DOI: 10.37190/abb/206095

Modelling and Sensitivity Analysis of Neuronal Signal Transmission Under Mechanical Loading

Romuald Będziński[1], Monika Ratajczak[1], Jagoda Kurowiak[1], Agnieszka Mackiewicz[1], Tomasz Klekiel[1*]

[1]Department of Biomedical Engineering, Institute of Material and Biomedical Engineering, Faculty of Engineering and Technical Sciences, University of Zielona Gora, Zielona Gora, Poland

[*]Corresponding author: Tomasz Klekiel, Department of Biomedical Engineering, Institute of Material and Biomedical Engineering, Faculty of Engineering and Technical Sciences, University of Zielona Gora, Zielona Gora, Poland, e-mail address: t.klekiel@iimb.uz.zgora.pl

Submitted: 16th January 2025

Accepted: 9th June 2025

Abstract

PURPOSE: The study of the neuronal structure of the nervous system is difficult due to the complexity and the occurrence of interactions between structures at different levels of hierarchy. The aim of presented research was to develop a mathematical model of signal transmission by a neuron, taking into account the structure of neurons and to analyse the sensitivity of model parameters in the scope of interaction of mechanical, biochemical and electrochemical phenomena in the context of disturbances of nerve signals caused by overloads.

METHODS: To modelling of the potential action then Hodgkin and Huxley (HH) model was used. The model consists of four coupled differential equations: one partial differential equation, which describes the temporal and spatial variation of the membrane potential, and three ordinary differential equations, which represent the dynamics of voltage-gated ion channels. The HH model consists of four coupled differential equations: one partial differential equation, which describes the temporal and spatial variation of the membrane potential, and three ordinary differential equations, which represent the dynamics of voltage-gated ion channels. This model was solved numerically by the finite difference method.

RESULT: The results indicate on change of the action potential for a nerve cell activated by a continuous electrical stimulus, assuming high conductivity of the Na+ and K+ channels. According to the presented model the ion channels respond to pressure, what modulate the permeability of the neuronal membrane for ions.

CONCLUSIONS: The results of the analyses suggest that pressure above 1.4 kPa can disrupt the normal functioning of nerve cells, leading to serious health consequences. In addition, a load of nerve cells, less than 1%, can cause disorders in the functioning of the nervous system. As a result, this mechanism leads to damage to nerve cells, disorders in the conduction of nerve impulses and affects the functioning of synapses.

KEYWORDS: Hodgkin and Huxley model, pressure, action potential, nerve cell, Na+ and K+ channels

1. Introduction

Neurons are the basic functional unit of the nervous system, responsible for receiving, processing, and transmitting information via bioelectrical impulses.

Understanding the mechanisms of signal transmission in the human nervous system is one of the fundamental challenges of modern neurobiology and bioengineering. The nervous system is not only a biological structure of exceptional complexity, but also a dynamic system in which interactions occur at many levels of organizational hierarchy - from molecular, through cellular, to the level of entire neuronal networks. The key link in this system are individual nerve cells - neurons - whose ability to generate, propagate and modulate electrochemical signals is the basis of all cognitive, motor and sensory processes.

Neurons, despite their common principle of operation, differ in morphology, biophysical properties and sensitivity to environmental variables. One of the important, but still insufficiently studied, factors influencing the functioning of neurons are mechanical stimuli. Changes in intracranial pressure, mechanical deformation of the cell membrane or shear forces can lead to significant changes in the membrane permeability to ions and thus to disturbances in nerve conduction. These phenomena are gaining importance in the context of mechanical injuries, sports micro-injuries and chronic overloads associated with professional activity. In recent years, there has been increasing interest in the influence of mechanical impacts – such as pressure or micro-injuries – on nerve conduction disorders and potential damage to neuronal structure [11],[26].

The process of nerve impulse conduction is not limited to electrochemical phenomena only – as long thought – but also depends on the mechanical properties of the surrounding tissues and the neuronal cell membrane itself. In recent years, increasing attention has been paid to the interaction between mechanical phenomena and the functioning of ion channels. It has been shown that changes in mechanical pressure can affect the permeability of the membrane to ions, which in turn changes the dynamics of the action potential [20]. Understanding these relationships requires the integration of biological, biophysical and mathematical approaches.

Mathematical modelling of biophysical processes in neurons allows for precise representation and analysis of signal conduction dynamics in conditions that are impossible or difficult to obtain in experimental studies. Such models enable not only the analysis of healthy functions of nerve cells, but also the simulation of the effects of pathology, mechanical injuries or metabolic disorders. A special place in this field is occupied by the model of Hodgkin and Huxley (1952), which remains the foundation of mathematical neurophysiology to this day [15], [19]. The model consists of four coupled differential equations: one partial differential equation, which describes the temporal and spatial variation of the membrane potential, and three ordinary differential equations, which represent the dynamics of voltage-gated ion channels.

These equations contain nonlinear conditions and do not have analytical solutions, so it is necessary to use numerical methods. It is worth noting that there are other models that have been inspired by the HH equations, such as the Morris-Lecar equations and the FitzHugh-Nagumo equations. These are simplified variations of the HH model, and the Fitz-Hugh-Nagumo equations in particular are often used to study neuronal excitability [3], [9].
In recent years, extensions of the HH model have been developed that take into account additional physical factors, including variable mechanical pressure. Experimental and theoretical studies[17], [28] indicate that the mechanosensitivity of ion channels – especially Na+ and K+ channels – can affect their activity even with small changes in pressure (of the order of 1–2 kPa). Such mechanosensory coupling can lead to improper activation or deactivation of channels, resulting in disruption of the action potential.

In the context of mechanosensory phenomena, experimental studies have shown that ion channels can be activated or modulated by mechanical stress, pressure changes, or membrane deformations [17], [20]. These channels, called mechanosensitive ion channels, are capable of dynamically changing the conformation of proteins under the influence of mechanical forces, which leads to a change in their conductance and, as a result, to the modification of the electrochemical response of the neuron. Such properties may play a key role both in the physiological processes of development and plasticity of neurons, as well as in the pathomechanisms of injuries or neurodegeneration.

However, in the context of mechanical injuries – such as micro-injuries in sports, vibrations transmitted through soft tissues, or pressure exerted by surrounding anatomical structures – even small deformations can lead to chronic disorders of neural signalling. Modelling such phenomena can provide a basis for developing new therapeutic strategies, methods of injury prevention, as well as diagnostic technologies using biophysical markers of neuronal overload.

The purpose of this article was to perform analyses leading to the development of a mathematical model of information transmission through a neuron, taking into account the structure of neurons, and to analyse the sensitivity of model parameters in terms of the interaction of mechanical, biochemical and electrochemical phenomena in the context of perturbation of neural signals caused by overloads and, as a result, local deformations of brain tissue. A modified variant of the Hodgkin-Huxleymodel (H-H) was used to develop the numerical model [1], The H-H model was developed to describe the electrical activity of neurons. It is a nonlinear model based on electrical conductivity.

The aim of the presented research was to develop a mathematical model of signal transmission by a neuron, taking into account the structure of neurons and to analyse the sensitivity of model parameters in the scope of interaction of mechanical, biochemical and electrochemical phenomena in the context of disturbances of nerve signals caused by overloads.

2. Materials and Methods

The work of Francis Crick [3] indicates that, as a result of mechanical deformation, the following can occur:

- *Ion channel openings or closures*: Changes in the membrane structure can cause ion channels to open or close, which alters the flow of ions (such as Na^+, K^+, Ca^{2+}), affecting the membrane potential of the cell.
- *Depolarization or hyperpolarization of the cell membrane*: Mechanical strain can induce changes in membrane tension, leading to depolarization (reduction in potential difference) or hyperpolarization (increase in potential difference), which affects the ability of the neuron to generate an action potential.
- *Modulation of neuronal activity*: Depending on the nature of the strain, this can lead to an increase or decrease in neuronal activity, which has direct consequences for the function of the neural networks in which the neuron is involved.

2.1. The problem of nerve cell deformation

Biological tissues, including nerve cells, are made up of water, cytoskeleton, and lipid cell membranes, which together form a complex mechanical structure. The structure of membrane reacts both as an elastic material (e.g. elastin in cell membranes) and as a viscoelastic material (e.g. cytoskeletal elements such as actin filaments). The viscoelasticity of nerve cells is crucial for their function in the mechanical aspects of protection and response to injury. Therefore, biomechanical models of nervous tissue often use viscoelastic models (e.g. Kelvin-Voigt and Maxwell models). The Kelvin-Voigt model describes the behaviour of viscoelastic materials that combine elastic and viscous elements acting in parallel. In the case of external cell deformation, this model allows to determine the relationship between deformation and pressure inside the cell. Elastic component is described by Hooke's law has $\sigma_e = E * \varepsilon$, where E is the modulus of elasticity and ε is the strain. The viscous component described by Newton's law:

$$\sigma_{visc} = \eta \cdot \frac{d\varepsilon}{dt} \tag{1}$$

where η is the viscosity of the material and dε/dt is the rate of deformation (derivative of deformation over time).

$$\sigma(t) = E \cdot \varepsilon(t) + \eta \cdot \frac{d\varepsilon(t)}{dt} \quad (2)$$

Assuming that a nerve cell is subjected to a homogeneous external deformation (e.g. by mechanical action on its membrane), we can assume that the pressure $p(t)$ inside the cell is proportional to the total stress $\sigma(t)$ that arises as a result of deformation. For an isotropic material in which stresses and pressures are related to each other in a simple way, assumed that $p(t) = -\sigma(t)$. Substituting stress from the Kelvin-Voigt model give the relation:

$$p(t) = -E \cdot \varepsilon(t) - \eta \cdot \frac{d\varepsilon(t)}{dt} \quad (3)$$

In Maxwell's model, the total strain $\varepsilon(t)$ is the sum of elastic strain $\varepsilon_e(t)$ and sticky $\varepsilon_{visc}(t)$:

$$\varepsilon(t) = \varepsilon_e(t) + \varepsilon_{visc}(t) \quad (4)$$

Table. 1. Summary of data used to identify the model.

No.	Type of load	Pressure value	Effect in the nerve	Ref.
Short-term effect				
1	Extrinsic compression	4.0 kPa	Inhibits fast and slow anterograde, as well as retrograde axonal transport.	[4]
2	External nerve compression for a period of 2 minutes.	6.7 kPa	Change in the shape of myelin sheaths. At higher pressures, myelin is severely split and distorted.	[7]
3	Static extra-neural compression.	4.0 kPa	Observed decline in nerve function.	[24]
4	Compression applied cyclically at 1 Hz for 20000 cycles.	4.7 kPa on average; 2.7 to 6.7 kPa peak-to-peak	Decline in nerve function.	
5	Wrist nerve compression.	5.3 kPa	Decline in nerve function.	[12], [13], [23]
6	Wrist nerve compression.	6.7 kPa	Complete blockage of nerve function.	
Long-term effect				
7	Compression of the sciatic nerve for 2 hours with follow-up intervals of 5 to 7 days.	1.3 and 4.0 kPa	Swelling and inflammation of the nerve. Demyelination noted at 4 kPa compression and to a lesser extent at 1.3 kPa.	[18]

8	Compression of rabbit ganglion cells 7 days after 2h.	4.0 kPa	Reduction in the volume density of the nucleus accumbens. Functional changes in the neuron and nerve trunk.	[4], [5]

The stress for the Maxwell model is given by the differential equation:

$$\frac{d\sigma(t)}{dt} + \frac{\sigma(t)}{\eta} = \frac{E}{\eta} \cdot \frac{d\varepsilon(t)}{dt} \tag{5}$$

The differential equation for pressure takes the form:

$$\frac{dp(t)}{dt} + \frac{p(t)}{\eta} = \frac{-E}{\eta} \cdot \frac{d\varepsilon(t)}{dt} \tag{6}$$

2.2. Study of changes in cell potential

The Hodgkin-Huxley model is a fundamental mathematical model that describes how neurons generate and propagate electrical impulses (action potentials).

$$C\,\frac{\partial V}{\partial t} = I_{ext} - (I_{Na} + I_K + I_L) \tag{7}$$

where:

$$I_{Na} = g_{Na} m^3 h (V - E_{Na}) \tag{8}$$

I_{Na} −sodium current, determined by the conductance of sodium channels and the difference between the membrane potential and the sodium equilibrium potential.

$$I_K = g_K n^4 (V - E_K) \tag{9}$$

I_K − potassium current, similarly determined by the potassium channels' conductance and the membrane potential.

$$I_L = g_L (V - E_L) \tag{10}$$

I_L − Leak current, a smaller constant current due to the leak channels.

I_{ext} − External current applied to the neuron.

Main model parameters used to solution where assumed from applications used in eq. 7-10.

Table 2. include values for the model implementation.

Parameter name	Sign	Value
Membrane capacitance (uF/cm^2)	C	1
Base conductance for Na^+ (mS/cm^2)	g_{Na}	120
Base conductance for K^+ (mS/cm^2)	g_K	36

Conductance for leak current (mS/cm^2)	g_L	0,3
Equilibrium potential for Na^+ (mV)	E_{Na}	50
Equilibrium potential for K^+ (mV)	E_K	-77
Equilibrium potential for leak current (mV)	E_L	-54,4

These values are typically derived from the Hodgkin-Huxley model based on experimental tests.

2.3. Short Impact

The Hodgkin-Huxley model in the shape:

$$C\frac{\partial V}{\partial t} = I_{ext} - (G_{Na}m^3h(V - E_{Na}) + G_K n^4(V - E_K) + g_L(V - E_L)) \quad (11)$$

can be modified to account for the effects of pressure on membrane conductivity. The additional factors were proposed as:

$$G_{Na}(t) = g_{Na,0} + g_{Na,m} \cdot P(t) \quad (12)$$

$$G_K(t) = g_{K,0} + g_{K,m} \cdot P(t) \quad (13)$$

where:

$g_{Na,0}$ and $g_{K,0}$ – are typical conductance,

$g_{Na,0}$ and $g_{K,m}$ – are the maximum conductance for sodium and potassium channels under normal conditions,

$P(t)$ – is a function representing how pressure affects conductance.

The pressure's impact was proposed as the exponential decay function that reduces conductance as pressure increases:

$$P(t) = P_0 \cdot exp\left(\frac{-(t-t_0)^2}{\tau_p}\right) \cdot D(t) \quad (14)$$

where:

$D(t)$ – function described the changes in the cell membrane permeability,

τ_p – is responsible for the pulse width (standard deviation),

t_0 – the time at which the function reaches its maximum (the center of the pulse),

P_0 – the maximum value of the amplitude.

3. Results and Discussion

An analysis of the relationship between the deformation of nerve structures and pressure according to the relationships (3) and (6) was performed. Numerical tests have shown that as

the pressure increases, increased deformations occur. A pressure of about 5 kPa causes deformations that can affect the backflow of neurites in the cell. Similar conclusions were drawn at the work [10]. At the same time, in global terms, pressure values up to 78 kPa do not cause permanent changes in the brain [28]. Based on the data collected in the table 1, the minimal pressure involve changes activity inside brain are consists around 4-5kPa. These pressure changes should have influence on potential inside the neural cell, what was simulated solving HH model, which was modified according to presented method. The equation was extra developed by the element depended from the pressure.

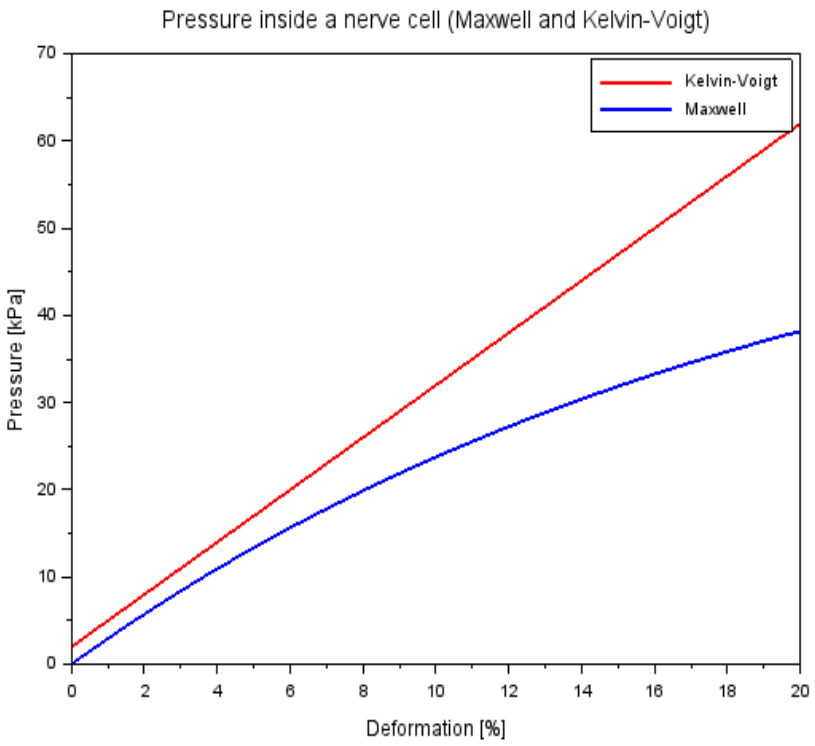

Figure. 1. Relationship between pressure and deformation.

The presented results in comparison with the pressure values calculated on the basis of the strain values predicted in the simulations [8], [21], [22] allowed to initially validate the model describing the formation of an action potential in the nerve cell described by equation (11).

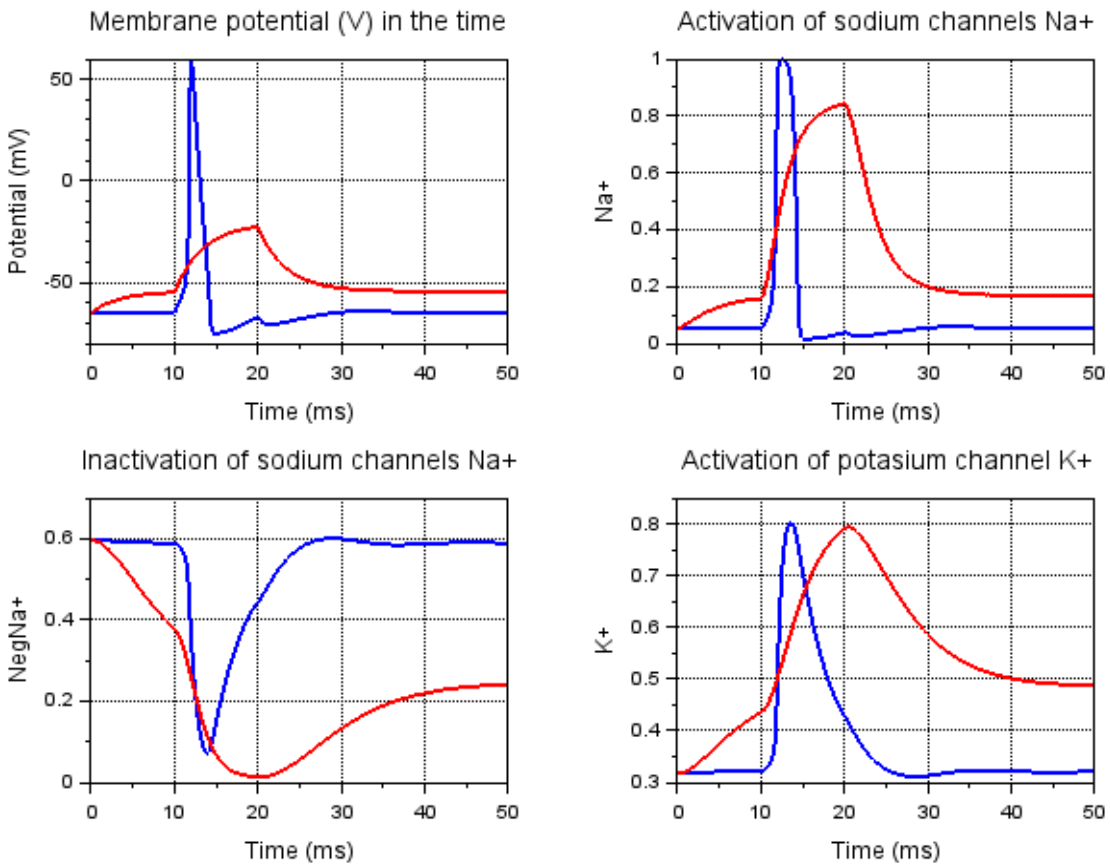

Figure. 2. Action potential for 50% conductivity of Na^+ and K^+ channel: blue line – 100% of conductivity, red line – 50% of conductivity.

The Figure 2. shows the course of the action potential and activation of potassium and sodium ions on the cell membrane, indicating the typical and well-known course of the action potential during impulse activation. Based on the numerical values of the coefficients of equations (8) and (9), the signal waveform was simulated by decreasing these coefficients by 50%, which resulted in the activation of the sodium and potassium channels being disturbed according to the model in such a way that it was maintained after the excitatory impulse ceased.

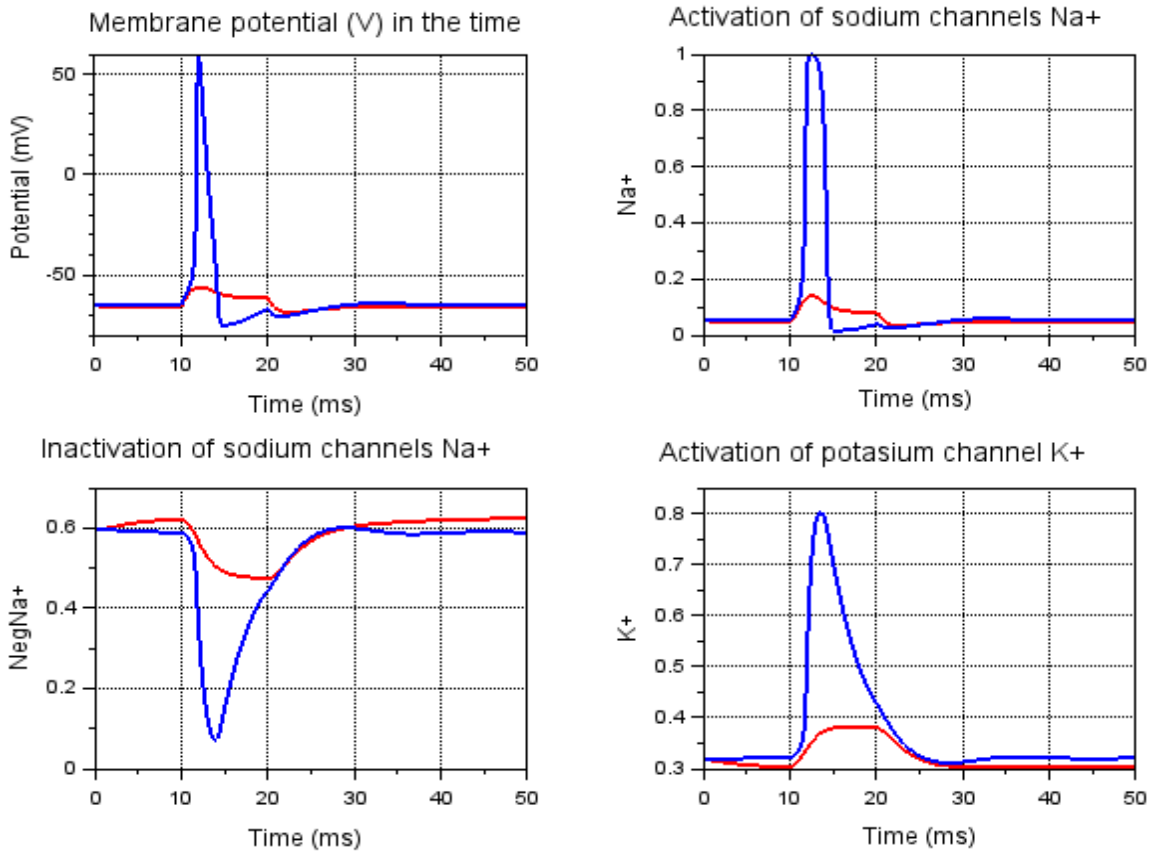

Figure. 3. Action potential for 10% conductivity of Na^+ and K^+ channel: blue line – 100% of conductivity, red line – 10% of conductivity.

The Figure 3. shows the course of action potential activation with a single pulse at low channel conductivity, at the level of 10%. Strong disturbances in the conductivity of the channels cause a decrease in both the amplitude of the potential and the activity of the channels, which in turn can lead to inactivity. Such symptoms can be related to the observation of the behaviour of the nervous system, where after a severe disorder, the body's reactions to stimuli disappear temporarily or are significantly delayed. This effect can be observed in martial arts fighters when motor functions are impaired during knockout (KO). Additionally, some boxers experience persistent residual cognitive and physical symptoms, such as temporary short-term memory loss, dizziness, difficulty maintaining balance, and headaches for days or weeks after a boxing fight [6].

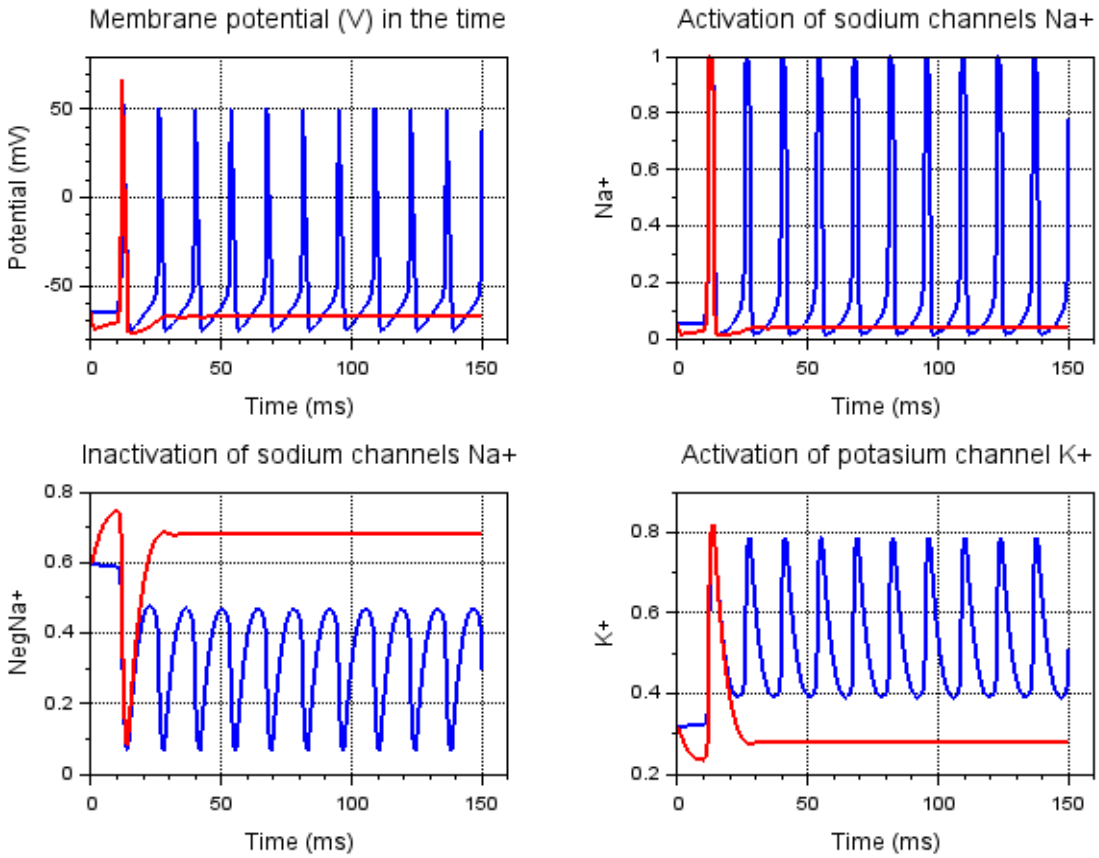

Figure. 4. Action potential for hyperconductivity of Na^+ and K^+ channels.

The Figure 4. presents simulations of the course of the action potential for a nerve cell activated by a continuous electrical stimulus, assuming high conductivity of the Na^+ and K^+ channels. The ion channels respond to pressure, which can modulate the permeability of the neuronal membrane to ions. For instance, increased pressure in the brain, such as elevated intracranial pressure (ICP), are activating Na^+ and K^+ channels, modifying ion flow. Pressure play a significant role in modulating neural activity by the change of conductivity. Therefore, it should be assumed that such a phenomenon will accompany cell loads during local deformations, and thus significant from the point of view of the danger of trauma formation and pressure increase disorders.

3.1. Analyse of relationship between pressure and neuron activate process

Further simulation concerns the inclusion of equation (14) describing the pressure impulse in equation (11) describing the course of action potential formation.

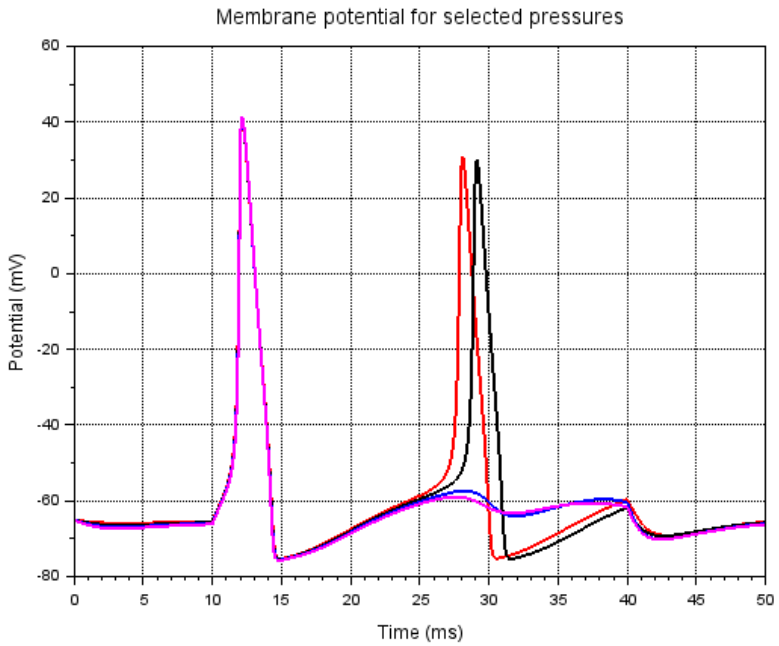

Figure. 5. Signal disturbances generated in the neural cell caused by a pressure pulse.

The Figure 5. shows the model's response to a single electrical stimulus, assuming the appearance of a pressure pulse interfering with the signal formation process.

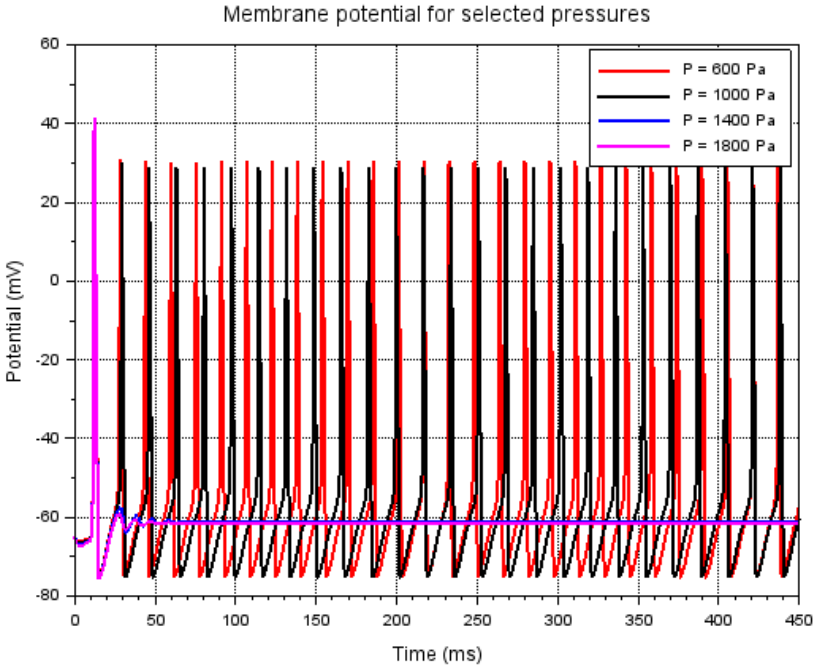

Figure. 6. Signal disturbances generated in the neural cell for selected pressure impulse.

The parameters of equation (14) were selected so that the model reacts to pressure changes above 1.3 kPa as the limit value of pressure, after which clear changes in the course of the cell action potential are observed, including signal loss, and clear changes and mechanical damage are observed in the cell structure. The adoption of this model identification methodology allowed to analyse the formation of disturbances at the borderline preceding permanent damage. Simulations were carried out for different pressure amplitudes of 6, 1, 1.4 and 1.8 kPa to observe how the action potential is formed. Observations of the results of the analyses allowed to draw the conclusion that pressure-induced disorders can significantly cause disorders in the formation of the action potential of nerve cells and thus lead to its long-term disappearance. Figure 6 shows the signal waveform for different pressures, which indicates that after exceeding the pressure limit and significant hyper conductivity of the ion channels, a strong disturbance occurs and the system does not stabilize and the potential disappears.

Increased intracranial pressure (ICP) can restrict blood flow to the brain, leading to ischemia (a lack of oxygen and nutrients) and reduced ability to effectively operate ion pumps. When these pumps are not functioning properly, the ionic conductivity of the membrane decreases, preventing the generation and transmission of action potentials. The high pressure impulse acting on the nerve cell causes a disturbance in the membrane potential leading to the loss of this potential.

4. Conclusions

The results of the numerical analysis based on the extended Hodgkin and Huxley model indicate a significant relationship between the mechanical pressure acting on the neuronal cell membrane and the dynamics of the action potential conduction. The simulations showed that even a relatively small increase in pressure (above 1.4 kPa) can cause disturbances in the functioning of ion channels, which results in significant changes in the amplitude, duration and frequency of nerve impulses. This is consistent with literature reports describing the mechanosensitivity of Na^+ and K^+ channels in neurons, both in physiological and pathological conditions [17], [20].

The HH model, although it did not initially take into account mechanical interactions, turned out to be a useful basis for the integration of electrochemical and biomechanical phenomena. Supplementing it with variables describing the effect of pressure allows for a more realistic representation of the cellular environment of the neuron, especially in the context of injuries, micro-injuries and overloads. Similar approaches, combining biophysical models with

solid-state mechanics, have been tested before, e.g. in studies on axonal stretching or intracranial pressure [29], [16].

Of particular interest are the results indicating that even a small mechanical deformation (of the order of <1% strain) can lead to disruptions in the transmission of the neural signal. This suggests the existence of a threshold of sensitivity of the neuron to overloads, below which the functioning of the cell is stable, while above which disruptions occur leading to potential damage. This phenomenon may be of particular importance in sports neurophysiology and occupational medicine, where repeated, cumulative stresses – even if subclinical – can lead to chronic changes in the nervous system [11], [16], [26].

The model results also indicate a dynamic response of ion channels to pressure: an increase in pressure leads to an increase in the conductance of Na^+ channels, which results in a faster achievement of the depolarization threshold, but at the same time may cause too rapid repolarization, disrupting the rhythm of impulse generation. This interpretation is consistent with the experimental results of Ranade et al. [20], who showed that mechanical activation of channels can lead to both hyperexcitability and conduction blockade.

In the context of clinical and technical applications, the developed model can be used in the design of medical devices such as neuroprostheses or systems for neuromodulation therapy, where understanding the effect of mechanical stimuli on nerve conduction is crucial. It can also serve as a basis for research on the effects of traumatic brain injury (TBI), where mechanical pressure is one of the main pathogenic factors [16].

It is worth noting, however, that the model has limitations. In its current form, it does not take into account the influence of the glial system, complex dendritic structures and local temperature and pH fluctuations, which can modify the cell membrane response. Homogenization of the mechanical parameters of the neuron can also lead to a certain simplification of the actual biological response. Therefore, further work is necessary to expand the model with components representing, among others, glial cells, neuronal networks and the complex extracellular environment.

Based on the conducted experimental analyses and theoretical assumptions, the authors concluded that intracranial pressure can affect neuronal conductivity. The results of the analyses suggest that pressure above 1.4 kPa can disrupt the normal functioning of nerve cells, leading to serious health consequences. In addition, a load of nerve cells, less than 1%, can cause disorders in the functioning of the nervous system. As a result, this mechanism leads to damage

to nerve cells, disorders in the conduction of nerve impulses and affects the functioning of synapses.

In the clinical literature, many pathologies are observed associated with a rapid change in intracranial pressure, such as:

- Cerebral edema: In the case of cerebral edema, excessive intracranial pressure can lead to compression of neurons and damage to their structures, which negatively affects nerve conduction. This can lead to neurological symptoms, such as impaired consciousness or problems with coordination.
- Spinal cord injuries: In the case of spinal cord injuries, pressure changes can lead to damage to nerve cells and disruption of impulse conduction, which can result in paralysis or loss of sensory and motor functions.
- Neurological disorders: In the case of some neurological diseases, such as multiple sclerosis, changes in the structure of nerve cells can affect their ability to conduct impulses.

Brain tissue damage is a complex mechanobiological problem, the spatial dimensions of which range from nanometre disturbances in the neuronal membrane to centimetre properties of the brain matter. The presented work has shown that even a small increase in pressure in the cell, repeated many times, can cause long-term consequences causing biochemical and electrical disturbances in cell functioning. In the literature, we can find similar conclusions, where nanosecond [14] impact of forces causes conformational changes in mechanically loaded proteins. However, over the years, it can cause neurodegenerative diseases. This phenomenon is often observed in contact sportsmen, e.g. boxers.

Summarizing the research conducted in this paper, the authors draw the following conclusions:

- Pressure, both internal and external, plays an important role in the conduction of nerve cells.
- The simulations performed allowed us to determine the conditions for the occurrence of disorders in the conduction of neurons.
- It was determined how the load affects the mechanical properties of cells, membrane tension and action potential.
- The causes leading to disorders in the conduction of nerve impulses in the case of excessive pressure were indicated.

Understanding these influences is crucial in the context of neurological health, rehabilitation and the development of medical technologies, which must take into account the effect of pressure on nerve cells to provide effective and safe solutions.

Future studies should focus on linking the effect of pressure to the connection of signalling pathways to better understand how the brain responds to external mechanical forces. As a result, this mechanism will allow for better identification of parameters that lead to secondary brain injury.

Conflict of interests

All authors declare no competing interests.

References

[1] Caceres J.L., Dzhimak S.S., Semenov D.A., Models of Nerve Impulse Generation and Conduction, Biophysics, 2022, 67, 582–592, 2022, DOI: 10.1134/S0006350922040078.

[2] Catterall W.A., Raman I.M., Robinson H.P.C., Sejnowski T.J., Paulsen O., The Hodgkin-Huxley Heritage: From Channels to Circuits, J. Neurosci., 2012, 32(41), 14064-14073, DOI: 10.1523/JNEUROSCI.3403-12.2012.

[3] Crick F.H., Thinking about the brain, Sci. Am., 1979, 241(3), 219-232, DOI: 10.1038/scientificamerican0979-219.

[4] Dahlin L.B., McLean W.G., Effects of graded experimental compression on slow and fast axonal transport in rabbit vagus nerve, J. Neurol. Sci., 1986, 72(1), 19-30, DOI: 10.1016/0022-510x(86)90032-8.

[5] Dahlin L.B., Nordborg C., Lundborg G., Morphologic changes in nerve cell bodies induced by experimental graded nerve compression, Exp. Neurol., 1987, 95(3), 611-621, DOI: 10.1016/0014-4886(87)90303-7

[6] Donnelly R.R., Ugbolue U.C., Gao Y., Gu Y., Dutheil F., Baker J.S., A Systematic Review and Meta-Analysis Investigating Head Trauma in Boxing, Clin. J. Sport Med., 2023, 33(6), 658-674, DOI: 10.1097/JSM.0000000000001195.

[7] Dyck P.J., Lais A.C., Giannini C., Engelstad J.K., Structural alterations of nerve during cuff compression, Proc. Natl. Acad. Sci. USA, 1990, 87(24), 9828-9832, DOI: 10.1073/pnas.87.24.9828.

[8] Dymek M., Ptak M., Ratajczak M., Fernandes F.A.O., Kwiatkowski A., Wilhelm J., Analysis of HIC and Hydrostatic Pressure in the Human Head during NOCSAE Tests of American Football Helmets, Brain Sci., 2021, 11(3), 287, DOI: 10.3390/brainsci11030287.

[9] Ermentrout G.B., Terman D.H., Mathematical foundations of neuroscience, Springer, 2010.

[10] Etten K., The Effect of Hydrostatic Pressure on Neuronal Cell Morphology In Vitro, Dissertation, Clemson University, 2017.

[11] Franze, K., & Guck, J., The biophysics of neuronal growth. Reports on Progress in Physics, 73(9), 2010, 094601. https://doi.org/10.1088/0034-4885/73/9/094601

[12] Gelberman R.H., Szabo R.M., Williamson R.V., Dimick M.P., Sensibility testing in peripheral-nerve compression syndromes. An experimental study in humans, J. Bone Joint Surg. Am., 1983, 65(5), 632-638.

[13] Gelberman R.H., Szabo R.M., Williamson R.V., Hargens A.R., Yaru, N.C., Minteer-Convery M.A., Tissue pressure threshold for peripheral nerve viability, Clin. Orthop. Relat. Res., 1983, 178, 285-291.

[14] Hemphill M.A., Dauth S., Yu C.J., Dabiri B.E., Parker K.K., Traumatic Brain Injury and the Neuronal Microenvironment: A Potential Role for Neuropathological Mechanotransduction, Neuron, 2015, 85(6), 1177-92, DOI: 10.1016/J.NEURON.2015.02.041.

[15] Hodgkin A.L., Huxley A.F., A quantitative description of membrane current and its application to conduction and excitation in nerve, J. Physiol, 1952, 117(4), 500-544, DOI: 10.1113/jphysiol.1952.sp004764.

[16] Meaney, D. F., & Smith, D. H., Biomechanics of concussion. Clinics in Sports Medicine, 2011, 30(1), 19–31. https://doi.org/10.1016/j.csm.2010.08.009

[17] Morris, C. E., Mechanosensitive ion channels. Journal of Membrane Biology, 2011, 244(2), 77–94. https://doi.org/10.1007/s00232-011-9407-3

[18] Powell H.C., Myers R.R., Pathology of experimental nerve compression, Lab. Invest., 1986, 55(1), 91-100.

[19] Powell C.L., Brown A.M., A classic experiment revisited: membrane permeability changes during the action potential, Adv. Physiol. Educ., 2021, 45(1), 178-181, DOI: 10.1152/advan.00188.2020.

[20] Ranade, S. S., Syeda, R., & Patapoutian, A., Mechanically activated ion channels. Neuron, 2015, 87(6), 1162–1179. https://doi.org/10.1016/j.neuron.2015.08.032

[21] Ratajczak M., Ptak M., Chybowski L., Gawdzińska K., Będziński R., Material and Structural Modeling Aspects of Brain Tissue Deformation under Dynamic Loads, Materials, 2019, 12(2), 271, DOI: 0.3390/ma120201271.

[22] Ratajczak M., Ptak M., Kwiatkowski A., Kubicki K, Fernandes F.A.O., Wilhelm J., Dymek M., Sawicki M., Żółkiewski S., Symmetry of the Human Head—Are Symmetrical

Models More Applicable in Numerical Analysis?, Symmetry, 2021, 13, 13(7), 1252, DOI: 10.3390/SYM13071252.

[23] Szabo R.M., Gelberman R.H., Williamson R.V., Hargens A.R., Effects of increased systemic blood pressure on the tissue fluid pressure threshold of peripheral nerve, J. Orthop. Res., 1983, 1(2), 172-178, DOI: 10.1002/jor.1100010208.

[24] Szabo R.M., Sharkey N.A., Response of peripheral nerve to cyclic compression in a laboratory rat model, J. Orthop. Res., 1993, 11(6), 828-833, DOI: 10.1002/jor.1100110608.

[25] Tuckwell, H. C., Introduction to theoretical neurobiology: Volume 1, linear cable theory and dendritic structure, Cambridge University Press,1988.

[26] Tyler, W. J. The mechanobiology of brain function. Nature Reviews Neuroscience, 2012, 13(12), 867–878. https://doi.org/10.1038/nrn3383

[27] Wang, J., Tofangchi, A., & Saif, T., Stretch-induced changes in action potential conduction in axons, Frontiers in Cellular Neuroscience, 2018, 12, 163. https://doi.org/10.3389/fncel.2018.00163

[28] Zhang J., Communication between neurons: neurotransmitters, receptors, and action potential, Proceedings of the SPIE, 12789, International Conference on Modern Medicine and Global Health (ICMMGH), 2023, DOI: 10.1117/12.2692217.

[29] Zhang L., Yang K.H., King A.I., A proposed injury threshold for mild traumatic brain injury, J. Biomech. Eng., 2004, 126(2), 226-236, DOI: 10.1115/1.1691446.

[30] Zhu, R., & Xu, J., Electromechanical model of neuron under mechanical loading, Journal of Biomechanics, 2015, 48(6), 1084–1090. https://doi.org/10.1016/j.jbiomech.2015.01.049