (c)) depending on if the attenuating force is smaller than (or equal to) the restoring force; the damped (oscillating angular) plasma frequency is,

$$\omega_{nK} = [n_K q_K^2/\varepsilon_x m_K - (\nu_K/2)^2]^{1/2} \text{............ (12)}$$

Any electrical, chemical or mechanical perturbation can trig the oscillation or vibration, but the oscillation or vibration will be attenuated to zero soon (Figure 1 (c)), if without continuing driving power, based on EEG or MEG data [14-23].

*Equation (11) is involved in two dimensional functions: one is the real part and one is the imaginary part; the real and imaginary axes are perpendicular ($90^o$) each other; the boundary and initial conditions will determine the final solutions.*

The complete solution of equation (6) is roughly a product of equations (9) and (11),

$$\xi_{nKx} = \xi_{nK0}(1 - |x|/|x_1|)\exp(-\Gamma_{nK}t + i\omega_{nK}t)\text{…………..(13)}$$

The equation (13) indicates: in time domain, there is a damped oscillation; but in spatial domain, the displacement attenuates to zero linearly and sharply without any oscillation (Figure 1 (c)).

The temporal and spatial decays can be completely or partially compensated by external driving powers.

### 3.3. The forced plasma oscillations and waves of the brain neuron fluids

Also based on equation (4), neglecting minor fluid pressure, $P_K$ [8, 12], we obtain the inhomogeneous longitudinal hydrodynamic equation for plasma K+. It is approximately,

$$n_K m_K\{\partial^2\xi_K/\partial t^2 + [(\partial\xi_K/\partial t)(\partial/\partial x)](\partial\xi_K/\partial t)\} + n_K m_K(\partial\xi_K/\partial t)\nu_K + (n_K q_K)^2\xi_K/\varepsilon_x = n_K q_K E_{ex}\text{ ………..(14)}$$

The left side terms of the equation (14) represent natural, transitory and damped oscillations; $E_{ex}$ (the right side term of the equation) represents the driving electric fields that are forced and steady oscillations and waves as well as that compensate completely or partially the damping attenuations (Figures 2, 3, 4). The driving electric field $E_{ex}$ is involved in not only K+ and Na+ ions but also Cl-, Ca2+, Mg2+, and it is usually a superposition value with a forced period (or frequency) and it is generally produced by the currents of ion channels, ATP pumps and (or) exchangers (transporters) [11-12]. The oscillations or waves of brain neuron plasma will mostly follow the frequencies (periods) and amplitudes of the forced oscillations of the driving electric fields, i.e., the forced oscillation of the driving electric fields will determine the steady frequencies (periods) and amplitudes of the brain neuron plasma oscillations or waves.

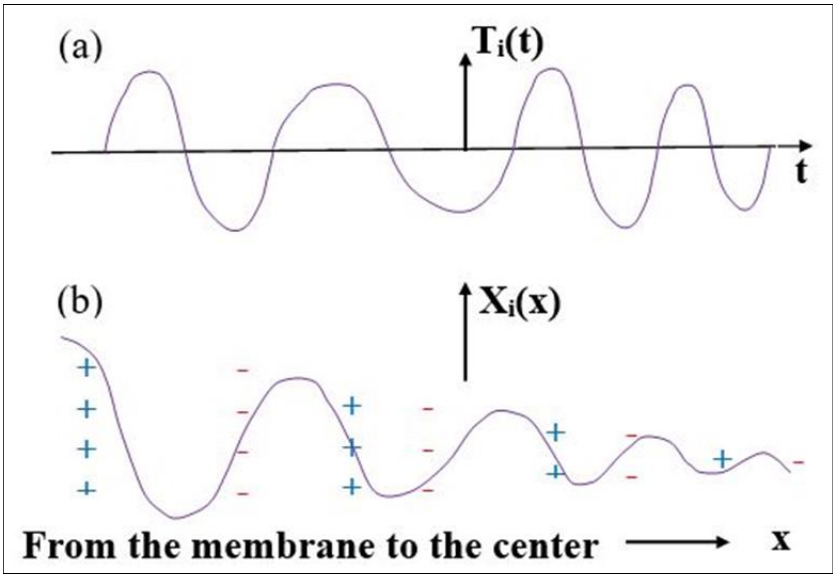


**Figure 4** Models of forced and powered ionic alternating (± bidirectional) waves in quasi (physics and liquid) plasma of a brain neuron (such as a pyramidal neuron). The waves are periodically powered or driven by APT pumps and ion channels. (a) In time domain, the attenuation of the quasi-sinusoidal oscillation has been completely compensated by the driving power. (b) In space domain, the wave is quasi sinusoidal and attenuating, but is compensated and transmitted over long distances in the brain neurons, neural networks and other physiological systems. Positive ions: + and negative ions: -; $T_i(t)$ and $X_i(x)$ denote the departure of the equilibrium positions of the ion species i (see the text and Figures 1, 2, 3). The draw is in two dimensions and not to scale. See the text

Any periodic motion of a fluid can be decomposed by Fourier analysis into a superposition of sinusoidal oscillations with different time and spatial frequencies ($\omega_e$ and $k_{eKx}$). When the oscillation amplitude is small, the waveform is generally sinusoidal [8].

In this investigation, we model the driving periodic electric field $E_{ex}$ respectively as underdamped and undamped waves in spatial and temporal domains, it is

$$E_{ex} = É_{ex}\exp(-\Gamma_{eKx}/x/)\exp[i(k_{eKx}x - \omega_e t)] \ldots\ldots\ldots\ldots(15)$$

Here $É_{ex}$ is a constant complex amplitude, $\Gamma_{eKx}$ (>0) is a spatial attenuation coefficient [8] and it represents a spatial decay of wave energy through dissipation. The solutions of waves can be determined by the boundary or (initial) conditions.

The correspondent departure of the equilibrium positions of the ion species K+ in x coordinate is,

$$\xi_{eKx} = \xi_{eK0}\exp(-\Gamma_{eKx}/x/)\exp[i(k_{eKx}x - \omega_e t)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

Where, where $\xi_{eK0}$ is a constant complex amplitude, is involved in a phase and is based on boundary (and initial) conditions. The decays of the oscillation energy through dissipation have been completely or partially compensated by the driving power in temporal or spatial domain (Figure 4). When $\omega_e \approx \omega_{nK}$, *quasi (scattering) resonant oscillations occur [13], the energies cost are minimum.*

The complete solution of equation (4) is approximately a superposition of equations (13) and (16). In a similar way, we can construct equations in other spatial dimensions and obtain similar solutions; we can also construct equations for other ion species and obtain similar solutions. Especially for the forced and steady dominant oscillations and waves, the solutions are identical or similar for all of the specie ions, because the driving electric fields are contributed by all of the specie ion currents in every period and the effective charges and masses are roughly (quasi) equal.

### 3.4. The frequency and amplitude modulations (encodings) of the brain neuron plasmas' (fluids') oscillations and waves

The electromagnetic power in a unit volume of an assumed isotropic plasma is [10],

$$\nabla\cdot(\mathbf{E_e}\times\mathbf{H_e}) = \mathbf{E_e}\cdot\mathbf{J_e} + \partial/\partial t(\varepsilon E_e^2/2 + \mu H_e^2/2) \ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Where, $\mathbf{E}_e\times\mathbf{H}_e$ is a Poynting vector and represents an energy flow density (per unit area) and information intensities (II) [7]; the multiple vectors can perform signal processing, such as auto and cross correlation (association) [7]; the energy is usually limited by biological energies, such as ATP; **J** denotes the electric current density. ε and μ respectively denote effective (or mean) electric permittivity and magnetic permeability (they are assumed to be approximately isotropic). Because the energy density (in a unit volume) $\varepsilon E_e^2/2 + \mu H_e^2/2$ is theoretically a constant, therefore, based on conservation law of energies, we have,

$$|\mathbf{E}_e\cdot\mathbf{J}_e|_x = |(\Delta\Phi_{ex}/\Delta x)[(I_x/(\Delta y\Delta z)]|_x$$

$$= |(\Delta\Phi_{ex}/\Delta x)[(q\Delta n/\Delta t)/(\Delta y\Delta z)]|_x$$

$$= |\Delta\Phi_{ex}(q\Delta n/\Delta t)/(\Delta x\Delta y\Delta z)|_x \le |C_{ex}| \ldots\ldots\ldots\ldots(18)$$

where, C denotes a constant complex, Δ and Φ respectively denote small change and electric potential; ΔxΔyΔz is the unit volume; qΔn is the change of the effective charge density (see 3.5). Based on equations (16), Figures 2, 3, 4, we have an ionic density $n_x$,

$$n_x = n_0\exp(-\Gamma_{ex}/x/)\exp[i(k_{ex}x - \omega_e t)] \ldots\ldots\ldots\ldots\ldots(19)$$

where $n_0$ is a constant complex amplitude. From equation (19), we have,

$$\Delta n_x/\Delta t \approx dn_x/dt = -n_0\omega_e\exp(-\Gamma_{ex}/x/)\exp[i(k_{ex}x - \omega_e t)] \ldots\ldots\ldots\ldots\ldots(20)$$

According to equations (18) and (20), we get,

$$|\Delta\Phi_{ex}\omega_e/ \le |C_{ex}| \quad \ldots\ldots\ldots\ldots(21)$$

Equations (18) - (21) imply the neuron signals (currents, voltages, fields) are mostly frequency [6-7] and amplitude encodings (modulations). Experimentally (clinically), the frequencies and (or) amplitudes of brain EEG (or MEG) α, ß, θ and δ waves do change with different electromagnetic, electrochemical or mechanical triggers (stimulations).

The nervous system as well as immune and endocrine systems involve the modulations by electromagnetic, chemic or mechanic stimulations. Generally, the more frequent stimulation the brain neurons receive, the higher the brain waves' frequencies; the more the excited brain neurons, the higher the brain waves' (voltage) amplitudes [16]. The *normal brain EEG and (or) MEG signals can be twisted by some abnormal brain activities, such as epilepsy.*

Our model inequality (21) semi quantitatively or qualitatively describes the product of frequency and voltage of the brain signals is finite.

### 3.5. Effective values of the alternating electric current densities, fields and voltages of the brain neuron plasmas' (fluids') oscillations and waves

We can theoretically and approximately get the results of oscillations or waves in the extracellular fluids for all ion species with the same way as the above, using different $q_i$, $m_i$, $\nu_i$ and $n_i$ for different ion species i in the above plasma hydrodynamic equations.

The different spatial directions and (or) time orders of the ionic particle flows work together to accomplish alternating (± bidirectional) electric currents. Periodical ionic inputs and outputs across the cellular membranes not only economically generate the alternating currents locally, (Figures 2, 3), but also economically transmit the alternating (± bidirectional) electric and magnetic fields, voltages and currents over long distances in the brain neurons, neural networks and other physiological systems.

The external and periodical driving electrochemical powers dominate the brain neuron plasma oscillations and waves, they act on all ion species. The driving electric currents are mostly contributed by K+, Na+ and Ca2+ ATP pumps and the related channels (Figures 2, 3) [14].

Based on neuroscience data [14], we estimate the effective (root mean square) values of electric current $\mathbf{I_x}$ with,

$$\mathbf{I_x} = \{\Sigma_i \langle \mathbf{I}_{ix}^2 \rangle\}^{1/2} \quad \text{............}(22)$$

Where < > denotes a mean value. $\mathbf{I}_i$ may be in different spatial directions and time orders. Therefore, we can consider the correspondent the effective values of the electric current densities $\mathbf{J_x}$, fields $\mathbf{E_x}$ and voltages $\Delta\Phi_x$ based on classic electric theories:

$$\mathbf{J_x} = \mathbf{I_x}/A_x \text{...............}(23)$$

$$\mathbf{E_x} = \mathbf{J_x}/\sigma_x \text{..............}(24)$$

$$\Delta\Phi_x = -\mathbf{E_x}\Delta x \text{...............}(25)$$

$$\nabla\times\mathbf{H}|_\varphi = \mathbf{J_x} + \partial/\partial t(\varepsilon\mathbf{E_x}) \text{.......................}(26)$$

Where, A and σ respectively denote the cross-section area and electric conductivity. The equations provide us theories of EEG and (or) MEG.

When the electric signals are transmitting through the skulls (Figures 2, 3) and scalps, displacement currents are involved based on the theory in Maxwell's equations, the correspondent electric current densities can be estimated with the second term of equation (26). Equations (25) and (26) respectively provide theories of EEG and MEG sampling mechanisms [27, 28].

Multiple brain (α, ß, θ, Σ or δ) waves may be produced from different brain neurons simultaneously, therefore the measured data of EEG (MEG) can be a superposition of the multiple waves (Figures 2, 3), based on our models in this study.

Additionally, the alternating signals enhance the brain neuron information encoding (decoding) and processing; different ions have different chemical effects in brain neuron plasma.

## 4. Discussions

In general, however, in the inhomogeneous plasma, the tensors of electric permittivity [13] and magnetic permeability respectively have all nine components nonzero and the oscillation or wave models are somewhat more complicated than our models of EEG and MEG mechanisms in this paper.

Various regions of the brain do not emit the same brain wave frequency simultaneously. An EEG signal between electrodes placed on the scalp consists of many waves with different characteristics. The large amount of data received from even one single EEG recording makes interpretation difficult. The brain wave patterns are unique for every individual. [23]

The electric potentials, densities and velocities have similar wave profiles to Figure 4.

Plasma oscillations propagate along the neuron membranes (or neurofibrils) in a finite medium because of fringing fields [8], such as waves propagate in myelinated fibers along axons (nodes) [6].

The electric oscillations of the plasma in extracellular fluids dominantly propagate along meridian channels that provide canals for the ion flows of the electric currents [25].

The attenuation of the plasma waves also increases rapidly with frequency, but decreases with increasing velocity. It also increases with increasing fluid viscosity [26].

Using EEG to exam brain activities is similar to using electrocardiogram (ECG) to exam heart activities. We believe, the modeling principles in this paper is applicable to the electric and magnetic activities of other biological cells, such as cardiac and skeleton muscles.

Artificial brain pacemakers are possible to send electrical pulses to encode or decode neuronal signals as well as to help our brain beats at a normal rate and rhythm. We believe our models in this study will be helpful to the researches or developments of brain-computer interface (BCI)， human-machine symbiosis or neuralink.

Brain and (or) neurons work in a similar way to a computer (electronic brain). The both have clocks, memories, central and graphic processing units (CPU and GPU*),* signal generators *and interfaces*. The ATP pumps and channels of biological ions work together as frequency variant biologic clocks depending on triggers or stimulations, i.e., states of consciousness*;* they are also signal generators and interfaces.

A system of coordinates with the real axis only is not complete for a complex data. A complex data is at least two dimensional; one is the real and another one is imaginary; the real and imaginary axes are perpendicular ($90^o$) each other. In theories of waves, oscillations or vibrations, the complex coordinates play important roles. Especially, in microscopic space – time, e.g., quantum mechanics and its wave (Schrodinger: energy or probability) equations, the imaginary axis cannot be neglected in the theory. We have to use a complex data (Xc) with both real (Xr) and imaginary (Xi) parts to represent the stereoscopic waves for the completeness, because the energy or probability densities are involved in $|Xc|^2 = XcXc^*$, where the complex is $Xc = Xr + \sqrt{-1}Xi$ and the complex conjugate is $Xc^* = Xr - \sqrt{-1}Xi$.

## 5. Conclusion

*We introduce the plasma physics into brain theory; based on plasma hydrodynamic equations and published data of the* brain or neuron sciences and molecular biology*, at an ionic level, we model the mechanisms of the complete procedures of* excitations, attenuations, *propagations (oscillations and waves) of the brain neuronal fluids and extracellular fluids in the both natural and forced modes; our models include* active pumps and passive channels of biological ions. Moreover, we also elucidate frequency and amplitude modulations (encodings), displacement currents, as well as effective values of the alternating electric current densities, electric and magnetic fields and voltages*,* based on the modeling results of the brain neuronal and extracellular plasma waves (oscillations). Our modeling results are qualitatively consistent with the published data of brain neuroscience as well as EEG and MEG.

We believe, our models can help us data analysis and diagnosis more accurately in clinic as well as understanding more deeply information-rich EEG and MEG by obtaining more complete electromagnetic signals of the brain neurons.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors declare no conflict of interest.

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