Neuron’s Power

Salama Abdelhady

Dep. of Mechanical Engineering

Faculty of Energy Engineering

Aswan University Aswan,

Egypt

salama_abedelhady@aswu.edu.eg

Abstract: **To find plausible explanations of generation of the nerve impulses and the measured brain waves, we modified in this study the volume conduction (VC) model by introducing a new definition of the flowing nerve impulses as electric charges. Such definition depends on a neuroscientific description of the flow of nerve impulses as electric signals. Recognizing a transmembrane Seebeck effect in the neurons, we found this effect can convert the thermal potential of the metabolic heat inside the neuron into an electric potential of the energy that crosses the neuron’s membrane by its thermal potential. Such conversion initiates a series of thermos-electrochemical processes, as in thermocells, that leads to generation of nerve impulses as electric charges. According to an innovative definition of the electric charges as electromagnetic (EM) waves that have an electric potential, it was possible to define the brain waves, or the electroencephalogram (EEG), as diffusion of the generated nerve impulses, or electric charges. Accordingly, the measured transmembrane potential is due to accumulations of the electric potentials of the generated electric charges. We also explain that the measured high consumption of metabolic heat in the brain is due to its conversion into electric energy by its neurons. The Ammeter’s readings have the flow unit “Watt/Volt.” Accordingly, the neuron’s power is directly determined as the product of the measured membrane’s potential times the Ammeter’s measurements of the flow through the neuron’s axon. According to this study, the Ammeter’ reading measures a neurodiagnostic property of the neural conductors that determines the conductor’s capacity to allow flow of electric power by a unit electric potential.**

Keywords:

Nerve Impulses, Electric Charges, Electromagnetic waves, Seebeck Effect, Entropy, Transmembrane Electric Potential, Thermocell.

i.INTRODUCTION

According to the introduction of the Hodgkin-Huxley model of action potential in the 1950s, the nerve impulse generation and propagation are often thought of as solely electrical events [1]. To this day, this model forms the physiological foundation for a broad area of neuroscientific research [2]. However, the physicians or neuroscientists working with electroencephalogram EEG found, according to this model, confusion in finding the theory that explains in an accessible way the physics of such bioelectrical activities [3]. Similarly, such an original model cannot find a plausible explanation of generation of action potential in the neuron’s membrane or the source of the measured brain waves [4]. Additionally, this model finds difficult understanding of the high metabolic load of the human brain, which is just 2% of the body’s weight, while it consumes 20% of the body’s metabolic heat and 10 times more consumption per gram than any muscle [5, 6].

Accordingly, the Hodgkin-Huxley model was developed by various modifications to find plausible explanations of the discussed problems in addition to measurements of peripheral conduction of the nerve impulses [7]. As an approach, the volume conductor (VC) model was introduced to explain the measured magnetic field produced by propagating nerve impulses by the transmembrane action potential up to peripheries of the neurites [8]. The volume conductor is defined as any neural fiber, as axons, which allows the flow of nerve impulses or action potentials by electric conduction. As proof of validity of the introduced VC model, the shape of the transmembrane potential was successfully calculated from the measured magnetic field. Results of the field’s measurements determined the internal resistance per unit length of the axon and the value of its internal conductivity. However, the measured electric conductivity proves the ability of the neural fibers to conduct electricity or nerve impulses in the form of electric charges. Such a conclusion violates the classical definition of the electric charges as electrons that cannot flow through organic materials. So, we introduced in this study an innovative definition of the electric charges as electromagnetic (EM) waves that have an electric potential [9,10]. Such definition of the electric charge can find a plausible explanation of the flow of the nerve impulses through the volume conductors as electric charges or electric signals. The classical definition of the flow of nerve impulses as slow ionic interaction contradicts the measured rapid conduction of the nerve impulses through neural fibers as electric signals [11]. Additionally, the measured magnetic field of the axons, as volume conductors, by induction is evidence of the propagation of the nerve impulses as electric charges through neural fibers according to Faraday's principles [12, 13]. However, literature of neuroscience defines the motion of the action potential as generators of the induced magnetic field in the volume conductors, while the motion of potentials cannot induce a magnetic field according to the laws of induction [14]. So, we introduced in our study a new definition of nerve impulses as the innovatively defined electric charges, i.e., EM waves that have an electric potential [15]. The definition of the nerve impulses as electric charges in the form of EM waves, also finds plausible explanations of the measured rapid conduction of the nerve impulses and the measured induced magnetic field through the volume conductors [16]. The word "Potential" is used in the scientific literature as a potential of energy, as the potential of electric energy or of the thermal energy, and it is proportional to the concentration of such energy and has the unit "Volt" [17]. The traditionally used definition of the nerve impulses in the neuroscientific literature as action potential represents a source of redundancy as the flow of nerve impulses is an electrical signal or electric energy which is measured by "Joule" [18]. While the action potential is the potential of the nerve impulses which is measured by "Volt." So, the innovative definition of the electric charge distinguished the "action potential" as the electric potential of flowing nerve impulses or potential of the neural signals and it is not a potential of nothing.

Neuroscientists recognized the neurons as generators of EM waves, but they failed to find the method of its generation because they defined the nerve impulse as an action potential and the electric charges as electrons [19]. So, modifying the VC model by a new definition of the nerve impulses, and an innovative definition of the electric charges as electrified EM waves, as well as recognizing a transmembrane Seebeck effect of neurons, we found the neurons have pillars to operate as the thermocells that convert the metabolic heat into electric charges, or nerve impulses [20]. Defining the function of a neuron as a thermocell, we can find a plausible explanation of the high consumption of the brain's metabolic heat. Additionally, the measured brain waves can be plausibly explained as diffusion of the generated nerve impulses as EM waves from the neurons through the neural fibers.

It will be introduced in our study a qualitative definition of the entropy flow through volume conductors as a neurodiagnostic property that is measured by the Ammeters and has the unit Watt/Volt [21]. Reasoning of the introduced definition of entropy will be investigated at the end of our study in addition to its mathematical definition as a tool to perfect understanding of the neural functions [22]. The measured possibility of flowing the nerve impulses as electric charges through the neural fibers violates their definition as electrons, as the electrons cannot flow through neural fibers. So, the physical concepts that found the innovative definition of the electric charges as energy in the form electrified EM waves will be firstly proved in this study.

ii. An innovative definition of electric charges:

The classical definition of the electric charges as electrons that have a theoretical drift speed in the order of millimeters per second in good conductors contradicts the measured speed of electric charges in such conductors or the wireless transmission of electric power which approaches the speed of light [23, 24]. Accordingly, our study introduces an innovative definition of the electric charges as flow of energy in the form of electromagnetic waves that have electric potential [25, 26]. Such definition found plausible explanations of different phenomena in the field of electromagnetism and solved redundancies in this field such as the duality confusion and achieving high efficiencies of modern photovoltaic cells that exceed the limits determined by Shockley and Queasier analysis [27, 28]. The following equations represent the mathematical formulation of such innovative nature of the flow of the electric charges as EM waves of electric potentials which were found as solutions of the Maxwell's EM wave equations [29, 30]

$$E = E_0 + E_1 \cos(\omega s) \quad (1)$$

$$H = H_1 \cos(\omega s) \quad (2)$$

Where "E" and "H" represent the electric and magnetic components of the wave in volts, "E_0" is the electric potential of the electric charge, "E_1" and "H_1" represent the amplitudes of the EM waves in Volts, "ω" represents the angular velocity of the wave as a function of its frequency, and "s" is the entropy flow as an electrodynamic property of the conduits [31].

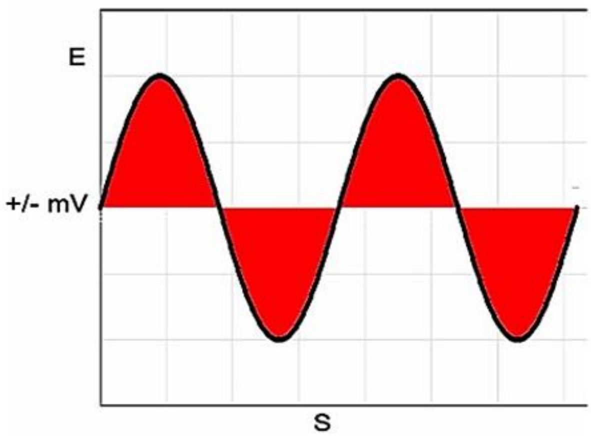

Fig. 1. Representation of flow of electric charges as energy of positive or negative electric potential in E-S coordinates [32]

Fig. 1 represents an "E-s" diagram of an electric charge defined as a component of an EM wave according to Eq. 1 whose electric potential is "E_0" [32]. Fig. 2 represents an "E-s" plot of a stimulating charge from an electric stimulator where the ordinate represents the flowing entropy "s Joule/Volt" determined by the product of the Ammeter's reading in "Watt/Volt" times the measured time of injection in the body of the patient in seconds [33].

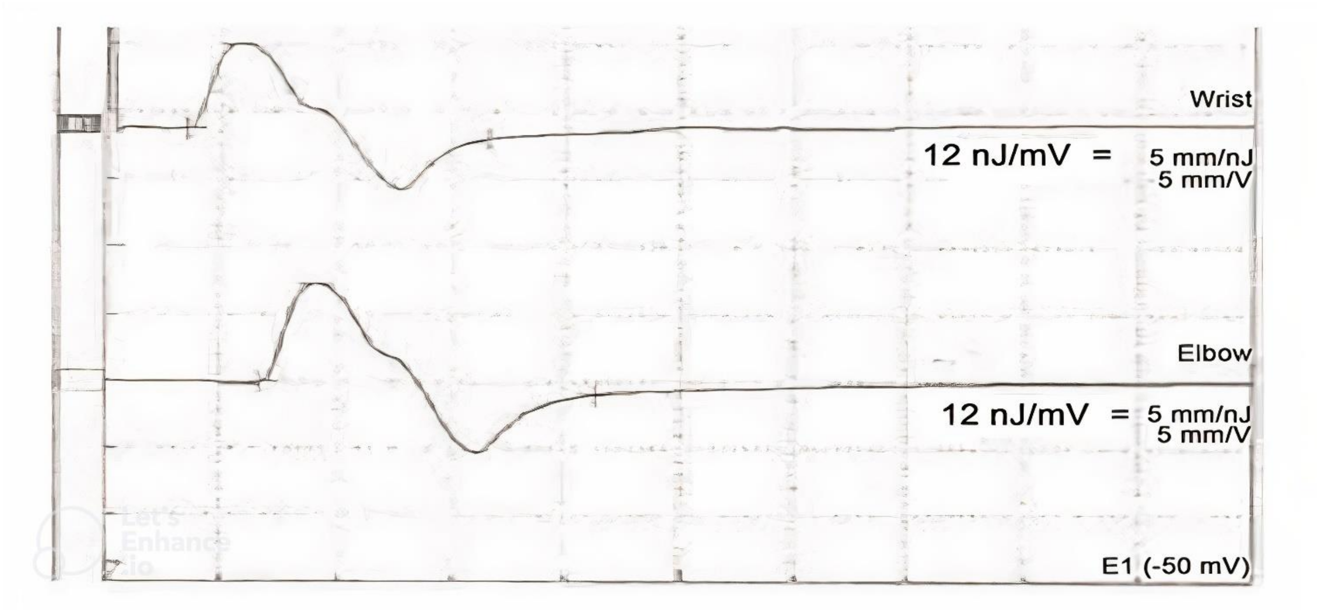

Fig. 2. A machine record of a stimulating electric charge injected inside the wrist (the upper wave) and the Elbow through neural system of patient. The ordinate shows the potential of the electric charge in mV and abscissa shows the entropy growth during the flow as the product of the Ammeter's reading times the time of flow through the Ammeter in nJ/mv [33].

Reviewing the representation of the electric charge as a theoretical solution of Maxwell's wave equations in Fig. 1 and the measured plot of the electric charge from a stimulation device in Fig. 2, we found both figures are similar. Such similar identity represents proof of the nature of the injected electric charge as an EM wave found by a theoretical solution of Maxwell's wave equations. So, the electric charge is an EM wave whose electric component has an electric potential "E_0" and its electric energy is the area enclosed by the E-s plot in Fig. 1 or Fig. 2 according to the following equation [32]:

$$Q_{elect} = \int E \, dS_{elect} \quad (3)$$

iii. A NEW DEFINITION OF NERVE IMPULSES:

Electrical signaling is found to be a cardinal feature of the nervous system and endows it with the capability of quickly reacting to changes in the environment [34]. However, neuroscientists describe the flow of nerve impulses as flow of action potentials that are slowly drifted by difference of concentrations of ions along the neural fibers [35]. The classical definition of electric charges as electrons which cannot flow through organic neural fibers abandon the proper definition of the nerve impulses as electric charges. However, the flow of the nerve impulses is defined as electric signals whose measured velocity is higher than the traditionally considered ions interactions [36]. Such improper definition of the electric charges as electrons also disables researchers to find the method of generation of brain waves [37].

According to the Hodgkin-Huxley model, the generation and propagation of the nerve impulse are solely electrical events [38]. This model was modified by the volume conductor (VC) model which considers the neural axon as a volume conductor that conducts electricity in the form of nerve impulses, or wrongly as action potentials [39]. Bradely and others used this model to calculate and measure the generated magnetic field in a single nerve axon and found the predicted shape of the magnetic field from a measured transmembrane potential is identical to the measured one [40]. They determined the internal resistance per unit length of the axon “Ri= 19.3 ± 1.9 k Ω/ mm, implying a value for the internal conductivity of 0.44 ± 0.033 mm/ k Ω. The found measurements of the electric conductivity of the neural fibers and the magnetic field generated by the flowing nerve impulses prove the truth of the new definition of the propagating nerve impulses as electric charges that can flow through such fibers and induce the measured magnetic field according to Faraday’s principles [41]. The recorded EEG in Fig. 3 of diffusion of the brain nerve impulses as EM waves through neural fibers are identical to the mathematical solution of Maxwell’s wave equations in Fig. 1 represents propagation of the nerve impulses as a generated EM wave [42]. Additionally, the recorded membrane potential in Fig. 4 is also identical to the graphical representation of EM wave of Eqn. 1 as plotted in Fig. 1 that indicates the following measured data [43]:

The wave potential: $E_0 = -60\ \mu V$,

Amplitude of the wave: $E_1 = 10\ \mu V$,

Frequency of the wave = 5 Hz.

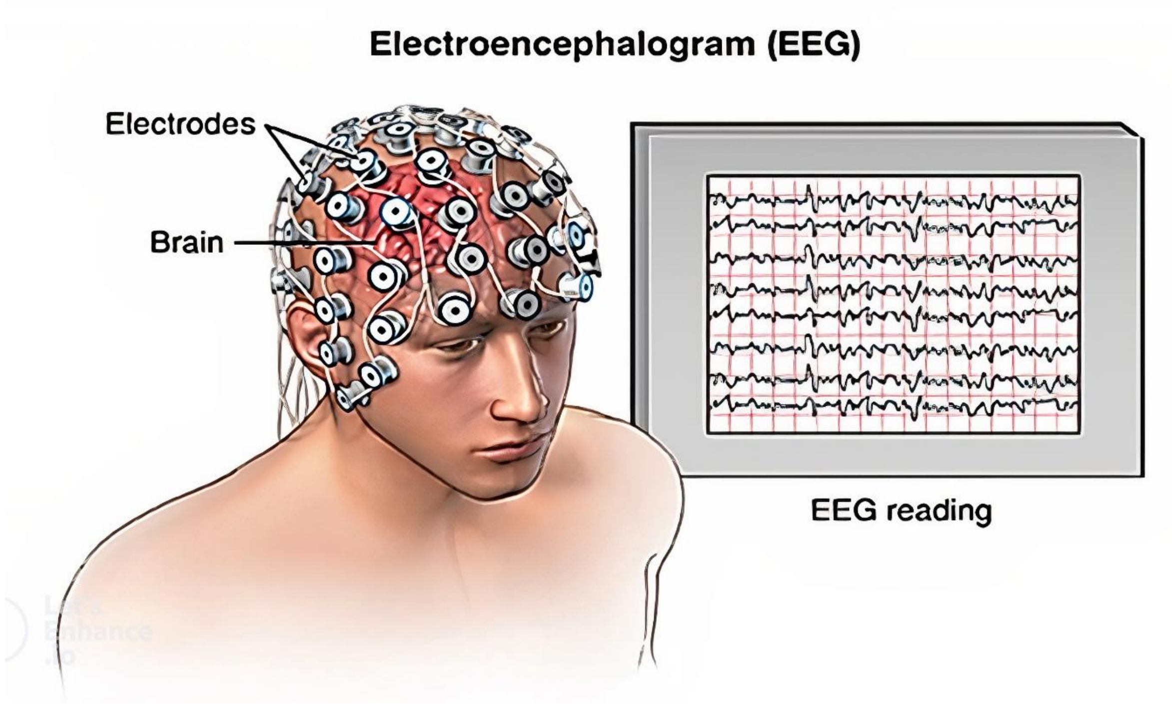

Fig. 3. A Scheme of recording the brain’s waves [42].

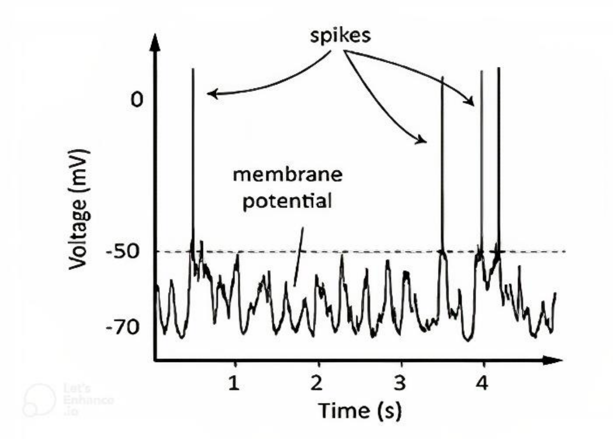

Fig. 4. An example of brain waves from an actual neuron in the mouse's cortex [43].

So, the measured transmembrane potential can be defined as the potential of generated nerve impulses in the neurons. Hence, the recorded brain waves of the human skulls as shown in Fig. 3, may represent the diffusion of generated nerve impulses in the brain neurons according to the following diffusion equation [44]:

$$\frac{\partial^2 E_{imp}}{\partial x^2} + \frac{\partial^2 E_{imp}}{\partial y^2} + \frac{\partial^2 E_{imp}}{\partial z^2} = \frac{\dot{s}}{\alpha_{elect}} \frac{\partial E_{imp}}{\partial S} \quad (4)$$

Where "E_{imp}" is the potential of the measured propagating nerve impulses in Volt, "α_{elect}" is the diffusivity of the neural fibers, "S" is the entropy of the fibers, and "$\dot{s}$" is the measured rate of entropy flow by an Ammeter [46].

The potential of the propagating nerve impulses was found as a solution of Eqn. (4) as follows [45]:

$$E(x, \tau) = E_{membrane} - E_0 e^{-x/\delta} \cos(\omega\tau + x/\delta) \quad (5)$$

Where:

$$\delta = \sqrt{\frac{2\alpha_{imp}}{\omega}} \quad (6)$$

So, the new definition of the nerve impulse, as electric charges that have the nature of EM waves, successfully predicts the brain waves according to Eqn. (5), as a solution of the diffusion equation of the propagating nerve impulses generated in the neurons.

iv. The transmembrane Potential

A typical human neuron can be mainly examined in three main sections as the dendrites, axon, and soma, Fig. (5) [46]. The cell body of the neuron, the soma, is about 20 μm in diameter and contains most of the organelles such as the nucleus, mitochondria, endoplasmic reticulum, ribosomes, and the membrane of the cell. At the cell body, the cell produces metabolic heat which is the source of energy in the neural system.

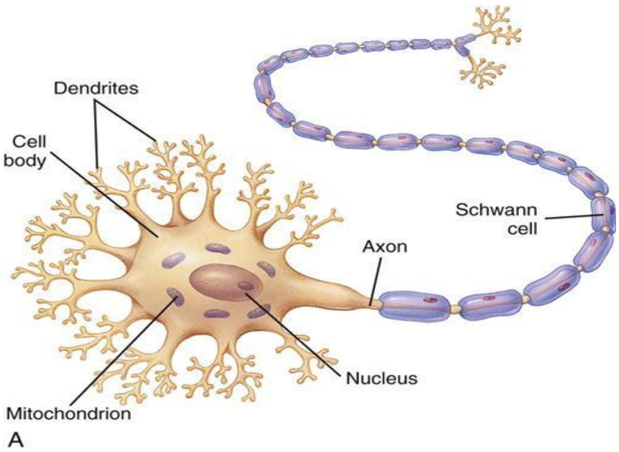

Figure 5. Structure of a neuron [46]

At the sides of the membrane of the nerve cell, there is Sodium as a principle extracellular cation and there is Potassium as the principle intracellular cation, as shown in Fig. (6) [49]. From tables of the Seebeck coefficients, we find the Seebeck coefficient of Potassium is – 9 μ V / deg, while the Seebeck coefficient of Sodium is - 2 μ V / deg [50]. According to such difference of the Seebeck coefficients on the sides of the membrane, there exist a transmembrane Seebeck effect "S_e" which is defined as the difference between the Seebeck coefficients on the sides of the membrane as follows [50]:

$$S_e = S_{Potassium} - S_{sodium} = -9 - (-2) - 7\mu V/deg \quad (7)$$

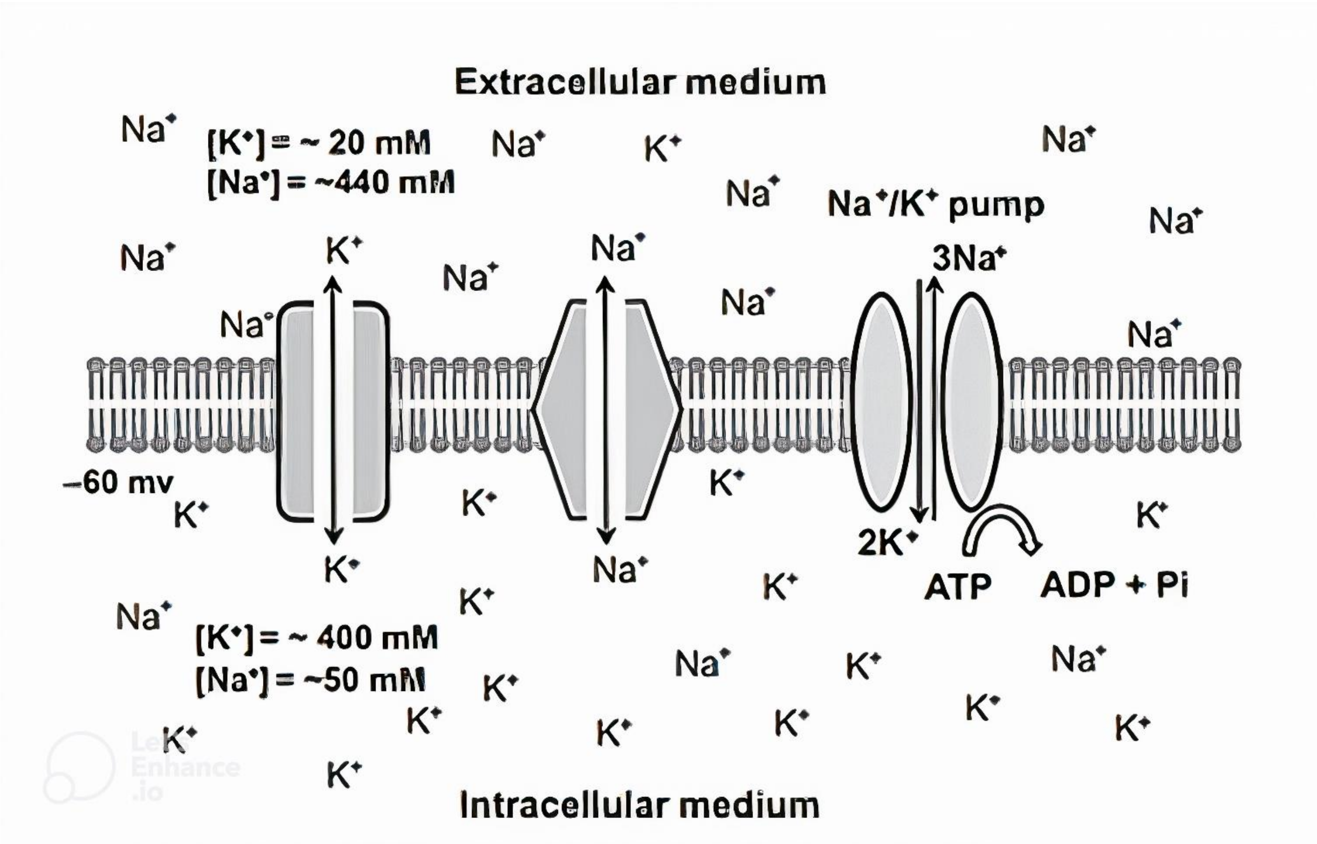

Fig. 6. Distribution of sodium and potassium ions across the phospholipid bilayer of a typical cell membrane [49].

The recognized transmembrane Seebeck effect encompass the conversion of the temperature gradient (Δ T) of the neuron's input metabolic heat into electrical potential (E_{output}) of the output nerve impulses, or electric charges, as done by the thermocells where such conversion is performed by thermos–electrochemical processes [51]. According to the laws of thermoelectricity, the transmembrane electric potential, "$E_{n.output}$," of the generated nerve impulses, that cross the membrane, is proportional to the thermal potential of the metabolic heat inside the neurons "ΔT, and the transmembrane Seebeck coefficient according to following Seebeck equation [52]:

$$E_{n.output} = S_e * \Delta T \quad \frac{\text{Volt}}{\text{nerve impulse}} \quad (7)$$

The measured temperature difference between the intercellular medium and the extracellular medium of a neuron due to evolution of the metabolic heat inside the neurons is 1.6 degrees [53]. According to Eqn. (7), it is possible to calculate the electric potential of the converted energy that crosses the neuron's membrane as electric charges, or nerve impulses, as follows:

$$E_{n.output} = -7 * 1.6 = -11.2\ \mu V \quad (8)$$

According to neuroscientific literature, the measured transmembrane potential is – 60 m. Volt [54]. So, it is possible to count the number of permanent nerve impulses whose accumulated electric potential produces the total transmembrane potential as follows [55]:

$$E_{membrane} = \sum_0^m E_{n.output} = m * Se * \Delta T \quad (9)$$

Where "m" is the number of generated nerve impulses in every neuron which can produce the measured transmembrane potential. Substituting the previous data in Eqn. (9), it is possible to estimate the value of the number "m" as follows:

$$m = 60\ \text{mVolts}/1.6\ \text{deg} * 7\ \mu\text{V} / \text{deg} = 5360\ \text{charges (or nerve impulses)} \quad (10)$$

The result found in Eqn. (10) indicates the frequency of the generated nerve impulses in the neurons, each in the form of Fig. 1or 2, that leads to the permanent accumulation of the measured membrane potential of 60 mVolt [56].

V. The Neuron's Electric Power

According to Eqn. 10, the neuron generates the transmembrane electric potential, called as the action potential, by accumulation of the potentials of the generated electric charges on the neuron's membrane. Such generated potential drives the flow of the generated nerve impulses through the neuron's axon shown in Fig. 5, as electric charges, or nerve impulses [57].

Following the VC model, it was possible to find the Ammeter's reading of the flow through the neuron's axon as $6\,nano\,\frac{\text{Watt}}{\text{Volt}}$ [58]. Hence, it is possible to calculate the neuron's power as the product of its generated transmembrane potential in Volts times the measured Ammeter's readings in $\frac{\text{Watt}}{\text{Volt}}$ as follows:

$$\dot{W}_{neuron} = Ammeter's\ reading * Membrane'spotential = 6\,nano\,\frac{\text{Watt}}{\text{Volt}} * 60\text{ mV} = 360 * 10^{-15} Watt. \quad (11).$$

Accordingly, the number of neurons in the brain is found by dividing the estimated brain power of 20 Watt by the power of a neuron as follows:

$$number\ of\ brain's\ neurons = {}^{20}/_{360 * 10^{-15}} \cong 55.5 * 10^{12}\ neurons \quad (12)$$

For half a century, the human brain was believed to contain less than 100 billion neurons and one trillion glial cells, with a glia: neuron ratio of about 10:1 [59]. However, such counting did not take into consideration the neuron's generation power and the brain's power. It is the first time to depend on measured neuron's power that depends on measurement data and on the estimated brain's power [60].

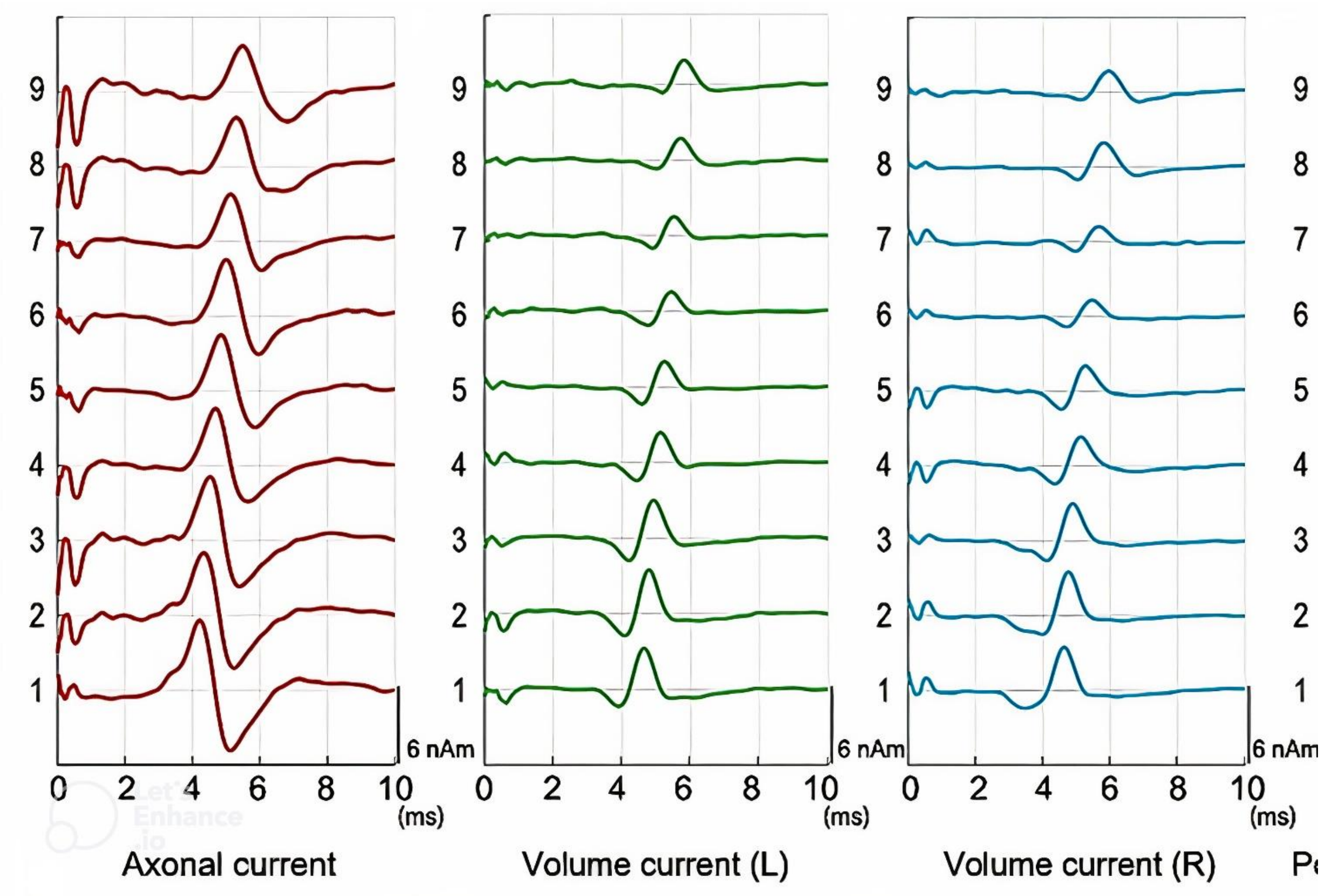

Fig. 7 The waveform of the current in the axonal direction (red plots), in the perpendicular direction to Left of the axon direction (L: the green plot), and in the perpendicular direction to Right (R: the red plot) of the axon direction [58].

vi. ENTROPY OF THE NEURAL FIBERS

The concept of entropy, as a fundamental property in the field of thermodynamics, has traditionally been oversimplified as a mere measure of disorder in the energy interaction processes. However, this simplistic perspective fails to capture the intricate and multifaceted nature of entropy, along with its profound influence on various phenomena in the field of energy [61, 62]. Through deeper understanding of entropy by moving beyond the conventional disorder, we followed the second law that founded entropy as a tabulated thermodynamic property of substances of the unit Joule/Volt. However, the classical second law of TD was devoted to defining the entropy in the thermal energy interactions according to the following equation [62]:

$$dS = \frac{\delta Q_{thermal}}{dT} \qquad (13)$$

According to the analogy between thermal and electric energy transfer, the following relation was introduced to define entropy in the electric energy interactions [63]:

$$dS = \frac{\delta Q_{electrical}}{dE} \qquad (14)$$

The entropy in Eqns. (13) is a tabulated property of substances that defines the capacity of a substance to allow flow of thermal energy through it by a unit thermal potential in Joule/Volt [64]. By analogy, the entropy in Eqn. 14 is recently defined as a property of substances that measure their capacity to allow flow of electric energy by a unit electric potential in Joule/Volt [65]. Investigating the units of the readings of Ammeters, it is defined as the quotient of the electric power in Watt divided by the measured electric potential in Volt, as Watt/Volt, which are units of the rate of entropy flow through the measured conductors [65]. Hence, the increase of entropy of a system in Joule/Volt is found as the product of the Ammeter's reading in Watt/volt and the time in second. Investigating Fig. 1 as a plot of a record of a stimulation electric charge during a stimulation process; we find the abscissa records a property of the units Joule / Volt which is the product of the Ammeter's reading in Watt/Volt times the measured time in second [35]. Such a unit is the unit of the entropy flow through the VC or the neural system [66]. Comparing the different records of many patients, we found it may indicate a neurodiagnostic property of the injected patients as the allowable injected energy is different in different patients. The injected energy or the energy of different nerve impulses the EEG records can be found from such plots by scanning the area under the wave according to the following integral [67, 68].

$$Q_{injected} = \int E \, dS_{elect} \qquad (15)$$

Reviewing the EEG measurements in Fig. 3, we found the dependence of the charge's potential on time in different locations of the human skull [69]. Multiplying the recorded time in this figure by Ammeter's readings that measure the rate of flow of entropy, such plots will help to determine the energy flow at different brain centers according to Eqn. 15 [70]. Measurement of the wave energy in every location may be indicator to some symptoms of the neural state.

CONCLUSIONS

By modifying the volume conducting the (VC) model through introducing a new definition of the nerve impulses as electric charges, which were innovatively defined as electromagnetic waves that have an electric potential, it was possible to find plausible explanations of mysterious questions in the field of neurosciences as follows:

1. The distribution of the Sodium and Potassium ions which have different Seebeck coefficients on the two sides of the cell's membrane creates a transmembrane Seebeck effect that converts the thermal potential of the neuron's metabolic heat into electric, or action, potential of generated nerve impulses that crosses the neuron's membrane. This conclusion is proved by the measured action potential of – 55 mV on the outer side of the neuron's membrane.

2. The accumulation of the converted potentials of the generated nerve impulses on of the neuron's membrane creates the measured transmembrane action potential.

3. The high brain's consumption of the body's metabolic heat is because of its conversion into electric power in the brain's neurons to perform the brain activities in the neural peripheries. This is proved by discovering the brain' consumption of the metabolic heat that represents 20% of the body's metabolic heat while the brain's wight do not exceed 2% of the body's weight.

4. This article deletes redundancies in the neurosciences that defines the action potential as a nerve impulse, as the action potential is measured by Volt and the nerve impulse is electric energy which should be measured by Joule. The truth of such understanding is supported by the fact that the electric potential is a potential of energy, and it cannot be a self-dependent entity as the nerve impulses which move as a wave.

5. The brain waves are plausibly explained as diffusion of the neuron's generated nerve impulses. whose nature

is EM waves, through the neural conductors. These diffused waves are measured by the electroencephalogram (EEG) for diagnosis of the neural system.

6. The Ammeters measure the entropy of the neural conductors as a neurodiagnostic property of the neural fibers that determine their capacity to allow flow a certain rate of flow of nerve impulses by a unit electric potential in addition to the entropy's definition as a mathematical tool for quantification of the neural functions. The truth of this statement depends on a previously published article that sows the entropy is a fundamental property of electric conductors. Accordingly, the measured entropy growth rate by Ammeters is also a property of the neural channels which perform as electric conductors.

7. According to the published brain's power of 20 Watt and the estimated neuron's power of $360 * 10{-}15 Watt$, found as the product of measured transmembrane potential of 60 m. Volt, times the current through the axon of 6 $nano$ Watt/Volt; we have estimated the number of neurons in the human brain as 55.5 * 1012 neurons.

8. The energy of the nerve impulses can be directly estimated by plotting the EEG in terms of the impulse's potential in Volt, and the entropy flow in Joule/volt, found as the product of Ammeter's readings and the time of pulse. Accordingly, the power of the nerve impulses, as a neurodiagnostic property, is found as the integral $\int E\, dS$. This relation is already used to estimate energy of the injected stimulating electric charges for diagnosis of the neural systems.

CONTRIBUTIONS:

The approach in this article to solve many redundancies in the neurosciences as the source of the action potential, the source of the brain waves, the nature of the neural signals as electric signals, and the high consumption of metabolic heat in the brain depends on modifying the volume conductor model. Such model was introduced in neurosciences and depends on considering the neural channels are conductors of electric energy that produces a magnetic field. Such approach is different than my previously followed approach in articles [25] and [67] that depended on an electromagnetic approach and deals with the neurons as a thermoelectric generator. The new approach, sustained by measurement results, found by used volume conductor model, led to the possibility of determining the neurons power and found plausible solutions of the mentioned redundancies

DECLARATIONS

COMPETING INTERESTS

The authors declare that has no competing interests.

ACKNOWLEDGEMENT

The author thanks Allah for His guide to write this article.

REFERENCES:

[1] A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve. J. Phy. 117 (4), 500-544 (1952).

[2] W. A. Catterall, et al, The Hodgkin-Huxley Heritage: From Channels to Circuits. J Neurosci 32(41), 14064–14073 (2012).

[3] S. Kaplan, OG. Deniz, et al., Electromagnetic field and brain development. J Chem Neuroanat. 75(Pt B):52-61(2016)

[4] R. Ploney, Action Potential Sources and Their Volume Conductor Fields Proceedings of the IEEE. 65 (5) 601-611 (1977)

[5] ME. Watts, R. Pocock, C. Claudianos, Brain Energy and Oxygen Metabolism: Emerging Role in Normal Function and Disease. Front. Mol. Neurosci. 11:216. (2018)

[6] V. Balasubramanian Brain power. PNAS. 118(32), 1- 3 (٢٠21).

[7] J.A. Connor, D. Walter, R. Mckown, Neural repetitive firing: modifications of the Hodgkin–Huxley axon suggested by experimental results from crustacean axons, Biophys. J. 18(1), 81–102 (1977)

[8] L. Mesin,Volume conductor models in surface electromyography: Applications to signal interpretation and algorithm test Computers in Biology and Medicine 43, 953–961 (2013)

[9] S. Abdelhady. An Advanced Review of Thermodynamics of Electromagnetism. International Journal of Research Studies in Science, Engineering and Technology. 3(6),10-25 (2015)

[10] S. Abdelhady, C. H. Cheng, Advanced Thermodynamics Engineering. Scitus Academics, N.Y. (2019)

[11] TD. Albright, TM Jessell, ER. Kandel, et al. Neural Science A Century of Progress and the Mysteries That Remain. Neuron Raghavan. 1(1),1-5 (2005)

[12] J.P. Wikswo, J.P. Barach, J.A. Freeman, Magnetic field of a nerve impulse: first measurements. Science. 208 (4439) 53-55 (1998)

[13] M. Fujimtu Physics of Classical Electromagnetism, Springer (2007)

[14] G. Ross, Grand Unified Theories, Westview Press, 1984

[15] Salama Abdelhady. Proper Understanding of the Nerve Impulses and the Action Potential. World Journal of Neuroscience. 13, 103-117 (2023)

[16] DK. Hartline, DR. Colman, Rapid conduction and the evolution of giant axons and myelinated fibers. Curr Biol. 17(1), 29-35 (2007)

[17] S. Abdeldhady, M. S. Abdelhady, Diffusion Equations of the Electric Charges and Magnetic Flux. Journal of Electromagnetic Analysis and Applications, 16, 69-83 (2024)

[18] K.H. Levin, P. Chauvel, Handbook of Clinical Neurology, Clinical Neurophysiology: Basis and Technical Aspects, Elsevier. 60(3) 2019.

[19] Y. Buskila, A. Bellot-Saez, JW. Morley, Generating Brain Waves, the Power of Astrocytes. Front. Neurosci. 13(1125), 1-10 (2019

[20] D. G. Gonçalves, C. Caspers, J. Dupont, P. Migowski, Ionic liquids for thermoelectrochemical energy generation, Current Opinion in Green and Sustainable Chemistry

[21] L.L. Frank, Entropy is Simple Qualitatively. J Chem Educ. 79 (1) 1241-1246 (2002)

[22] S. Keshmiri, N. S. Thomas, Entropy and the Brain: An Overview. BioMEC-X Laboratories, Advanced Telecommunications Research Institute International. (ATR) Kyoto Japan, 619- 623 (2020)

[23] RA. Serway, JW. Jewett, Physics for Scientists and Engineers. Brooks Cole. (2020)

[24] S. Abdelhady, An Entropy Approach to Tesla's Discovery of Wireless Power Transmission. Journal of Electromagnetic Analysis and Applications, 5(1) 157-161 (2013)

[25] S. Abdelhady, An Innovative Definition of the Nature of Nerve Impulses, Journal of Ain Shams University Engineering Journal, Engineering Physics and Mathematics, 11 (2) 1-5 (2019)

[26] S. Abdelhady, M. S. Abdelhady, An Entropy Approach to the Natures of the Electric Charge and Magnetic Flux. Journal of Electromagnetic Analysis and Applications. 7(11), 265- 275 (2015)

[27] S. Abdelhady, Innovative Solutions of Unsolved Problems and Misconceptions in Physics. International. Journal of Innovative Research in Science, Engineering and Technology. 6 (9), 1-18 (2017).

[28] S. Abdelhady, An Entropy Approach to a Practical Limit of the Efficiencies of Developed Multijunction Solar Cells. J. Electromagnetic Analysis & Applications. 6(1), 383 -390 (2014).

[29] S. Abdelhady. Thermodynamics: Fundamentals and its Application in Science, Auris Reference; 1st edition. London (UK), ISBN-10: International Textbook In Science. 2017.

[30] S. Abdelhady, Entropy Analysis of Duality Property. J. Electromagnetic Analysis & Applications. 3, 220-227, (2011)

[31] S. Abdelhady, Innovative understanding of the duality confusion, the photovoltaic and the Magnetocaloric effects. Ain Shams Engineering Journal, Engineering Physics and Mathematics. 9, 2283 –2291 (2018)

[32] S. Abdelhady. Proper Understanding of the Natures of Electric Charges and Magnetic Flux. Second Chapter of the Book: Electromagnetic Field in Advancing Science and Technology, IntechOpen, London. 2022; 28 pages

[33] A. Abdelhady. Machine Records of the Neurology Clinic. Records of Aswan University-Hospital. 5 (1) 1217- 1218 (2022)

[34] DS. Faber, AE. Pereda, Two Forms of Electrical Transmission Between Neurons. Front. Mol. Neurosci. 11, 427- 432 (2018)

[35] M. Häusser, The Hodgkin-Huxley theory of the action potential. Nat Neurosci. 3 (11), 1165- 1170 (2000).

[36] Y. Goldman, M. Morad, Ionic membrane conductance during the time course of the cardiac action potential. J Physiol. 268(3):655–695 (1977)

[37] S. Y. Zuodong, Neurons Can Generate Electromagnetic Waves. Natural Science. 14(11), 463-471 (2022)

[38] CJ. Schwiening, A brief historical perspective: Hodgkin and Huxley. J Physiol. 590(11):2571-2575 (2012)

[39] LE. Medina, WM. Grill, Volume conductor model of transcutaneous electrical stimulation with kilohertz signals. J Neural Eng. 2014 Dec;11(6), 1-10 (2014)

[40] R. Bradely, J. P. Wiksow, The Magnetic Field of a Single Axon, A Comparison of Theory and Experiment BIOPHYS. J. 48(1), 93-109 (1985)

[41] SB. Riffat SB, X. Ma, Thermoelectrics: a review of present and potential applications. Appl Therm Eng. 23, 913-918 (2003)

[42] M. Roohi-Azizi, L. Azimi, S. Heysieattalab, M. Aamidfar, Changes of the brain's bioelectrical activity in cognition, consciousness, and some mental disorders. Med J Islam Repub Iran. 31(1), 53 – 60 (2017)

[43] A. Woodruff. Image of Action potentials and synapses: in depth. Queensland Brain Institute. (2024)

[44] S. Abdelhady, M.S. Abdelhady. Innovative Diffusion Equation Nerve Impulses. Neurol Res Surg. 7(2), 1-7 (2024)

[45] P. L. Nunez, R. Srinivasan, Electric Fields of the Brain. The Neurophysics of EEG, second ed. Oxford University Press, Oxford (2005)

[46] J. Zhang, Basic Neural Units of the Brain: Neurons, Synapses and Action Potential. IFM Lab Tutorial Series. 5 (1), 1–38 (2019)

[47] M. Raghafan, F. Dominic, P. E. Barkhaus, Generation and Propagation of the Action Potential. Clinical Neurophysiolo gy: Basis and Technical Aspects, Elsevier, Amsterdam, 160 (1), 3-22 (2019)

[48] RR. Heikes, W. Roland, GW. Ur, Thermoelectricity: Science and Engineering. New York Interscience Publishers Inc. (1961).

[49] Electric Fields of the Brain. The Neurophysics of EEG, second ed. Paul L. Nunez, Ramesh Srinivasan. Oxford University Press, Oxford (20050

[50] A. W. van Herwaarden, The Seebeck Effect in Silicon ICs. Sensors and Actuators. 6(1), 245-254 (984)

[51] Li, Meng et al., High-efficiency thermocells driven by thermo-electrochemical processes, Trends in Chemistry, 3(7) 7, 561 – 574 (2021)

[52] EK.Iordanishvili, Thermodynamic potential of thermoelectricity. J Thermoelectricity. 41, 1-10 (1981)

[53] R. Tanimoto, et al., Detection of Temperature Difference in Neuronal Cells. Scientific Reports, 6, Article No. 22071, 1-10 (2016)

[54] H. Bertille, Ionic Basis of Resting and Action Potentials, Supplement 1. Handbook of Physiology, The Nervous System, Cellular Biology of Neurons, Wiley. (2011)

[55] Abdelhady S. Advanced physics of thermoelectric generators and photovoltaic cells. Am. J Phys Appl. 6, 133-140 (2018)

[56] P. P. Furlan, Brain-body communication in metabolic control. Trends in Endocrinology & Metabolism 34, 12-20 (2023)

[57] ME. Raichle, Two views of brain function. Trends Cogn Sci. 14, 180 -187 (2010)

[58] K. Nakayamaa, et. Al, Visualization of axonal and volume currents in median nerve compound action potential using magnetoneurography. Clinical Neurophysiology. 152, 57-67 (2023)

[59] C.S. von Bartheld, J. I. Bahney, S. Herculano-Houze, The Search for True Numbers of Neurons and Glial Cells in the Human Brain: A Review of 150 Years of Cell Counting, The Journal of Comparative Neurology |Research in Systems Neuroscience 00 (00), 1-31 (2016)

[60] M.E. Raichle, D. A. Gusnard, Appraising the brain's energy budget. PNAS. 99 (16), 10237-10239 (2002).

[61] J. Alzeer. Beyond Disorder: A New Perspective on Entropy in Chemistry. American Journal of Medicinal Chemistry. 5(1),1-5 (2024)

[62] R. F. Sekerka, Thermal Physics - Thermodynamics and Statistical Mechanics for Scientists and Engineers. Elsevier. (2015)

[63] S. Abdelhady, A Fundamental Equation of Thermodynamics that Embraces Electrical and Magnetic Potentials' "J. Electromagnetic Analysis & Applications", 2(1),162- 166 (2010)

[64] M. Moran, H. Shapiro, D. D. Boemer, M. Bailley, Fundamentals of Engineering Thermodynamics, Wiley, ninth edition (2024)

[65] Abdelhady S. Comments concerning measurements and equations in electromagnetism. J Electromagnet Anal Appl. 2, 217-222 (2010)

[66] S. Abdelhady, A Thermodynamic Analysis of Energy Flow in Optical Fiber Communication Systems. Applied Physics Research.4(1), 22-29 (2012)

[67] S. Abdelhady, Electric and Magnetic Energies in the Human Body, International Journal of Applied Energy Systems, 2(1), 44-52 (2020)

[68] S. S. L. Andersen, A. D. Jackson, T. Heimburg, Towards a thermodynamic theory of nerve pulse propagation. Prog. Neurobiol. 88, 104-11(2009)

[69] F. Bretschneiderm, J. de Weille, Introduction to Electrophysiological Methods and Instrumentation. Elsevier. Second Edition (2006)

[70] SG. Hormazd et al. Electrical synapses: a dynamic signaling system that shapes the activity of neuronal networks. Biochim Biophys Acta. 1662, 113-120

[71] S. AbdelHady innovative definition of nature of the nerve impulses. Ain Shams Engineering Journal, Engineering Physics and Mathematics, Production and hosting by Elsevier. 2019;11:2. DOI: 10.1016/j.ase