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Electricity and Cellular Applications

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Abstract
This present study was aimed at investigating electricity and its cellular applications. The study designed adoptedanarrative review format. The investigation employed the comprehensive search of relevant literature by checking Googlescholar, PubMed and Scopus databases by employing the key words related to the sections and subsections respectively. The study found that electricity is known to interrelate with cellular life forms of different categories. Historically, electricity has both been generated and utilized in cells within varied scenarios. Where, and to what extent this interrelationship exists, how it occurs, magnitude, and regularity are important discuss to be explored. Moreover, harnessing of electrical resource as manipulative tools to serve a host of cellular functions is also covered in this review. The relevance, challenges and the future prospects of continued development of cell-based and utilizable techniques for applications in biological fields of study and practice in the context of this discussion were equally addressed in this review article. This review has shown that cellular factors and entities in certain scenario can constitutively acquire and generate electricity. The electricity so generated can be deployed towards various applications.
Keywords*: Electricity, charge, electrons, cells, cellular, biological, application.*

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I. INTRODUCTION

Electricity as aphenomenon deals with stationary or moving electric charges where electrical charge is a fundamental inherent property of matter borne by elementary particles. Electrons which are the particles involved in electricity carry a designated negative charge whose accumulated motion results in electricity which is used to power or drive a wide variety of needs (Electricity, 2025; EIA, 2025).

Indeed, electricity is associated with a wide variety of activities ranging from the liberal arts, physical sciences, and to the life sciences (Funk and Scholkmann, 2023). In the various fields of relevance, electricity is either the result of inherent by-production of specific activities, or it is harnessed, manipulated to power, drive specific processes. Electrical phenomena in the life sciences are quite varied, and keeps developing into newer frontiers thus increasing the potential relevance in this arena (EIA, 2025). It is therefore important to appraise the activities of electricity in the life sciences with emphasis on its current and potential applications in cellular manipulations.

ELECTRICITY IN THE BIOSCIENCES

Electricity generation and utilization within the context of biosciences is as old as creation itself. Bioelectricity, the concept normally used to describe this phenomenon refers to the generation or action of electric currents or voltages in biological processes (Khan et al. 2020).

Bioelectric phenomena include fast signaling in nerves and the triggering of physical processes in muscles or glands. There is some similarity among the nerves, muscles, and glands of all organisms, possibly because fairly efficient electrochemical systems evolved early (Bioelectricity, 2025). Electric activity in living tissue is a cellular phenomenon, dependent on the cell membrane. The membrane acts like a capacitor, storing energy as electrically charged ions on opposite sides of the membrane. The stored energy is available for rapid utilization and stabilizes the membrane system so that it is not activated by small disturbances (Bioelectricity, 2025).

In addition to the potentials originating in nerve or muscle cells, relatively steady or slowly varying potentials (often designated dc) are known. These dc potentials occur in the following cases: in areas where cells have been damaged and where ionized potassium is leaking (as much as 50 millivolts); when one part of the brain is compared with another part (up to one millivolt); when different areas of the skin are compared (up to 10 millivolts); within pockets in active glands, e.g., follicles in the thyroid (as high as 60 millivolts); and in special structures in the inner ear (about 80 millivolts).

A small electric shock caused by static electricity during cold, dry weather is a familiar experience. While the sudden muscular reaction it engenders is sometimes unpleasant, it is usually harmless. Even though static potentials of several thousand volts are involved, a current exists for only a brief time and the total charge is very small. A steady current of two milliamperes through the body is barely noticeable. Severe electrical shock can occur above 10 milliamperes, however. Lethal current levels range from 100 to 200 milliamperes. Larger currents, which produce burns and unconsciousness, are not fatal if the victim is given prompt medical care (Above 200 milliamperes, the heart is clamped during the shock and does not undergo ventricular fibrillation). Prevention clearly includes avoiding contact with live electric wiring; risk of injury increases considerably if the skin is wet, as the electric resistance of wet skin may be hundreds of times smaller than that of dry skin (Khan et al. 2020; Bioelectricity, 2025).

CELLULAR ELECTRICITY

Living cells are capable of generating, maintaining and coordinating a variety of electrical signals which are very representative of the dynamic electrochemical evens that occur both within the cells and between cell interfaces (Norfleet et al. 2024), and plants (Ghildiyal et al. 2025). Therefore, there are descriptive activities that truly indicate of the occurrences (Figure 1). Several of such events will be explained in the following discuss.

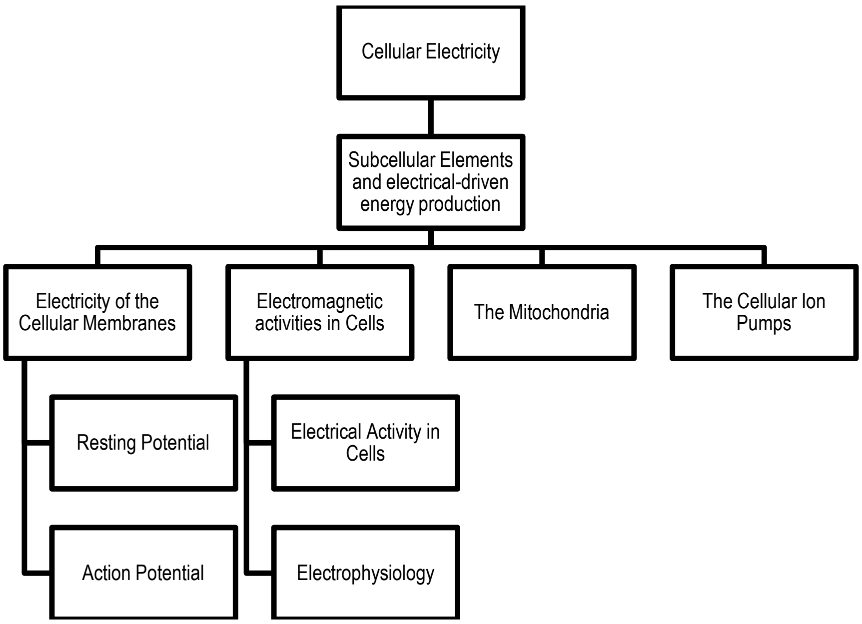

Figure 1: The Cascade of Cellular Electricity

Electricity of the cellular membranes

Cells capable of electric activity show a resting potential in which their interiors are negative by about 0.1 volt or less compared with the outside of the cell. When the cell is activated, the resting potential may reverse suddenly in designation; as a result, the outside of the cell becomes negative and the inside positive, signaling an action potential. More specifically, this resting and action potential can be explained further as follows (Carvalho, 2022):

Resting Potential: Cells maintain a difference in electrical charge across their membrane,known as the membrane potential. This potential is crucial for maintaining homeostasis and the ability of cells to respond to stimuli (Kruger et al. 2015; Carvalho, 2022).

Action Potentials: In neurons and muscle cells, the rapid changes in membrane potential (action potentials) are key to transmitting signals. This electrical signal is what allows neurons to communicate and muscles to contract. This condition lasts for a short time, after which the cell returns to its original resting state (Kruger et al. 2015; Carvalho, 2022).

This sequence, called depolarization and repolarization, is accompanied by a flow of substantial current through the active cell membrane, so that a “dipole-current source” exists for a short period. Small currents flow from this source through the aqueous medium containing the cell and are detectable at considerable distances from it. These currents, originating in active membrane, are functionally significant very close to their site of origin but must be considered incidental at any distance from it (Kruger et al. 2015). In electric fish, however, adaptations have occurred, and this otherwise incidental electric current is actually utilized. In some species the external current is apparently used for sensing purposes, while in others it is used to stun or kill prey. In both cases, voltages from many cells add up in series, thus assuring that the specialized functions can be performed. Bioelectric potentialsdetected at some distance from the cells generating them may be as small as the 20 or 30 microvolts associated with certain components of the human electroencephalogram or the millivolt of the human electrocardiogram (Electricity, 2025). On the other hand, electric eels can deliver electric shocks with voltages that un in hundreds of volts.

Electromagnetic activities in cells

Living cells are known to generate a plethora of electrical and magnetic impulses that travel down to where they are needed to drive some critical biological processes in human, animal and plant cells, tissues and organs of the body. These activities can be further disaggregated to derive other functional operations within the biological spaces (see Figure 1). Two main ways this can happen are hereby subsequently presented as follows.

Electrical Activity in Cells: Every living cell generates small electrical signals. The flow of ions within and across the cell membrane (like sodium, potassium, calcium, and chloride ions) creates these electrical potentials. Furthermore, the gravitation of ionic components towards set targets within the cells further creates transient and, in some cases, persistent electromagnetic flux within the cellular compartments. These can serve varied purposes, enabling the cells to drive certain critical cellular events crucial for the cell's vital living and survival (Carvalho, 2022; 2023).

Electrophysiology: This relates to the study of electrical properties of biological cells, tissues and organ system, including how they function constitutively. In electrophysiology, concern is given to understanding the elaborate nature of, constitution and operation of physiological events involving the cellular, tissue and systemic compartments of the living organism in the context of the impacting electromagnetic dynamics occurring within the cells. Thus, electrophysiology is quite essential in understanding how cells communicate, as well as diagnosing and treating various diseases, such as arrhythmias and neurological disorders (Carvalho, 2022; 2023; Cervera et al. 2024).

SUBCELLULAR ELEMENTS AND ELECTRICAL-DRIVEN ENERGY PRODUCTION

All subcellular structures within the cells conflict either positively or negatively with electrically-driven energy events. However, there are two main events that stand out and they are hereby discussed shown in Figure 1.

The Mitochondria

The mitochondria are rightly described as the powerhouse of the cell, a placement that it has earned due to its large capacity for energy generation and management. It generatesadenosine triphosphate (ATP), which is the units in which cellular energy is generated, stored and utilized, through a process called oxidative phosphorylation. As such, ATP may well be referred to as the main energy currency of living cells (although, there are other forms in which energy can be stored and utilized in the cells such as adenosine diphosphate, and other phosphorylated energy storage elements). Overall, this process involves creating an electrochemical gradient across the mitochondrial membrane, which is then used to drive ATP synthesis (Lautemann et al. 2016; Cervera et al. 2023).

The Cellular Ion Pumps

The cellular ion pumps are critical subcellular structures that living cells deploy to enable it drive some critical cellular events that are crucial to the cell's survival. To do this, cellular processes such as the sodium-potassium pump rely on electricity. The movement of sodium and potassium ions across the cell membrane uses energy in the form of ATP to maintain electrical gradients that are essential for nerve and muscle cell function (Cervera et al. 2019; 2020). Consequently, vital tissue-level function such as muscular and nervous activities are only enabled when the relevant ion pumps is functioning effectively.

TECHNIQUES AND APPLICATIONS OF ELECTRICITY IN CELLULAR PROCESSES

Cellular electrical processes have bequeathed a host of applications and techniques in the biological terrain. Some earlier developments are chronicled in the following discussion andas depicted in Figure 2.

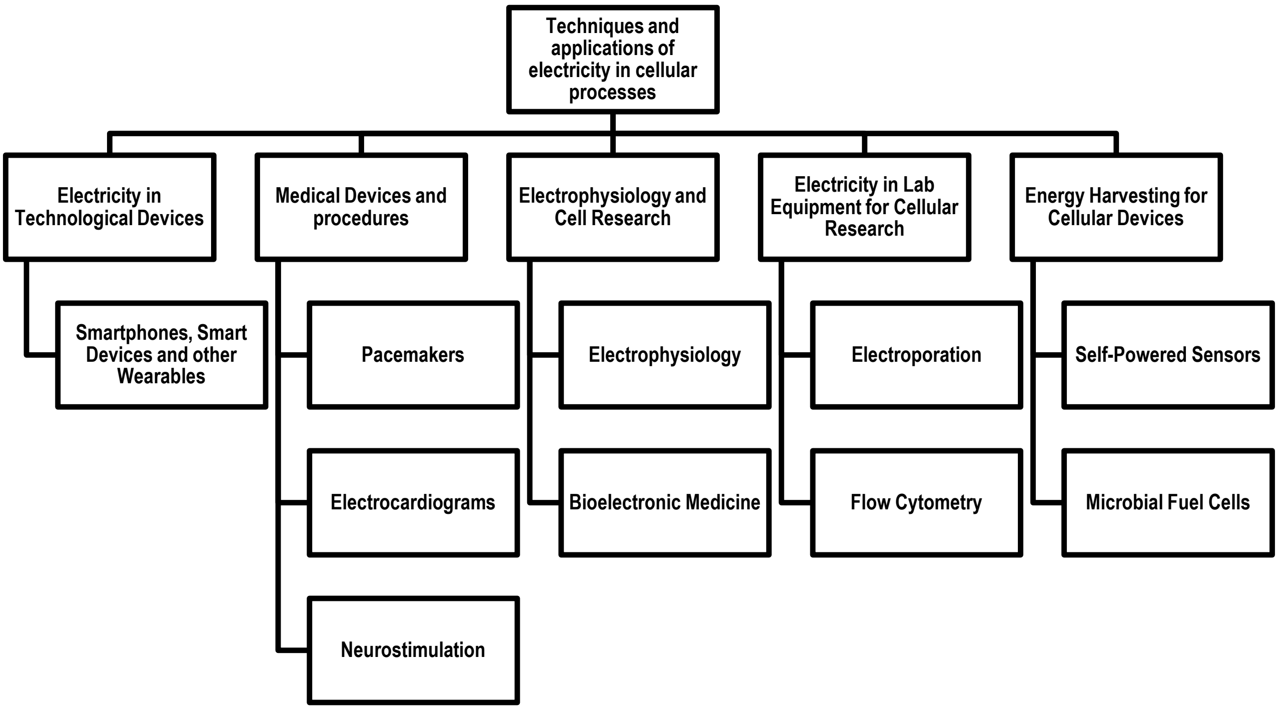

Figure 2: Techniques and Applications of Electricity in Cellular Processes

One of theearly developments in the application of electricity in the biosciences is the utilization of short and intense electric pulses (EP). In almost all molecular and cellular biology laboratories, EP is regularly used to introduce foreign DNA, as well as other exogeneous molecules, into living cells. Application of EP leads to electroporation of the recipient cells whereby the cells membrane is transiently made accessible to permissible molecules and agents (Mir et al. 1995; Norfleet et al. 2024). These agents could be DNA, proteins, chemical moieties, and other biological agents. The cells membranes are usually able to revert back to its barrier function upon withdrawal of the transient electrical field.

Besides these *in vitro* applications, some *in vivo* applications have also emerged in the use of EP where the electrical field is applied to localized body areas to allow for delivery of biomedical tools for local and systemic effects. Therefore, biomedical application of EP represents a new interdisciplinary field at the frontier of physics, chemistry and biology. Two procedures have already entered clinical trials: the electroinsertion of CD4 molecules on red blood cell membranes, which uses EP delivered ex vivo, and antitumor electrochemotherapy, which uses EP delivered in vivo. An overview of current research on the latter is given in more detail. There has been report of the delivery of electrical pulses for the treatment of tumour cells (Geboers et al. 2020).

Specifically, the applications of electricity in cellular and biological space, including the technological deployment of the underlying principles to solve real problems will be further discussed under applicable headings.

Electricity in Technological Devices

Smartphones, Smart Devices and other Wearables: Electricity powers the devices that monitor biological cells, such as smartphones, fitness trackers, and wearables that can track heart rate, body temperature, and other cellular parameters. Clearly, there has to be a communication between the powering electricity and the cellular factors to be propelled, monitored or measured.These smart wearable devices are modern emerging tools and gadgets that in many ways simulated varied biological functions for accurate monitoring of parameters (Kassavou et al. 2022; Wall et al. 2023).See also Figure 2.

Medical Devices and procedures:

Pacemakers: Pacemakers are medical devices that use electrical impulses to regulate the heart's rhythm. The pacemaker sends small electrical pulses to the heart to help it beat at a normal rate. This is therefore used to correct cellular electrically-induced heart (cardiac) abnormalities that causes the heart to beat either very slowly (bradycardia) and too fast (tachycardia). There are variety of customized pacemakers for use in deserving medical patients for their health wellbeing (Badger et al. 2017; Beinart& Nazarian, 2013; Huang et al. 2020).

Electrocardiograms: Electrocardiogram (ECGs or EKGs) is a test to record the heart rhythm by relying on electrical principles. In the course of developing an electrocardiogram, electrodes, usually sticky patches may be placed on the chest, and sometimes on the arms or legs,are used to detect the electrical activity of the heart and thereby help in diagnosing heart conditions.Usually, a computer placed in proper connection is employed as a read-out to display the readings and recordings (Sattar & Chhabra, 2023; Friedman, 2024). These are all based on the relevant electrical principles.
Neurostimulation: In neurostimulation, electrical impulses are used in the treatment of certain neurological disorders, such as deep brain stimulation for Parkinson's disease. In this situation, electricity is applied to the neurons (brain cells) to fix the underlying problems or diseased condition. In that case, the disease itself is related to defective operations associated with electrical impulses (Edwards et al. 2017; Katic Secerovic et al. 2024).

Electrophysiology and Cell Research
Electrophysiology: Electrophysiology is an important aspect of the application of electricity in biosciences. It is the study of the electrical properties of biological cells and tissues. Researchers use electrophysiology techniques to understand how cells generate electrical signals and how they respond to stimuli (Rubaiy, 2017). Several techniques may be employed for the purpose of doing research in this field (Figure 2). One of such techniques is the application of patch-clamp which allow scientists to measure and manipulate the electrical properties of individual cells. The procedure works since the cells are able to respond electrically (Asadi et al. 2025).
Bioelectronic Medicine: In bioelectronic medicine, practitioners employ diverse electrical processes and components to heal diseases. Therefore, researchers are exploring the use of electricity to treat various diseases by interfacing directly with the nervous system or other cellular systems. For instance, electrical stimulation of nerves has been used to treat chronic pain and inflammation.The techniques associated with the bioelectric operations hold immense promises in medicine (González-González et al. 2024;Koutsouras et al. 2024).
Electricity in Lab Equipment for Cellular Research:
Electroporation: Electricity can be deployed to help traffic substances though living cells. One of those techniques developed through that principle is electroporation. This technique uses an electric field to temporarily open pores in cell membranes, allowing researchers to introduce substances (such as drugs or DNA) into the cell. It is often used in genetic engineering and drug delivery (Kotnik et al. 2019; Balantič et al. 2021; Spugnini et al. 2024).In outlook, electroporation can be further developed to possibly transport diverse elements into the cell and tissues.
Flow Cytometry: Flow cytometry is a technique that has been applied in a multidisciplinary scope of related scientific areas. This technique uses electricity and lasers to analyze the properties of cells and other relevant particles in a fluid stream. It can measure cell size, complexity, and protein expression, and is frequently used in research and diagnostics. Flow cytometry is operated on a flow cytometer which is practically and electro-mechanized chamber designed to carry out the operations of cell and particles analyses in very convenient background that may include a set of diverse parameters (Schmnit et al. 2021; El-Hajjar et al. 2023; Kala & Zubair, 2024).
Energy Harvesting for Cellular Devices:
Self-Powered Sensors: Self-powered sensors is another emerging area of technological development in gadgets for human use involving electrical energy. In this domain, advances in energy harvesting technologies involving power sensors are allowing cells and wearable devices to be powered using small electrical charges generated by human body movements, heat, or even the energy produced by metabolic processes. This is all geared towards making allowable for the human body or biological host to self-power, operate and modulate the technological gadgets coupled to it (Lee & Yoo, 2021; Ma et al. 2025).
Microbial Fuel Cells: Microbial cells for fuel generation are a concept in an emerging field that holds tremendous opportunity especially in the light of new knowledge of advances made in cellular and microbial researches. Some research explores using microbial fuel cells to generate electricity from bacteria, which could potentially be used to power small devices in biological or cellular applications (Srivastava et al. 2022; Jalili et al. 2024). Electricity so generated can be deployed to any applicable area where it can be conveniently extended.

II. Conclusion

Cellular electricity is a critical sector of the energy landscape that has not been fully tapped. It holds immense promises, however, a great deal of understanding and sophistication must be ingeniously built into it to properlyunderstand the terrain, and to develop cutting-edge technology for maximal deployment and utilization of input and products of cellular electricity, all the way through its developmental pipelines.

Authors Declaration
Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1]. Asadi, A., Wiesman, A.I., Wiest, C. *et al.* (2025). Electrophysiological approaches to informing therapeutic interventions with deep brain stimulation. *npj Parkinsons Dis.* 11, 20. https://doi.org/10.1038/s41531-024-00847-3.

[2]. Badger, J., Taylor, P., & Swain, I. (2017). The safety of electrical stimulation in patients with pacemakers and implantable cardioverter defibrillators: A systematic review. *Journal of rehabilitation and assistive technologies engineering*, *4*, 2055668317745498. https://doi.org/10.1177/2055668317745498.

[3]. Balantič, K., Miklavčič, D., Križaj, I., & Kramar, P. (2021). The good and the bad of cell membrane electroporation. *Acta chimicaSlovenica*, *68*(4), 753–764. https://doi.org/10.17344/acsi.2021.7198.

[4]. Beinart, R., & Nazarian, S. (2013). Effects of external electrical and magnetic fields on pacemakers and defibrillators: from engineering principles to clinical practice. *Circulation*, *128*(25), 2799–2809. https://doi.org/10.1161/CIRCULATIONAHA.113.005697.

[5]. Bioelectricity. https://www.britannica.com/science/electricity/Kirchhoffs-laws-of-electric-circuits#ref71583 [Accessed 9.3.2025].

[6]. Electricity. https://www.britannica.com/science/electricity. [Accessed 9.3.2025].

[7]. Carvalho, J. (2022). A computational model of organism development and carcinogenesis resulting from cells' bioelectric properties and communication. *Scientific reports*, *12*(1), 9206. https://doi.org/10.1038/s41598-022-13281-3.

[8]. Carvalho, J. (2023). A computational model of cell membrane bioelectric polarization and depolarization, connected with cell proliferation, in different tissue geometries. *Journal of theoretical biology*, *557*, 111338. https://doi.org/10.1016/j.jtbi.2022.111338.

[9]. Cervera, J., Pai, V. P., Levin, M., & Mafe, S. (2019). From non-excitable single-cell to multicellular bioelectrical states supported by ion channels and gap junction proteins: Electrical potentials as distributed controllers. *Progress in biophysics and molecular biology*, *149*, 39–53. https://doi.org/10.1016/j.pbiomolbio.2019.06.004.

[10]. Cervera, J., Meseguer, S., Levin, M., & Mafe, S. (2020). Bioelectrical model of head-tail patterning based on cell ion channels and intercellular gap junctions. *Bioelectrochemistry (Amsterdam, Netherlands)*, *132*, 107410. https://doi.org/10.1016/j.bioelechem.2019.107410.

[11]. Cervera, J., Levin, M., & Mafe, S. (2023). Correcting instructive electric potential patterns in multicellular systems: External actions and endogenous processes. *Biochimica et biophysica acta. General subjects*, *1867*(10), 130440. https://doi.org/10.1016/j.bbagen.2023.130440.

[12]. Cervera, J., Levin, M., & Mafe, S. (2024). Multicellular adaptation to electrophysiological perturbations analyzed by deterministic and stochastic bioelectrical models. *Scientific reports*, *14*(1), 27608. https://doi.org/10.1038/s41598-024-79087-7.

[13]. Edwards, C. A., Kouzani, A., Lee, K. H., & Ross, E. K. (2017). Neurostimulation Devices for the Treatment of Neurologic Disorders. *Mayo Clinic proceedings*, *92*(9), 1427–1444. https://doi.org/10.1016/j.mayocp.2017.05.005.

[14]. El-Hajjar, L., Ali Ahmad, F., &Nasr, R. (2023). A Guide to Flow Cytometry: Components, Basic Principles,Experimental Design, and Cancer Research Applications. Curr Protoc. 3(3):e721.

[15]. Friedman, P.A. (2024). The Electrocardiogram at 100 Years: History and Future. *Circulation*,149 (6), 411-413. doi:10.1161/CIRCULATIONAHA.123.065489.https://www.ahajournals.org/doi/abs/10.1161/CIRCULATIONAHA.123.065489.

[16]. Funk, R.H.W., Scholkmann, F. (2023). The significance of bioelectricity on all levels of organization of an organism. Part 1: From the subcellular level to cells. Progress in Biophysics and Molecular Biology, 177: 185-201. https://doi.org/10.1016/j.pbiomolbio.2022.12.002.

[17]. Geboers, B., Scheffer, H. J., Graybill, P. M., Ruarus, A. H., Nieuwenhuizen, S., Puijk, R. S., van den Tol, P. M., Davalos, R. V., Rubinsky, B., de Gruijl, T. D., Miklavčič, D., &Meijerink, M. R. (2020). High-Voltage Electrical Pulses in Oncology: Irreversible Electroporation, Electrochemotherapy, Gene Electrotransfer, Electrofusion, and Electroimmunotherapy. *Radiology*, *295*(2), 254–272. https://doi.org/10.1148/radiol.2020192190.

[18]. Ghildiyal, V., Altaner, C.M., Heffernan, B. *et al.* Electrical Phenomena in Trees and Wood: A Review. *Curr. For. Rep.* **11**, 7 (2025). https://doi.org/10.1007/s40725-024-00238-0.

[19]. González-González, M. A., Conde, S. V., Latorre, R., Thébault, S. C., Pratelli, M., Spitzer, N. C., Verkhratsky, A., Tremblay, M. È., Akcora, C. G., Hernández-Reynoso, A. G., Ecker, M., Coates, J., Vincent, K. L., & Ma, B. (2024). Bioelectronic Medicine: a multidisciplinary roadmap from biophysics to precision therapies. *Frontiers in integrative neuroscience*, *18*, 1321872. https://doi.org/10.3389/fnint.2024.1321872.

[20]. Huang, J., Lin, K., Lu, W., Ding, R., Wu, B., Cai, M., Nazarian, S., Zhao, W., Li, J., & Huang, D. (2020). An *in vitro* Evaluation of the Effect of Transient Electromagnetic Fields on Pacemakers and Clinical Mitigation Measures. *Frontiers in cardiovascular medicine*, *7*, 607604. https://doi.org/10.3389/fcvm.2020.607604.

[21]. Jalili, P., Ala, A., Nazari, P., Jalili, B., & Ganji, D. D. (2024). A comprehensive review of microbial fuel cells considering materials, methods, structures, and microorganisms. *Heliyon*, *10*(3), e25439. https://doi.org/10.1016/j.heliyon.2024.e25439.

[22]. Kala, P.S., &Zubair, M. Flow Cytometry Blood Cell Identification. [Updated 2024 Sep 11]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK608011/.

[23]. Kassavou, A., Wang, M., Mirzaei, V., Shpendi, S. & Hasan, R. (2022). The association between smartphone app–based self-monitoring of hypertension-related behaviors and reductions in high blood pressure: systematic review and meta-analysis.JMIR mHealth uHealth 10, e34767.

[24]. Katic Secerovic, N., Balaguer, J. M., Gorskii, O., Pavlova, N., Liang, L., Ho, J., Grigsby, E., Gerszten, P. C., Karal-Ogly, D., Bulgin, D., Orlov, S., Pirondini, E., Musienko, P., Raspopovic, S., &Capogrosso, M. (2024). Neural population dynamics reveals disruption of spinal circuits' responses to proprioceptive input during electrical stimulation of sensory afferents. *Cell reports*, *43*(2), 113695. https://doi.org/10.1016/j.celrep.2024.113695.

[25]. Khan, Kamrul & Hassan, Lovelu&Obaydullah, A K M & Islam, Shahinul& Al Mamun, Mohammad & Akter, Tanjila& Alam, Md & Ibrahim, M. & Rahman, M. & Shajahan, Md. (2020). Bioelectricity: a new approach to provide the electrical power from vegetative and fruits at off-grid region. Microsystem Technologies. 26. 10.1007/s00542-018-3808-3.

[26]. Kotnik, T., Rems, L., Tarek, M., & Miklavčič, D. (2019). Membrane Electroporation and Electropermeabilization: Mechanisms and Models. *Annual review of biophysics*, *48*, 63–91. https://doi.org/10.1146/annurev-biophys-052118-115451.

[27]. Koutsouras, D.A., Malliaras, G.G. &Langereis, G. (2024). The rise of bioelectronic medicine. *Bioelectron Med* 10, 19. https://doi.org/10.1186/s42234-024-00151-8.

[28]. Krüger, J., &Bohrmann, J. (2015). Bioelectric patterning during oogenesis: stage-specific distribution of membrane potentials, intracellular pH and ion-transport mechanisms in Drosophila ovarian follicles. *BMC developmental biology*, *15*, 1. https://doi.org/10.1186/s12861-015-0051-3.

[29]. Lautemann, J., &Bohrmann, J. (2016). Relating proton pumps with gap junctions: colocalization of ductin, the channel-forming subunit c of V-ATPase, with subunit a and with innexins 2 and 3 during Drosophila oogenesis. *BMC developmental biology*, *16*(1), 24. https://doi.org/10.1186/s12861-016-0124-y.

[30]. Lee, E., & Yoo, H. (2021). Self-Powered Sensors: New Opportunities and Challenges from Two-Dimensional Nanomaterials. *Molecules (Basel, Switzerland)*, *26*(16), 5056. https://doi.org/10.3390/molecules26165056.

[31]. Ma, Q., Zhang, Z., Li, L. *et al.* (2025). An editable yarn-based flexible supercapacitor and integrated self-powered sensor. *Sci. China Mater.* https://doi.org/10.1007/s40843-024-3261-2.

[32]. Mir, L.M., Orlowski, S., Belehradek, Jr., Teissie, J., Rols, M.P., Sersa, G., Miklavcic, D., Gilbert, R., &Heller, R. (1995). Biomedical applications of electric pulses with special emphasis on antitumor electrochemotherapy. Bioelectrochemistry and Bioenergetics. 38 (1): 203-207.

[33]. Norfleet, D. A., Melendez, A. J., Alting, C., Kannan, S., Nikitina, A. A., Caldeira Botelho, R., Yang, B., & Kemp, M. L. (2024). Identification of Distinct, Quantitative Pattern Classes from Emergent Tissue-Scale hiPSC Bioelectric Properties. *Cells*, *13*(13), 1136. https://doi.org/10.3390/cells13131136.

[34]. Rubaiy, H. N. (2017). A Short Guide to Electrophysiology and Ion Channels. *Journal of pharmacy & pharmaceutical sciences : a publication of the Canadian Society for Pharmaceutical Sciences, Societe canadienne des sciences pharmaceutiques*, *20*, 48–67. https://doi.org/10.18433/J32P6R.

[35]. Sattar, Y., & Chhabra, L. (2023). Electrocardiogram. In *StatPearls*. StatPearls Publishing.

[36]. Schmit, T., Klomp, M., & Khan, M. N. (2021). An Overview of Flow Cytometry: Its Principles and Applications in Allergic Disease Research. *Methods in molecular biology (Clifton, N.J.)*, *2223*, 169–182. https://doi.org/10.1007/978-1-0716-1001-5_13.

[37]. Spugnini, E. P., Condello, M., Crispi, S., & Baldi, A. (2024). Electroporation in Translational Medicine: From Veterinary Experience to Human Oncology. *Cancers*, *16*(5), 1067. https://doi.org/10.3390/cancers16051067.

[38]. Srivastava, R. K., Sarangi, P. K., Vivekanand, V., Pareek, N., Shaik, K. B., & Subudhi, S. (2022). Microbial fuel cells for waste nutrients minimization: Recent process technologies and inputs of electrochemical active microbial system. *Microbiological research*, *265*, 127216. https://doi.org/10.1016/j.micres.2022.127216.

[39]. U.S. Energy Information Administration. https://www.eia.gov/energyexplained/electricity/the-science-of-electricity.php. [Accessed 9.3.2025].

[40]. Wall, C., Hetherington, V., &Godfrey, A. (2023). Beyond the clinic: the rise of wearables and smartphones in decentralising healthcare. npj Digital Medicine, 6:219; https://doi.org/ 10.1038/s41746-023-00971-z.