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Innovative Diffusion Equations of the Nerve Impulses

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ABSTRACT

Introduction: *We recently achieved a new definition of the electric charges as electrified energy or electromagnetic waves of electric potential, and a new definition of the nerve impulses as electric charges. Neurologists succeeded in the measurement of the electrical conductivity and capacitance of neural channels. Accordingly, we explain the transfer of the nerve impulses through the neural channels by diffusion like the heat. Then we derive in an innovative Diffusion Equation (D.E) of the flow of the nerve impulses as the D. E. of heat.*

Method: *We firstly derive a D.E. as an innovative mathematical model the flow of electric charges through conductors by the principles of conservation of energy. According to the definition of nerve impulses as electric charges, we find a similar D. E. for the flow of the nerve impulses through the neural channels like D.E. of the electric charges.*

Conclusions: *Innovative definition of the diffusivity of the nerve impulse of the units "m^2/sec" A new proportionality relation between the volumetric concentration of the nerve impulses and its electric potential or the action potential. Innovative mathematical models of the flow of the nerve impulses through the neural channels by D. E. that involve the defined diffusivity, the potential of the nerve impulses, the Laplacian operator, and the time or the entropy of the flowing nerve impulses. Corrections of redundancies in the neurosciences as the definition of the action potential as moving nerve impulses.*

Keywords
Nerve Impulses, Electric Charge, Action Potential, Volumetric concentration, Diffusivity, Diffusion Equations, Entropy.

Introduction
Recent studies recognized the nature of electric charges as electromagnetic waves which have an electric potential, like the nature of heat as radiation or electromagnetic waves that have a thermal potential [1]. However, literature defined the electric current as flow of electrons while the measured velocity of electrons through good conductors does not exceed millimeters per second [2]. As the measured velocity of the electric signals is near the velocity of light, the proper definition of the nature of flow of electric charges as energy or electromagnetic waves that have electric potential is the prevailing definition and succeeded in finding plausible explanations of different electromagnetic phenomena [3]. As electric conductors have electric conductivity and capacitance, we firstly introduce an innovative definition of the diffusivity of electric charges through conductors. By applying the principles of conservation of energy, we derive an innovative D. E. of the electric charges like the D. E. of heat. Recent studies also proved the nature of the nerve impulses as electric charges or electrified energy measured by "Joule" and the unit of its electric potential is the "Volt". Additionally, neurologist succeeded in measuring electrical conductivity and electrical capacitance of the neural tissues [4,5]. So, diffusion is the mechanism of transfer of the nerve impulses, as electric charges, though the conductive neural channels. So, we introduce an innovative definition of the diffusivity of the nerve impulses, as the diffusivity of heat, and an innovative D. E. of the nerve impulses that simulates the electric field of the neural networks. Recognizing the nature of electric charges as energy, we recently found the Ammeter's reading,

whose unit is "Watt/Volt" measures the rate of growth of entropy inside the electric conductors [6]. Such a rate is function of the irreversibility of the process of transfer of energy through the neural channels, as electric conductors, and indicates their capacity to pass certain power by a unit electric potential [7]. As the neurologists found entropy a neurodiagnostic property of the neural channels, we derive an innovative D. E. of the nerve impulse that introduces the entropy, as a function of time, to map the dependence electric field in the neural networks on growth of channel's entropy. We also present the mathematical solutions of the innovative D.E. to hold a comparison between the predicted results and the machine records of the flow of nerve impulses during diagnostic processes. At the end of this study, a survey of the introduced innovations is summarized in the conclusions.

Diffusion Equation of the electric charges

Ohm's law states a proportionality relation between the current density in an ohmic conductor and the electric field [9]. According to the recently defined nature of the electric charge as energy, denoted as "Q_{elect}," the rate of flow of such energy, denoted as "$\frac{d\,Q_{elect}}{d\tau}$," across a thin slab of thickness "dX," by the force of potential difference "dV," as shown in Figure 1, can be determined in terms of the potential gradient "$\frac{dV}{dX}$" according to the Ohm's law as follows [9]:

$$\frac{dQ_{elect}}{d\tau} = k_{elect}\, A\, \frac{dV}{dX} \qquad \text{Watt} \tag{1}$$

To define the diffusivity of electric charges as energy like the heat energy, we may look at the thermal diffusivity which is defined as follows [10]:

$$\propto_{therm} = \frac{k_{therm}}{\rho\, c_{therm}} = \left. k_{therm}\, \frac{Joule}{\sec deg} \middle/ \rho\, \frac{kg}{m^3}\, c_{therm}\, \frac{Joule}{kg\ deg} \right. = \left. k_{therm}\, \frac{Joule}{\sec deg} \middle/ c_{therm,vol}\, \frac{Joule}{m^3\ deg} \right. \tag{2}$$

According to the previous equation, units of the product "$\rho\, c_{therm}$" in the dominator has the units "$\frac{Joule}{m^3\ deg}$." Such quotient has the unit of specific volumetric thermal capacity denoted as "$c_{therm,vol}$" or the heat capacity per unit volume of a conductor. Accordingly, the thermal diffusivity can be expressed as follows:

$$\propto_{therm} = \frac{k_{therm}}{c_{therm,vol}} \qquad \frac{m^2}{sec} \tag{3}$$

Recognizing the nature of electric charges as electrified energy or electromagnetic waves that have electric potential, like the heat as energy that has thermal potential, the electric charges also have an electric diffusivity which can be defined by a similar quotient of the electric conductivity and the specific volumetric electric capacity of the electric conductor, as defined for heat by Equation (3), as follows:

$$\propto_{elect} = \frac{k_{elect}}{c_{elect,vol}} \quad \frac{m^2}{sec} \tag{4}$$

Literatures define the electric capacitance "C_{elect}" as the *capability of a material object or device to store electric energy or charge per unit voltage according to the following equation:*

$$C_{elect} = \frac{Q_{elect}}{V} \quad \frac{Joule}{Volt} \tag{5}$$

According to this definition, the relation between the electric capacitance and the introduced definition of specific volumetric electric capacitance, that is defined as the electric capacitance per unit volume "v," can be expressed as follows:

$$c_{elect,vol} = \frac{C_{elect}}{v} = \frac{Q_{elect}/V}{v} \quad \frac{Joule}{Volt\ .m^3} \tag{6}$$

According to Equation (6); it is possible to the express the potential "V" *as a function of the stored* electric energy "Q_{elect}" per unit volume "v" as *follows:*

$$V = \frac{Q_{elect}/v}{c_{elect,vol}} = \frac{1}{c_{elect,vol}}\, (Q_{elect}/v) \qquad \text{Volt} \tag{7}$$

According to Equation (7); the electrical potential "V" is directly proportional to the volumetric concentration of the electrical energy in a medium "Q_{elect}/v" where the proportionality constant is a reciprocal of the *specific volumetric electric capacitance' i.e.,* "$\frac{1}{c_{elect,vol}}$".

Multiplying and dividing the R.H.S. of Eqn. (1) by $c_{elect,vol}$

$$\frac{dQ_{elect}}{d\tau} = \frac{k_{elect}}{c_{elect,vol}}\, A \left[\frac{d(V \cdot c_{elect,vol})}{dx}\right] \tag{8}$$

Substituting the voltage "V" from (7) and the ratio "$\frac{k_{elect}}{c_{elect,vol}}$" from (6) into (8), we get:

$$\frac{dQ_{elect}}{d\tau} = \alpha_{elect}\, A \left[\frac{(V.\frac{Q_{elect}/V}{v})}{dx}\right] = \alpha_{elect}\, A\, \left(\frac{d\,(Q_{elect}/v)}{dx}\right) \tag{9}$$

The differential "$\frac{d(Q_{elect}/v)}{d\,x}$" is the gradient of the volumetric concentration of the electric energy or charge inside the conductor. According to Equation (9), the rate of charge transfer in a conductor is directly proportional to the gradient of the volumetric concentration of the electrical energy or charge in such conductor. The proportionality constant of this relation, according to Equation (9), is the electrical diffusivity "$\propto_{electric}$".

According to thermodynamics literature, the following D. E. is concluded by applying the principles of conservation of energy [10]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\propto_{thermal}}\, \frac{\partial T}{\partial \tau} \tag{10}$$

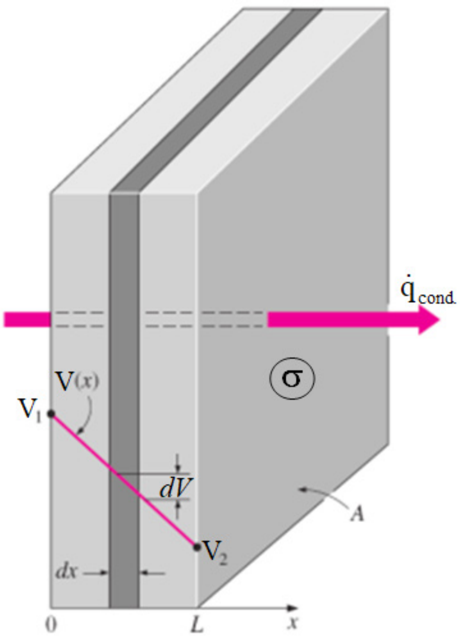

Figure 1: Charge transfer rate in a plane conductor due to a potential gradient "$\frac{dV}{dx}$" [9].

Equation (10) determines the thermal field in a conductor that passes thermal energy, or heat, by the force of the thermal potential "T" through conductors that have the thermal diffusivity "$\propto_{thermal}$." The similarity of the natures of the thermal and electrical energies as electromagnetic waves of thermal or electric potentials guides to find, by application the principles of conservation of energy on the slap of Figure 1, a D. E. of the electric energy like Equation (10) is as follows:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = \frac{1}{\alpha_{elect}} \frac{\partial V}{\partial \tau} \qquad (11)$$

Equation (11) replaces the thermal potential in Equation (10) by the electric potential "V" and the thermal diffusivity by the electric diffusivity "Q_{elect}" As an experimental proof of the analogy of the thermal and electric fields that assures the validity of the D. E. (11) for electric fields, as the validity of Equation (10) for determining temperatures in thermal fields, is the experimental use of electric field to model or to predict the temperatures of an analogical thermal field [11]. The found measurement results of the temperatures and electric potentials in both fields proves the analogy of the D. E. equations that govern both fields, i.e., Equations (10) and (11) [12].

In a case of steady state condition, we get the known Laplace equation for electric field, by substituting $\frac{\partial V}{\partial \tau} = 0$ in (11), as follows:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \qquad (12)$$

Substituting the voltage "V" as a function of volumetric concentration of the electric charge "(Q_{elect}/v)" according to Equation (7) in Equation (11); we get the following D. E. of concentration of the nerve impulses:

$$\frac{\partial^2 (Q_{elect}/v)}{\partial x^2} + \frac{\partial^2 (Q_{elect}/v)}{\partial y^2} + \frac{\partial^2 (Q_{elect}/v)}{\partial z^2} = \frac{1}{\propto_{elect}} \frac{\partial (Q_{elect}/v)}{\partial \tau} \qquad (13)$$

Diffusion Equation of the Nerve Impulses.

Hodgkin found scientific evidence of transmission of the nerve impulses as electric charges in the neural systems [13]. According to the neural references, the formed myelin sheath around the nerves allows the transmission of the nerve impulses, as electric charges, by conduction along such channels [14,15]. The measured electric specific resistance of myelin sheath is $9.10^{-6}\ \Omega.m$ and the electric capacitance for the 2 mm-length of such sheath is 1.8×10^{-12} F [14]. The measured axon's diameter is 0.5 micron, and the thickness of the myelin sheath is 0.3 micron in most cases [15]. Defining the nerve impulses as electrified energy, it is possible to state that the nerve impulses flow through the neural channels by diffusion. According to the measured values of conductivity and diffusivity of the neural channels, it is possible to calculate the specific volumetric electric capacity of the myelin sheath "$c_{imp,vol}$" according to Equation (6), and the diffusivity of the neural channels according to Equation (4) as follows:

$$c_{imp,vol} = \frac{Q_{elect}/V}{v} \quad \frac{Joule}{Volt\ .m^3} \qquad (14)$$

$$\alpha_{imp} = \frac{k_{imp}}{c_{imp,vol}} \quad \frac{m^2}{sec} \qquad (15)$$

So, it is possible to write the D. E. that describes the propagating potential of the nerve impulses, as electrified energy, through the neural axons by a similar equation like Equation (11) as follows:

$$\frac{\partial^2 V_{imp}}{\partial x^2} + \frac{\partial^2 V_{imp}}{\partial y^2} + \frac{\partial^2 V_{imp}}{\partial z^2} = \frac{1}{\alpha_{imp}} \frac{\partial V_{imp}}{\partial \tau} \qquad (16)$$

According to Equation (14), it is also possible to define the potential of the nerve impulses as a function of its concentration per unit volume as follows:

$$V_{imp} = \frac{1}{c_{imp,vol}} \left(Q_{impl}/v \right) \quad \text{Volt} \qquad (17)$$

Where the reciprocal of the volumetric capacitance of the nerve impulses "$1/c_{imp,vol}$" is the proportionality constant in this relation.

Substituting "V_{imp}" from Equation (17) into Equation (16), another D. E. that maps the concentration of the nerve impulses into the neural network is as follows:

$$\frac{\partial^2 (Q_{imp}/v)}{\partial x^2} + \frac{\partial^2 (Q_{imp}/v)}{\partial y^2} + \frac{\partial^2 (Q_{imp}/v)}{\partial z^2} = \frac{1}{\propto_{imp}} \frac{\partial (Q_{imp}/v)}{\partial \tau} \qquad (18)$$

Studying the generation of the energy required for generation the nerve impulses, as electric charges, the production of the metabolic heat starts inside the brain neurons [16]. This heat increases the temperature of the core of the cell than the temperature of the surrounding neural channels [17]. So, heat transfers from the neuron cell across its membrane by the action of its thermal potential forcing it to flow to the surrounding neural channels. When the flowing heat crosses the neuron's membrane, which has Sodium-Potassium junctions, the thermal potential of the transferred heat changes to electric potential, or an action potential, by the Seebeck effect [18]. By crossing the membrane, the transferred energy from neurons gains an electric potential and becomes electric energy whose potential is proportional to the thermal potential of the metabolic heat. Such a process of neurons is analogic to conversion of thermal energy to electric energy in the thermoelectric generators [19]. So, nerve impulses, as electric charges of certain electric potential, accumulate outside the membrane of the neurons. Such accumulation increases the volumetric concentration of the nerve impulses, as electric charges. According to Equation (17), the accumulated nerve impulses of high concentration outside the membrane determine the potential of the nerve impulses, as electric charges, which is proportional to its concentration. This potential was traditionally called "action potential" which was not recognized as an electrical potential of the nerve impulses but as a moving nerve impulses or ion's concentration [20]. So, the introduced explanation of the nerve impulses ends the found confusions in neurosciences regarding its nature and how it is generated [21].

According to the thermodynamics of energy, the flow of energy in any system leads to growth of its irreversibility defined as the system's entropy [22]. So, the entropy of the neural channels increases by the flow of the nerve impulses as energy and its growth represents a neurodiagnostic property [23]. However, Ammeters measure the rate of growth of such entropy, denoted as "$\dot{s}$," and determines the ability of the neural channels to allow a certain flow rate of energy, as nerve impulses, by a unit electric potential. According to the importance of entropy of the neural channels as a diagnostic property, it is possible to introduce a new diffusion equation that predicts the entropy change during the flow of nerve impulses by replacing the time "τ" in the diffusion equation (14) by the entropy "s." Such replacement depends on the direct relation between the entropy and time according to the following equation:

$$\dot{s} = \frac{\partial s}{\partial t} \frac{Watt}{Volt\ sec} \tag{19}$$

Where "$\dot{s}$" is the measured rate of increase or growth of entropy and represents a property of the neural channels. Multiplying and dividing the R.H.S. of Equation (11) by the differential "∂s", we get:

$$\frac{\partial^2 V_{imp}}{\partial x^2} + \frac{\partial^2 V_{imp}}{\partial y^2} + \frac{\partial^2 V_{imp}}{\partial z^2} = \frac{1}{\alpha_{imp}} \frac{\partial V_{imp}}{\partial \tau}\, x\, \frac{\partial S}{\partial S}$$

$$= \frac{1}{\alpha_{imp}} \frac{\partial S}{\partial \tau} \frac{\partial S}{\partial S} = \frac{\dot{s}}{\alpha_{elect}} \frac{\partial V_{imp}}{\partial S} \tag{20}$$

The D. E. (19) involves the rate of growth of entropy "$\dot{s}$" as a measurable parameter by the Ammeters. Such equation maps the dependence of the potential of the nerve impulses, known as the action potential, as a function of the entropy though the neural networks.

Replacing the potential of the nerve impulse "V_{imp}" in Equation (20) by the volumetric concentration of nerve impulses "$Q_{imp/v}$" according to Equation (7), we get the following innovative D. E. that maps volumetric concentration of the nerve impulses as a function of the growing entropy "S" during the diffusion of the nerve impulses through the neural channels.

$$\frac{\partial^2 (Q_{imp}/v)}{\partial x^2} + \frac{\partial^2 (Q_{imp}/v)}{\partial y^2} + \frac{\partial^2 (Q_{imp}/v)}{\partial z^2} = \frac{\dot{s}}{\alpha_{imp}} \frac{\partial (Q_{imp}/v)}{\partial s} \tag{21}$$

Mathematical Solution of the One-Dimensional Diffusion Equation of the Nerve Impulses

The one-dimensional nerve impulse diffusion equation, according to Equation (16), can be written as follows:

$$\frac{\partial V_{imp}}{\partial \tau} = \alpha_{imp} \frac{\partial^2 V_{imp}}{\partial x^2} \tag{22}$$

Such an equation looks a bit like a wave equation. Therefore, one method to solve it is to look for wave-like solutions of the form [24]:

$$V_{imp}(x,\tau) \propto e^{(i(kx-\omega\tau))} \tag{23}$$

Where "$k = 2\pi/\lambda$" is the wave vector, "$\omega = 2\pi f$" is the angular velocity, "λ" is the wavelength, and "f" is the frequency. Substitution of "$V_{imp}(x,\tau)$" from Equation (22) into Equation (22) yields:

$$-i\,\omega = -\alpha_{imp}\, k^2 \tag{24}$$

According to Equation (24), the general solution of Equation (23) for $x \geq 0$ can be found as follows [30]:

$$V_{imp}(x,\tau) = \sum_{\omega} A(\omega)\, e^{((i-1)\sqrt{\frac{\omega}{2\alpha_{imp}}}x)} \tag{25}$$

According to previous studies, the generation of the nerve impulses starts at neuron's membrane by conversion the cell's metabolic heat, as electromagnetic waves of thermal potential, into nerve impulses in the form of electric charges, or electromagnetic waves of electric potential or the action potential by Seebeck effect [25]. The found solution of the modified Maxwell's wave equations that define the flow of the nerve impulses as electromagnetic waves of mean electric potential "V_{imp}" is as follows [26]:

$$V_{imp} = V_m + B\cos\omega\tau \quad \text{Volt} \tag{26}$$

Where "B" is the amplitude of the oscillating wave, and "ω" is the angular velocity of the wave. According to measurements of initial nerve impulses at the neural centers of a human skull due to light stimulation, Figure 2, the dependence of their electric potential on time is like the found solution of the modified Maxwell's wave equations as modelled by Equation (26) [27].

Considering the start of flow of the nerve impulses is at the cell's membrane, as the first point of diffusion of the nerve impulses into the neural channels, it is possible to consider Equation (25) as formulation of the boundary conditions at $X = 0$ as follows:

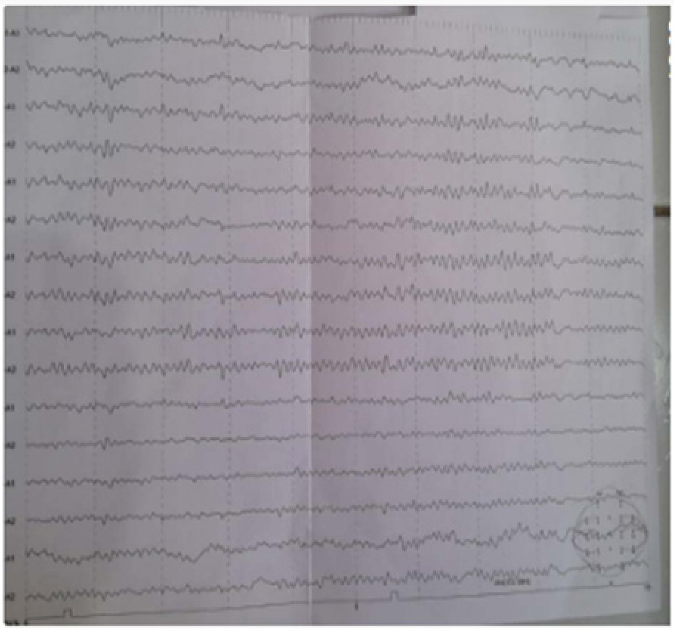

Figure 2: A machine record of stimulated responses, or nerve impulses, at different neural centers on scull of a man [27].

$$V_{impulse}\ (0,\tau) = V_{membrane} + B\cos\omega\tau \tag{27}$$

This boundary condition is as follows [25]:

$$V_{impulse}\ (0,\tau) = V_{membrane} \pm B(\tfrac{1}{2}e^{i\omega\tau} + e^{-i\omega\tau}) \tag{28}$$

However, substituting "$x = 0$" in the general solution (25), the boundary condition is as follows:

$$V_{impulse}\ (0,\tau) = \textstyle\sum_{\omega} A(\,V_{membrane}\,\omega)\,e^{-i\omega\tau} \tag{29}$$

Comparison of Equations (28) and (29), leads to state the only nonzero values of $V(\omega)$ are as follows:

$$A(0) = V_{membrane}, A(-\omega) = \tfrac{B}{2}, A(\omega) = \tfrac{B}{2} \tag{30}$$

Hence, the solution for $x \geq 0$ is as follows:

$$V_{imp}(x,\tau) = V_{membrane} - Be^{-x/\delta}\cos(\omega\tau + x/\delta) \tag{31}$$

Where:

$$\delta = \sqrt{\frac{2\alpha_{imp}}{\omega}} \tag{32}$$

"δ" is known as the skin depth [24]. It is possible to note the exponential fall of potential of the nerve impulses, or the action potential, along the length of the neural channel "$e^{-x/\delta}$."

According to Equation (21), it is possible to find the following one-dimensional impulse diffusion equation in terms of entropy growth:

$$\frac{\partial^2 V_{imp}}{\partial x^2} = \frac{\dot{s}}{\alpha_{elect}}\frac{\partial V_{imp}}{\partial s} \tag{32}$$

Solving the D.E. (32) by the same procedure that was followed to solve Equation (17), where the measurable time in Equation (17) is replaced by the measurable entropy in Equation (32) according to the following relation:

$$S = \dot{s}\,x\,\tau \tag{33}$$

Where "$\dot{s}$" is the measured rate of growth of entropy in the neural channels as measured by the connected Ammeter.

$$V_{imp}(x,s) = V_{membrane} - Be^{-x/\delta}\cos(\omega\, s/\dot{s} + x/\delta) \tag{34}$$

Where "" is the measured rate of growth of entropy in the neural channels as read by Ammeters. Equation (33) defines the decay of the amplitude "$V_{imp}(x,s)$" as function of the dimensionless term "$(\omega\, s/\dot{s} + x/\delta)$." Figure 3 represents a predicted decay of the amplitude of the nerve impulse that depends on a computational property of the neural systems that depends on dimensionless irreversibility of the neural network which is called " Diffusion Anisotropy (D. A)" [28]. The same decay of the Amplitude of the wave of the nerve impulse is also predicted according to Equation (33) by its dependence on the dimensionless parameter "$(\omega\, s/\dot{s} + x/\delta)$." Such coincidence may indicate a dependence of the D. A. on the dimensionless term "$(\omega\, s/\dot{s} + x/\delta)$."

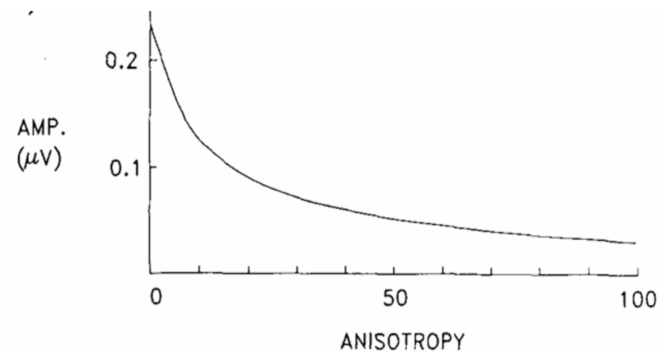

Figure 3: "$V_{imp}(x,s)$" as a function of Anisotropy (or "$\omega\, s/\dot{s} + x/\delta$") .

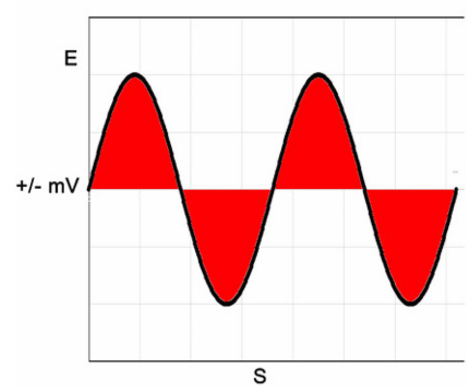

Figure 4: Representation of the initial wave of nerve impulses (at x=0) as energy of electric potential "$V_{membrance}$" in the E-s coordinates according to Equation (35).

Substituting × = 0 in Equation (34); we find the initial nerve impulse as a wave of the following form:

$$V_{imp}(o,s) = V_{membrane} - B\cos(\omega \, {}^{s}/_{\dot{s}}) \tag{35}$$

The horizontal coordinate in the Figure 4 represents the growth of entropy "s" during diffusion of the nerve impulse, calculated as the product of the Ammeter's readings "$\dot{s}$" Watt/Volt times the measured diffusion time "τ" according to Equation (30). The vertical axis represents the electric potential of the flowing nerve impulse. Figure 5 represents the machine record of the response of the neural system to injected impulse that has the same shape of the calculated nerve impulse in Figure 4 [29]. The main advantage of representation the nerve impulse in the E-s diagrams is that enclosed area by the wave, the hatched area, represents the electric energy of the nerve impulse according to the following equation [23]:

$$Q_{imp} = \int_0^{2\pi} E \, dS \tag{36}$$

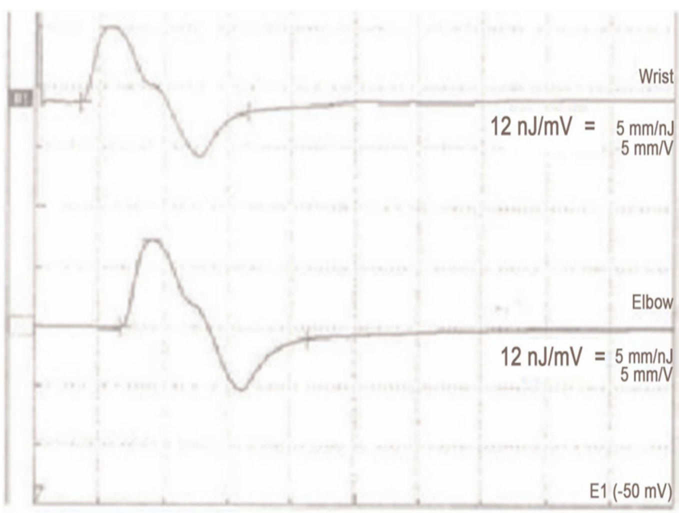

Figure 5: A machine record of response of the neural system to an injected stimulating electric charge of potential – 50 mV where the ordinate represents the entropy growth in nJ/mV and the vertical axis represents the potential of the nerve impulse [29].

Conclusions

According to this article, we achieve the following experimentally verified innovations:

1. An innovative definition of the impulse diffusivity that has the units "$\frac{m^2}{sec}$."
2. A proportionality relation between the volumetric concentration of the nerve impulses and the action potential. Such relation violates the traditional definition of the action potential as moving nerve impulses as the nerve impulse is energy whose unit is "Joule" while the action potential has the unit "Volt."
3. An innovative diffusion equation of the nerve impulses that involves the potential of the nerve impulses, a Laplacian operator, and the defined electric diffusivity as the nerve impulses are energy in the form of electrified electromagnetic waves that have electric potential.
4. An innovative diffusion equation of the nerve impulses that involves the volumetric concentration of the nerve impulses, a Laplacian operator, and the defined electric diffusivity.
5. Another new diffusion equation of the nerve impulses that replaces the time, in the traditional diffusion equations, by entropy of the neural channels as it represents an important neurodiagnostic property.
6. A dependence of the Anisotropy as a computational property of the neural channels on the dimensionless parameter "$\left(\omega \, {}^{s}/_{\dot{s}} + {}^{x}/_{\delta}\right)$" which involves the terms "$\dot{s}$" and "δ" as measurable properties of the neural channels.

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