World Journal of Neuroscience, 2023, 13, 103-117
https://www.scirp.org/journal/wjns
ISSN Online: 2162-2019
ISSN Print: 2162-2000

Proper Understanding of the Nerve Impulses and the Action Potential

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How to cite this paper: Abdelhady, S. (2023) Proper Understanding of the Nerve Impulses and the Action Potential. *World Journal of Neuroscience*, **13**, 103-117.
https://doi.org/10.4236/wjns.2023.133007

Received: May 29, 2023
Accepted: July 28, 2023
Published: July 31, 2023

Abstract

Neurologists define the transmission of nerve impulses across the membranes of the neural cells as a result of difference in the concentration of ions while they measured an electric potential, called as an action potential, which allows the propagation of such nerve impulses as electrical signals. Such measurements should guide them to a logical explanation of the nerve impulses as electric charges driven by the measured action potential. However, such logical conclusion, or explanation, is ignored due to a wrong definition of the flow of electric charges as a flow of electrons that cannot pass through neural networks. According to recent studies, electric charges are properly defined as electromagnetic (EM) waves whose energy is expressed as the product of its propagating electric potential times their entropy flow which is adhered to the flow of such energy. Such definition matches the logical conclusion of the nerve impulses as electric charges, as previously explained, and defines the entropy of the neural network, measured by Ammeters, in Watt or Joule/Volt. The measured entropy represents a neurodiagnostic property of the neural networks that measures its capacity to allow the flow of energy per unit action potential. Theoretical verification of the innovative definition of nerve impulses is presented by following an advanced entropy approach. A proper review of the machine records of the stimulating electric charges, used in the diagnosis of the neural networks, and the stimulated nerve impulses or stimulated responses, represents practical verifications of the innovative definitions of the electric charges and the nerve impulses. Comparing the functioning of the thermoelectric generators and the brain neurons, such neurons are defined as thermoelectric generators of the electric nerve impulses and their propagating, or action, potential.

Keywords

Nerve Impulses, Action Potential, Electric Charges, Entropy, Electromagnetic Waves, Thermoelectric Generators

1. Introduction

The electric current was traditionally defined, by a wrong recognition, as flow of electrons while the electrons are mass particles whose rate of flow should be measured by the unit kg/s [1]. This definition is followed by a wrong nomination of the unit of the Ammeter's reading as the rate of flow of electrons measured by "Ampere". However, the Ammeter's reading should be limited to its logical unit as "Watt/Volt" which is, according to known measuring fundamentals, the division quotient of the electrical power by the electrical potential [2].

In recently published research depending on an entropy approach and results of Faraday's experiments, the electric charges are properly defined as electrified energy or electromagnetic waves that have an electric propagating potential like the heat which is defined as EM waves that have a thermal driving potential [3] [4]. According to such a definition, the Ampere should not be used as a unit of the rate of flow of electric charges as the rate of flow of electric charges if the electric charges are properly defined as the energy of the unit "Joule", it should have the unit "Watt". So, this unit, "Watt", conflicts it postulated measuring unit "Watt/Volt". Hence, the Ampere represents a confusing unit in the electricity field, and it shouldn't be regarded as one of the Ammeter's readings. However, the postulated Ammeter's unit, Watt/Volt, is a unit of the rate of entropy growth through a connected conductor in the Ammeter's circuit, **Figure 1**. Such entropy also represents a physical property of the inserted conductor in this figure [5] [6]. Thermodynamically, it is possible to explain the meaning of Ammeter's reading as the capacity of the measured conductor to allow the flow of electric power by the action of a unit electric potential, where such capacity is a function of the conductor's entropy [3].

While neurologists define the flow of nerve impulses as the flow of electrical signals, they refrain from defining the nature of nerve impulses as electric charges. This is due to the fact that the flow of electric charge, according to their understanding, is incorrectly defined as the flow of electrons, which are unable to pass through organic tissues [7]. So, they describe the transmission of the nerve impulses across the membranes of the neural cells as due to a difference between concentration of ions while they measure a propagating electric potential, or an action potential, that allows the propagation of the nerve impulses as electric signals without attenuation [8]. The newly defined nature of the nerve impulses as electric charges which have an electric potential matches the measured features of the nerve impulses and its propagating action potential [9]. In this article, it will be verified, theoretically and practically, the truth of the submitted innovative definitions of the electric charges and the nerve impulses. The theoretical verification is accomplished by following an entropy approach that represents the electric charge as EM wave of electric potential [3]. The practical verification depends on a smart comparison between the represented electric charge as a wave and the machine records of stimulating electric charge and its stimulated response. Then, it will compare the analogous operations of the

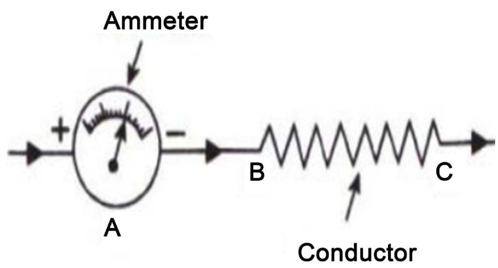

Figure 1. Ammeter's connection to a conductor to measure the rate of growth of entropy though such conductor in Watt/Volt [2].

motor neurons as generators of the action potential of the nerve impulses and the thermoelectric generators as devices that convert the heat flux from metabolic reactions into electric charges by the Seebeck effect.

2. The Dimension of Entropy

Maxwell predicted the energy as EM waves that consist of an oscillating electric field "*E*" and an oscillating magnetic field "*H*", where both fields propagate perpendicularly at a speed which has the same speed of light "*c*". Maxwell's equations can be simply written as follows [2]:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)E = 0, \quad (1)$$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)H = 0, \quad (2)$$

Equations (1) and (2) consider the time "*t*" as the coordinate of simultaneous propagation of the electric field *E* and the magnetic field H [2]. **Figure 2** represents graphically the Maxwell's wave equations. The coordinates of the vertical plane are the electric field "*E*" and the time "*t*" as a measure of the propagation of the electric wave while the coordinates of the horizontal plane are the magnetic field "H" and the time "*t*" as a measure of a simultaneous propagation of the magnetic field [2].

Introducing the entropy as a thermodynamic property of materials whose growth is a unique function of time to replace the time in Maxwell's wave equation as it determines the capacity of such materials to allow the energy flow. Such replacement casts the Maxwell's wave equations into an energy frame of reference that presents the energy flow in each plane, the time "*t*" in the Maxwell's equations. Such transformation modifies Maxwell's space of propagation of the EM waves into an energy frame that shows, as seen in **Figure 3**, the propagating electric and magnetic energies in the E-s and H-s planes of such *E-H-S* energy coordinates [10]. So, the modified Maxwell's wave equations that have such energy coordinates can be expressed as follows [11]:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial s^2}\right)E = 0 \quad (3)$$

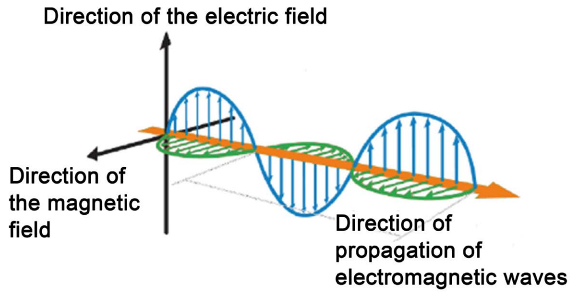

Figure 2. Representation of propagation of Electromagnetic waves as described by Maxwell's Equations where the coordinates are the Electric Field "*E*", the Magnetic Field "*H*", and the time "*t*" [2].

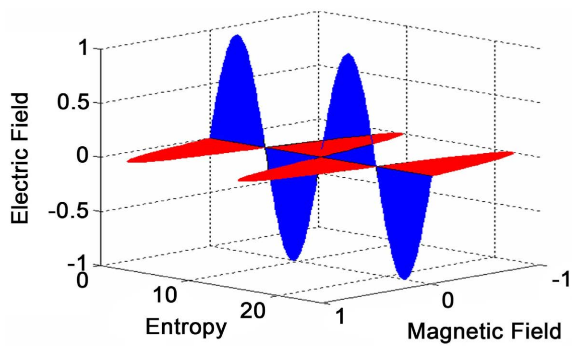

Figure 3. Representation of flow of Electromagnetic waves as described by modified Maxwell's Equations in *E-H-s* Energy coordinates [10].

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial s^2}\right)H = 0, \tag{4}$$

Such representation succeeded in showing the flow of electric and magnetic energies during the flow of an electromagnetic wave as the areas swept by the electric and the magnetic waves in **Figure 3** as follows [12]:

$$Q_{\text{electical}} = \int E\text{d}S \tag{5}$$

$$Q_{\text{magnetic}} = \int H\text{d}S \tag{6}$$

So, the energy flow per wave can be estimated as follows:

$$\tilde{h} = \int_0^{2\pi}\left(\left|E\text{d}S_e\right| + \left|H\text{d}S_{mag.}\right|\right)\text{Joule/wave} \tag{7}$$

The first integral in the R.H.S. in Equation (7) is the imparted electric energy of zero electric potential and the second term is the imparted magnetic energy of zero magnetic potential in one flowing EM wave [12].

3. Proper Nature of the Electric Charges

Faraday succeeded in converting the light or normal electromagnetic waves into electric current when passing the light through an electric field [13]. So, the electric charge can be considered as electrified energy or as EM waves that has an electric potential. Such waves are visualized in the frame of energy coordinates as shown in **Figure 4**, where the electric-wave energy has a non-zero electric potential [14]. Such visualization depends on considering the following wave equations as the solution that fits the results of Faraday's experiments and represent the electric current as a special solution of the modified Maxwell's equations. Such solution considers the flow of electric current as EM waves that have an electric potential of the magnitude $+/-\Delta\bar{E}$ according to **Figure 4** as follows [14]:

$$E(r,s) = E\cos(kr + \omega s + \varphi) +/- \Delta\bar{E} \tag{8}$$

$$H(r,s) = H\cos(kr + \omega s + \varphi) \tag{9}$$

According to **Figure 4**, it is possible to represent the electric charge in *E-s* coordinates as a wave oscillating around a negative or positive electric potential as shown in **Figure 5**. The energy flow per wave can be calculated according to Equation (7) as follows:

$$Q_{\text{electical}} = \int_0^{\lambda} |E\mathrm{d}s| \tag{10}$$

4. Proper Nature of the Nerve Impulses

The record of an injected stimulating charge inside the neural system of a patient in the hospital of Aswan university and its stimulated response, as a nerve impulse, are shown in **Figure 6** [15]. The ordinate of the plots shows the measured potential of the charge or the nerve impulse in Volts, while the abscissa shows the product of the readings of the inserted Ammeter in the stimulating device, in Watt/Volt, times the measured time of injection in seconds. So, the unit of the ordinate, as seen in the record, is nano-Joule/milli-Volt which is a unit of the entropy growth through the neural network during the injection process, as previously explained, as a property of the neural network [16]. The matching between the measured record of the stimulating, or the stimulated nerve impulses, and the visualized solution of the modified Maxwell's equation in **Figure 6**, proves the truth of the definition of the electric charge, and hence the nerve impulses, as EM waves which have negative or positive electric potential "E". The energy of the nerve impulses, or the injected energy in Joules, is found by multiplying plotted entropy growth, as found on the abscissa of **Figure 5** in nano. Joule/milli-volt, times the measured potential of the charge on the ordinate in milli-Volts.

According to understanding the entropy as a property of the conducting networks, it is possible to consider the measured rate of flow of entropy, by the Ammeter, during the injection process as a fundamental neurodiagnostic parameter. Such entropy measures the capacity of the tested neural network to allow the flow of definite amount of power in Watts by the force of a unit of electric potential, *i.e.*, by 1 Volt. Unfortunately, statistical scientists ignore the entropy as a physical property of substances and conductors, and estimate the entropy only as an information parameter of mathematical probabilistic or statistical significance

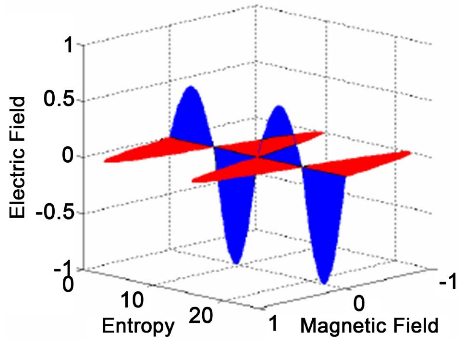

Figure 4. Representation the flow of a negative electric charge as a solution of modified Maxwell's equation for an electromagnetic wave of –ve potential where the electric energy in the *E-s* plane is oscillating around the negative potential " $-\Delta\overline{E}$ " [13] [14].

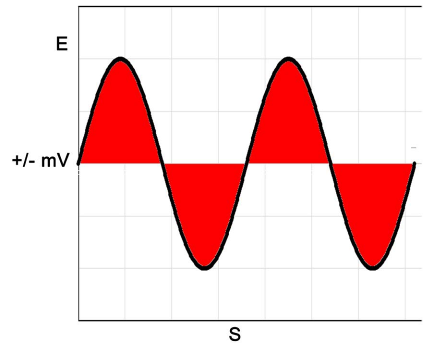

Figure 5. Representation of flow of electric charges as energy of positive or negative electric potential in *E-S* coordinates as concluded from **Figure 3**.

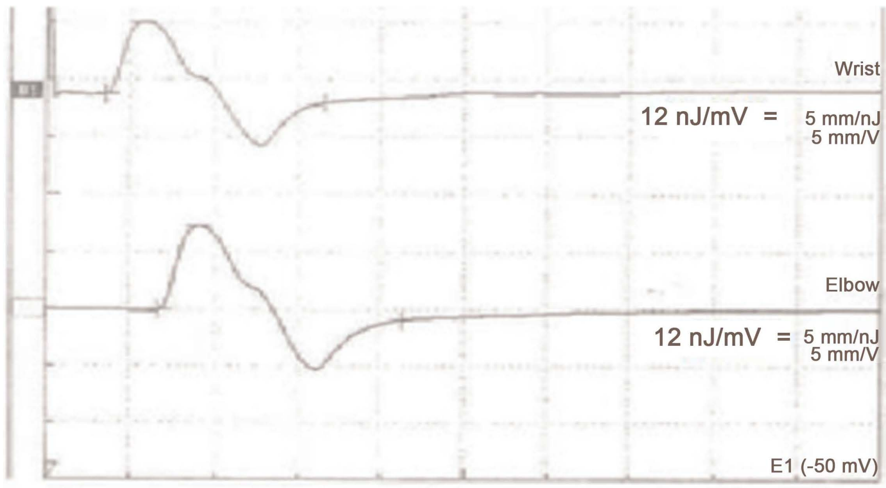

Figure 6. A machine record of a stimulating electric charge injected inside the neural system (the upper wave) and the stimulated response of the neural system (or nerve impulse). The ordinate shows the potential of the electric charge in mV and abscissa shows the entropy growth during the flow through the Ammeter as the product of the Ammeter's reading times the time of flow through the Ammeter in nJ/mv [15].

[17]. They miss its relations to the thermodynamic entropy that represents a measurable neurodiagnostic property of the neural networks [18].

Figure 7 shows the recorded electrical stimulated responses at different neural centers on the scull of a man [19]. Such records, shown in **Figure 7**, have similar wave forms as the Maxwell's solution in **Figure 5** and of the electrical stimulating charge in **Figure 6**. Such similarities also prove that these stimulated responses are records of nerve impulses sent from the brain as a response to stimulating actions in the form of the newly defined electric charges, *i.e.*, as EM waves that have electric potential [3]. Each record of the nerve impulses at various brain centers, as seen in **Figure 7**, has its own frequency, amplitude, and entropy flow. Such recorded parameters indicate the truth of the published three independent functions of the nerve impulses: communication, modulation, and computation [20]. Such functions determine computational characteristics of the required action of the receptors by the sent impulses [21]. Such plots also represent the experimental verification of the stimulated response as nerve impulses in the form of electric charges that owns a definite propagating potential and computational biological parameters [22].

5. Understanding the Thermoelectric Generators

Recognizing the electric charge as energy of electrical potential finds plausible explanations of the thermoelectric effects according to proper understanding of the electric charges [23]. The thermocouple in **Figure 8** is constructed of two different metals "A" and "B" connected into two junctions. If these junctions are placed into two heat reservoirs "1" and "2" where the difference in temperature between them is "ΔT", defined as $\Delta T = T_2 - T_1$, then an open circuit voltage "ΔE" will be obtained between the ends of the two junctions [24].

The measured difference of electric potential is found to be proportional to the temperature difference between the junctions of the two conductors A and B according a Seebeck equation defined as follows [24]:

$$\Delta V = \alpha_{AB} \Delta T \tag{11}$$

where "α_{AB}" is the relative Seebeck coefficient, between the conductors A and B, expressed in Volts/Kelvin. This coefficient depends mainly on the choice of the two materials used in the thermocouple and the temperature of the junction at the higher "$T_{\max}$". The magnitude of the relative Seebeck coefficient of the junction between any two materials as the metals A and B can be evaluated as the difference between the Seebeck coefficient of the two metals as follows [25]

$$\alpha_{AB} = \alpha_A - \alpha_B \tag{12}$$

The direct relation between the produced electric potential and the difference of the thermal potentials between the two junctions plays the main role in the use of thermocouples in temperature measurements and in thermoelectric generators. However, there is a relation between the Seebeck coefficient "α" and the energy band gaps of materials "E_g" for any material as can be estimated according to Goldsmid and Sharp by the following Equation [25]:

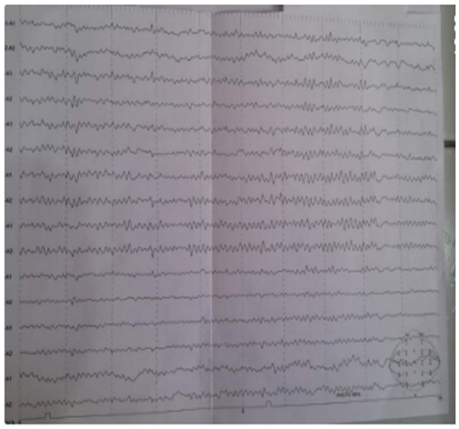

Figure 7. A machine record of stimulated responses, or nerve impulses, at different neural centers on scull of a man [19]. Such plots are like the solution of the modified Maxwell's equation that represents the electric charge as EM waves of negative potential as shown in Figure 5.

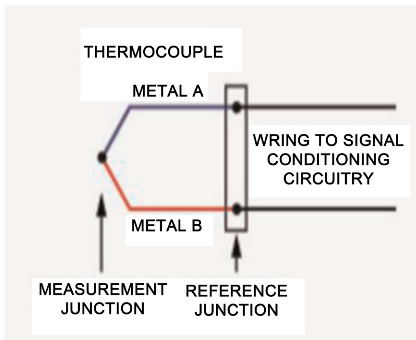

Figure 8. A thermocouple of two different materials "A" and "B" that has a reference and a measuring junction where the difference in the Seebeck effect between the two materials convert the thermal potential of the input heat into electric potential [23].

$$E_g = 2e\left|\alpha_{\max}\right|T_{\max} \tag{13}$$

where e is the electron's charge = $1.602.10^{-19}$ Joule at potential 1 Volt. Equation (13) signifies a relation between the Seebeck coefficient and the energy-bandgaps of materials of the junction that characterize the transitional effect from thermal potential "ΔT" to electric potential "ΔV". The tables of Seebeck coefficients of materials and the tables of its energy bandgaps indicate a direct relation between these two physical properties [26].

According to the new definition of flow of electric charges as a flow of EM waves that have electric potential, it is possible to explain thermoelectric effect as converting the thermal potential of the incident heat, as E.M. waves of thermal potential, into electric potential by Seebeck effect when crossing junctions of materials of different band gaps [27].

As the emf produced by one thermocouple is a tool to measure the temperature, it is usually of very small value in case of small temperature differences. So, it is employed thermopiles where several thermocouples or junction-pairs are connected in series, as shown in **Figure 9**, to amplify the electric potential and to reduce the error of measurements [28]. The thermocouple junction pairs are placed in series between a source of heat at high temperature "T_h" and a heat sink at low temperature T_L, as shown in **Figure 9**. The output voltage in this case can be estimated as the sum of the gained electric potentials during the flow of the electromagnetic waves of thermal potentials in a unique direction across the successive junctions. So, their thermal potentials, $\left(T_h - T_L\right)$, will be converted by the Seebeck effect into electric potentials which will be accumulated as the sum of the separate potentials [29]. So, it is possible to estimate the total electric potential as the sum of these individual gains at successive junctions as follows [29]:

$$\Delta V = \propto_{AB}\left(T_h - T_l\right) + \propto_{BA}\left(T_l - T_h\right) + \propto_{AB}\left(T_h - T_l\right) + \propto_{BA}\left(T_l - T_h\right) + \propto_{AB}\left(T_h - T_l\right) + \cdots \quad (14)$$

$$As \ \propto_{AB} = \propto_B - \propto_A, \quad (15)$$

$$Then, \ \propto_{BA} = \propto_A - \propto_B = -\propto_{BA}, \quad (16)$$

$$And \ \left(T_h - T_l\right) = -\left(T_l - T_h\right) \quad (17)$$

Using Equations (15) and (16) to replace the corresponding terms in Equation (14), the total electric potential gained by the flowing electromagnetic waves by Seebeck effect is estimated as follows [30]:

$$\Delta V = \sum\left[\propto_{AB}\left(T_h - T_l\right)\right] = n \propto_{AB}\left(T_h - T_l\right) \quad (18)$$

Equation (18) indicates that the electric potential of a thermopile is duplicated by the number of the used junctions.

A thermoelectric generator is shown in **Figure 10**. It is defined in literature as a Seebeck generator or a solid-state device that converts heat flow of thermal potential directly into electrical energy of electrical potential by Seebeck effect [31]. It applies the same principles of operation of the thermopiles for magnifying the output electrical potential difference corresponding to input heat of small thermal potential by Seebeck effect through increasing the number of the junctions of the generator [31].

6. Generation of the Inverse Impulses and Its Action Potential

The generation of the nerve impulse and the action potential remains as one of the mysteries that remain in the neural sciences [32]. Nerve impulse generation and propagation are often thought solely as electrical or electrochemical events [33]. According to Benjamin *et al.*, they found the Hodgkin-Huxley model which formed the physiological foundation for a broad area of neuroscientific research cannot account for measured non-electrical phenomena in the field of neurology [33]. However, traditional bioelectric references also avoid the description

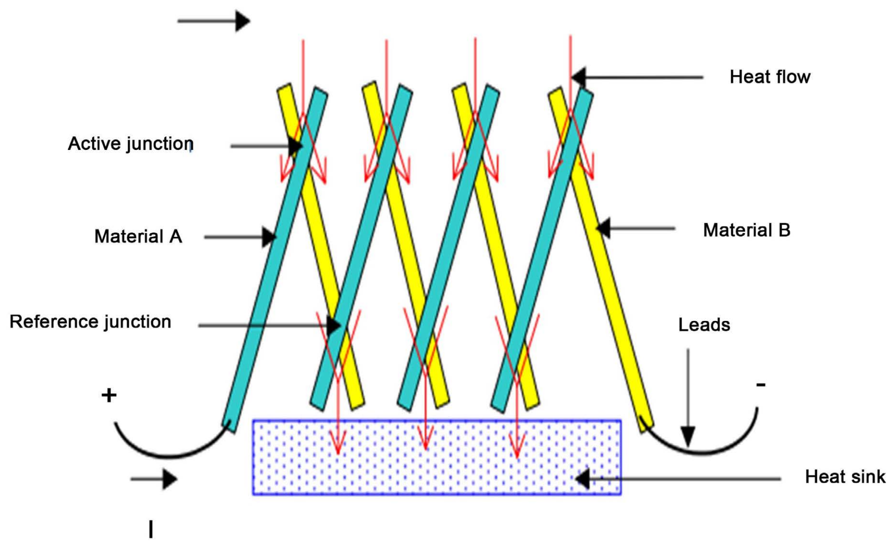

Figure 9. A thermopile made of thermocouple junction pairs of two metals connected electrically in series to increase the generated E.M.F. Successive conversions of the thermal potentials into electric potentials through the successive junctions leads to accumulation of the electric potentials and decease the error of temperature difference by the thermopiles [29].

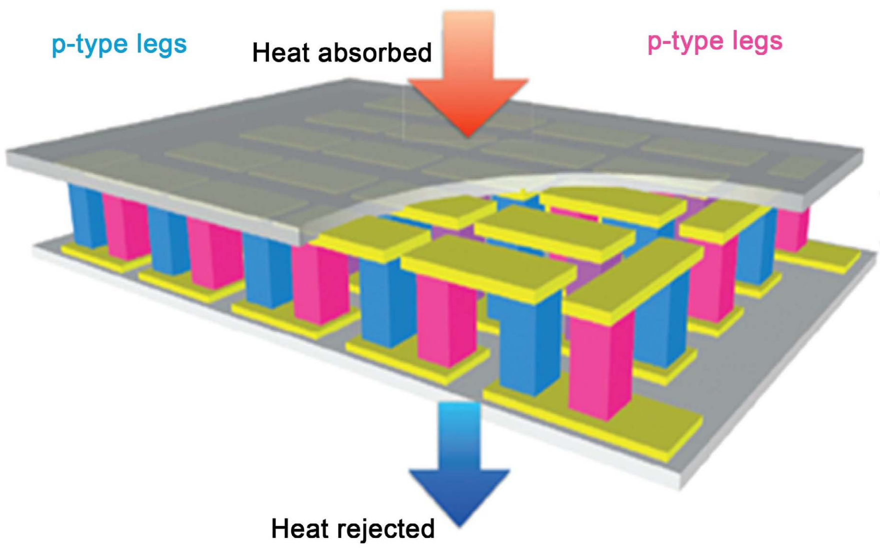

Figure 10. A schematic diagram of a thermoelectric module of thermoelectric generator where multiple p-type and n-type legs are bonded together to increase the accumulated electric potential across the faces of the generator for limited temperature difference [31].

of the nerve impulses as electric charges and assume the existence of an electrochemical "Na^+/K^+ pump" to describe a neuron mechanism that generates the action potential across the cell membrane, **Figure 11** [34]. Imaginary motions of an action potential impulse like the motion of the nerve impulse are also hypothesized while both, the action potential and the nerve impulse, have different natures and dimensions [9]. Such ionic hypothesis cannot also describe the high speed of the nerve impulses which have its own propagating-action potential, and it also ignores the measured nature of tissues of the nervous system that imitates the electrical wiring [35]. The new definition of the electric charges as energy that have its own electric potential matches the conclusions and measurements of the neurologists where this definition finds a more logical function of the Na^+/K^+ pump. The function of the A/B junctions of thermopiles in **Figure 9**, or junctions of the thermoelectric generator in **Figure 10**, represents a thermoelectric pump that converts the potential of heat input to electrical potential of the output electricity by thermoelectric effects, or by effect of the difference between the Seebeck coefficients of the two elements A and B. Accordingly, it is possible to represent the membrane of a neuron that incorporate sodium and potassium ions to be arranged into adjacent pairs, that form successive junctions, as shown in **Figure 12**. Such arrangement resembles the junction pairs of a thermopile, shown in **Figure 9**, or the junction pairs of a thermoelectric generator, shown in **Figure 10**. So, it is possible to explain that the Na^+/K^+ pump is also working as a thermoelectric pump or as a generator of the electric nerve impulses that owns its electric, or action, potential. According to literature, the brain consumes 20% of the human body's energy while its weight doesn't exceed 2% of its weight [36]. Such high energy consumption is logically devoted for production the required energy for the nerve impulses that propagate by its electric potential from the brain neurons to the receptors of the nerve impulses [9].

According to some scientific reports, the recorded temperature difference between the temperature in the brain neurons is 1.6˚C higher than the temperature of the neurites [37]. Such temperature difference is converted during the flow of heat across the membrane of a brain neuron into electric potential by the Seebeck effect, or by the difference between the Seebeck coefficients of Sodium

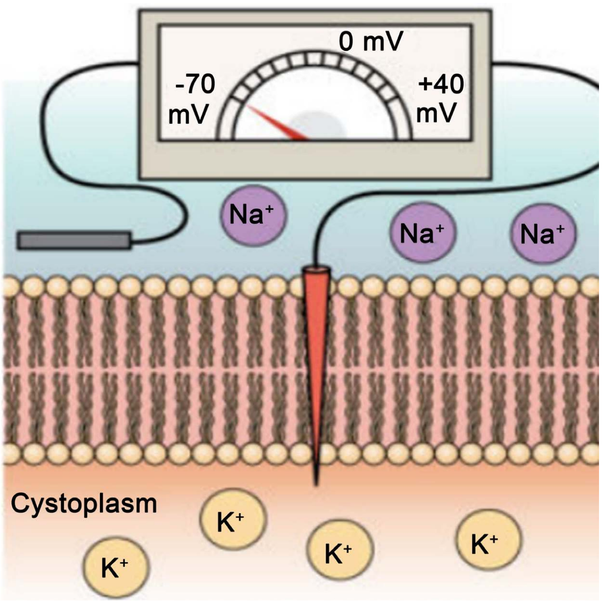

Figure 11. A graphical representation of the Na^+/K^+ pumps in the neuron's membrane as electrochemical generators of the action potential [33].

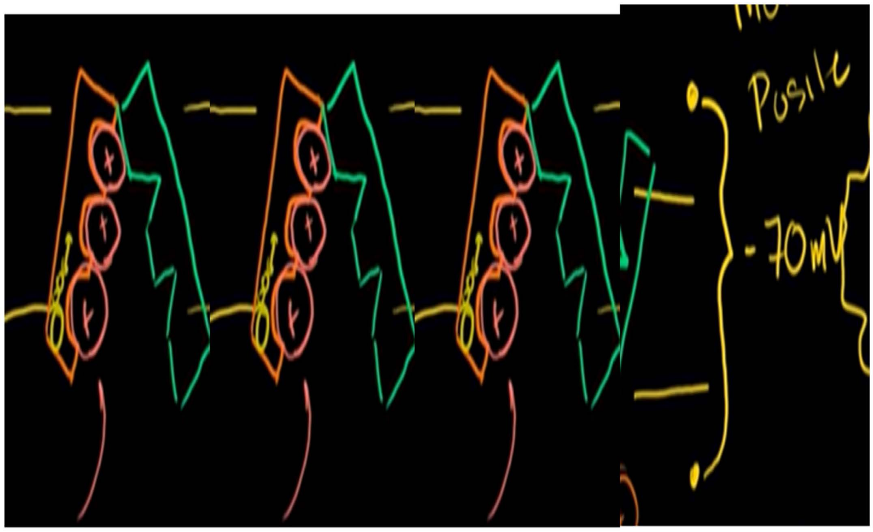

Figure 12. A graphical Representation of the Sodium-Potassium junctions as thermoelectric generators of the action potential in the neuron's membrane.

and Potassium. However, structure of neuron membrane, as seen in **Figure 12**, incorporate many sodium-potassium junctions that also magnify the conversion of the thermal potential of the neuron cell, limited to 1.6 deg, into greater electric potential according to Equation (27). So, it is possible to compute the number of the sodium-potassium junctions that may lead to magnify the small electric potential that corresponds to such temperature difference up to the measured electric potential of 70 mV. This number of junctions in neuron membrane can be found by substituting in Equation (18).

Firstly, the Seebeck effect of Na/K junctions, $\propto_{SK}$ can be calculated by the difference of Seebeck coefficients of the Sodium and Potassium found from the tables of such coefficients as follows:

$$\propto_{SK} = \propto_K - \propto_S = -9 - (-2) = -7 \ \mu\text{V/deg} \tag{19}$$

Substituting the measured action potential, $\Delta E = 70 \text{ mV}$, the temperature difference $\Delta T = 1.6 \text{ Deg}$, and the Seebeck effect as found from Equation (19), in Equation (18), as follows:

$$-70 \text{ mV} = (-7 \times 0.001 \text{ mV/deg.}) \times 1.6$$

The number of the membrane junction is found as follows:

n = 6250 couples

So, the membrane should have 6250 junctions of accumulated sodium-potassium ions to get the required magnified potential of the nerve impulses of the value 70 milli-Volts.

7. Conclusions

By adopting a recently published definition that identifies electric charges as energy or electromagnetic (EM) waves possessing propelling electric potential, a proper understanding of the nature of nerve impulses has been achieved. Such achievement led to achieving the following conclusions:

1) The nerve impulses are electric charges in the form of electromagnetic waves which have energy measured by Joule, electric potential measured by volts, and entropy is measured, according to Ammeter's readings, by Joule/volt.

2) The entropy of the stimulating charge is a physical property of the neural networks that can be used in the diagnosis of the neural systems. It determines a measurable property of the stimulated neural network and may help in a proper diagnosis of such networks.

3) The stimulated response of the neural systems by any stimulator is a nerve impulse and proves that the nerve impulse also is sent from the brain as an electric charge or EM waves that have energy, measured by Joules, and an electrical potential or action potential measured by Volts.

4) The assumed "Na^+/K^+ pump" works as a thermoelectric pump that pumps the metabolic heat of the neuron across the membrane of the neuron by converting the thermal potential of the neurons into electric, or action, potential. The value of such potential is determined by the difference between the Seebeck coefficients of Sodium and Potassium, or the Seebeck effect, and the thermal potential of the metabolic heat in the brain neurons.

5) The rate of flow of energy through the neural network can be estimated according to the following equation:

$$\dot{Q}_{neural} = E \cdot \dot{S}$$

where $\dot{S}$ is the rate of entropy growth in the neural network, measured by an Ammeter, and E is the potential of the nerve impulses measured by a Voltmeter.

Acknowledgements

The author thanks Allah for his guidance in writing this article. The author also thanks the team of the Neurology Clinic in the Hospital of Aswan University for their cooperation in supplying the stimulation cards.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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