

# Integrating Biological Systems with Electronic Technologies in Bioelectronics Advancements

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**Abstract.** Bioelectronics is a multidisciplinary field that seamlessly integrates the biological systems with electronic techniques, driving the progress in areas such as modern medication, military management and environmental monitoring. This paper explores the fundamental underlying the bioelectronic devices, viewing some recent advancement in biometric sensors that are central to their operation. By examining the recent research on the different applications of the bioelectronic devices, including medical diagnosis, real-time health monitoring and environmental detection, this paper provides some future prospect on this technique to address contemporary issues. In addition, paper discusses some main challenges it faces such as the biocompatibility and the efficiency to process enormous information. The transformative impact that bioelectronics provide enhance people's understanding of the way humans interact with their own bodies and the external environment. This integration of biology and electronics also offers people a new insight on the biological process and revolutionize the way human use to treat disease and the environment detection.

**Keywords:** Bioelectronics, Biometric sensors, Environmental monitoring, Medication.

## 1. Introduction

Bioelectronics, an intersection of biology, electronics, and material engineering, has brought the possibility to treat some disease in an innovative way. With different types of bioelectronics devices including the wearable one and the implantable one, this technology is widely used in different areas. In medicating, instead of taking in traditional drugs that might carry side effects, bioelectronics offer a new solution that would bring fewer side effects. In specific cases, bioelectronics medicine could be used to monitor the body condition such as heartbeat and blood pressure to check the abnormal figures for treatment and analysis. In terms of military, it could be used as a monitor implanted in the uniform for health detection and compass real-time communication and information about enemies [1]. This would be further utilized between soldiers during wars to promote better strategies and reduce the loss. Another application would be found in environmental monitoring. Taking advantage of biosensors, this method could detect the pollutants in the air, soil, and water. Different types of biosensors are used to perform various functions such as pesticides, detecting detrimental pathogens, dealing with toxins, endocrines and other chemicals in different scenarios [2]. The primary challenges of the applications above fields include relentless reaction times, painful experiences gained by patients and the high cost of it [3]. The way of designing these devices to ensure the biocompatibility and its ability to process a large amount of information to filter the unnecessary figure are equally important. The choose of its materials for better combination is also an unsolved issue.

This paper will explore some basic theoretical principles of how bioelectronic devices work by introducing two different types of bioelectronic devices, implantable one and wearable one, the material and the design of these devices and the sensors used in the devices. Meanwhile, the application of the bioelectronic devices in different areas would be covered, mainly about its application in medication, military and environment. Acting as an alternative to the traditional pills, these portable devices could be used to monitor the health condition of the soldiers in the military as well as an indicator for environment monitoring. Also, some challenges and future expectations will be included as well.

## 2. Theoretical principles

### 2.1. Types of bioelectronics devices

#### 2.1.1 Wearable bioelectronic devices

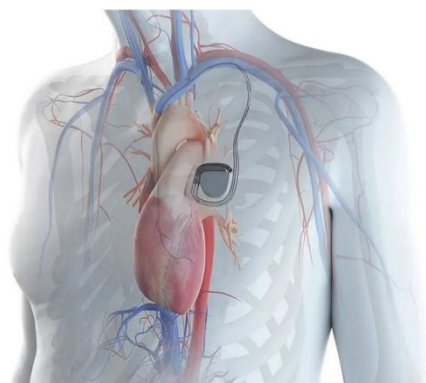
Wearable bioelectronics are sophisticated devices that are worn on the body in order that the integrated electrical components could interact with the biological systems to track, diagnose, and possibly treat medical conditions. The flexibility and the comfort of wearable technology are combined with the accuracy and functionality of bioelectronics. Different types of sensors including electrical, mechanical, optical ones are normally worn on the skin of human body to detect the signals [4]. By trapping and analyzing biological fluids secreted on the surface of the skin, the sensors measure and monitor the activity inside the human body through saliva, sweat, and tears [5]. The data collected by the sensors are then processed by the microprocessors, located inside the whole sensor. First filtering some noise and unnecessary data, the microprocessor then starts to analyze and tries to interpret the data. This is followed by the matching process between the data collected and the database to see that whether the person's heartbeat or body temperature is abnormal or not. After carrying out these algorithms in the processors, if some unpredicted data was detected, it would then transmit the signal to other devices through network so that the person or the doctor could know what is wrong with the person and offer corresponding solutions. An example could be found in a smart watch in Fig.1 where the watch could monitor the heartbeat of the owner.



**Figure 1.** Smart watch monitoring heartbeat

#### 2.1.2 Implantable bioelectronic devices

Operating a similar principle, implantable bioelectronic devices could be connected to some organs or tissues inside the human body to analyze the electrophysiological signals and cure behavioral disorders [5]. This is specialized in the treatment of nerve-related diseases. The basic process, again, contains sensors so that the physiological change about the electrical signals used to depicting electrocardiogram and electro-cephalogram, the concentration of chemicals like hormones, and other indicators like the body temperature and the blood pressure could be detected. Then, all the data is analyzed to ensure that no abnormal figures were omitted. Once they are detected, the actuators would then send signals for some interventions to address the problem by controlling the pacemakers or sending data to the doctors. In some cases, with living cells protected to carry out certain function, the device could stimulate the secretion of some hormones in these cells by electrical signal or nerve impulses. This would be further utilized in the treatment of Type 1 diabetes. By using the implantable devices carrying cells that could produce insulin, the injection could be replaced at least in the experiment on mice. Once the sensor detects the enormous high or low blood glucose concentration, the device would be triggered to release the cells that are capable of secreting insulin to help control the glucose level [6]. An example could be seen in Fig.2. An integrated sensors along with the processors are implanted into the heart so that it could monitor the heartbeat continuously and accurately.



**Figure 2.** Implantable monitor in heart

## 2.2. Material and design

A number of factors are included while choosing the material of a bioelectronic device. The primary factor that should be taken into consideration is about the biocompatibility, especially for implantable bioelectronic devices [7]. Since these devices would be put inside the human body, it is essential that the components and material of the device is not toxic otherwise it would pose a threat to users. Meanwhile, the choice of the material should ensure that the human body would accept the devices as part of them. In other words, no rejection reaction would occur during the whole process, which is one of the most difficult parts of work. This usually includes some testing carrying out in both the in vitro environment and then the in vivo one. Some living cells are usually used in the initial step of in vitro environment to identify whether some reaction would occur at the cellular level in order that following experiments could be performed. Then, the devices would be further tested in some animal models to look for immune response and other reactions. After all these tests, some detailed modification such as coating or their texture. Furthermore, the flexibility of the material and the durability are key factors as well. This is valued as these devices need to interact with some moving parts of the body such as muscles. Another factor when choosing material is the chemical stability of the material to make sure that the devices are inert enough to avoid the reaction with the body fluid. Mostly, the organic materials and the inorganic ones would be used together, usually alternatively when constructing these devices. Nanomaterials could also be used as its importance of obtaining the exceptional confluence of great miniaturization, high dependability, cheap cost, and scalable production is emphasized [8].

## 2.3. Biometric sensor

Biometric sensors could measure biological data and then convert it into electrical signals, which is the reason why it can be used in bioelectronics. The basic principle of it is basically how sensors work in those wearable devices. These sensors are usually used for safety purpose. One type of the biometric sensor is the fingerprint sensors. These sensors record each person's fingertip's distinct patterns of ridges and valleys and in different situations such as dirty fingers with some mud or water, the fingerprints could still be recognized so that it could be used in some safety check or authentication [9]. Meanwhile, the facial recognition sensors are used as well. Working quite similarly as the fingerprint sensors, they catch some facial features and those real-time systems and some recognition from various angles or different light conditions are utilized to perform specific functions like security check [10]. Iris and retina scanners, another type of sensor, is used as well. Capturing the figure or pattern of people's eyes, the sensors map people's vessels and match them to the database with high speed and accuracy.

### 3. Applications analysis

#### 3.1. Medication monitor

One major application of bioelectronics is in medication. By sending electrical signals, these devices could target at specific cells during the process of neural interface to avoid the side effect brought by the traditional pills that do not have targeted cells. By activating the inflammatory reflex, Y. A. Levine and their team designed a microregulator system that is implantable and would not cause tissue damage to be tested on a canine vagus nerve which showed no damage and abnormal phenomenon. This offer people a new perception on the choice of electrodes in the implantable bioelectronic devices—the microregulator which could activate the nerve efficiently and cause no damage to the adjacent nerves [11]. This might could be used after more safety-related experiments to be further implanted in a wider variety of species to gain a much more general result. This might ensure a safer and more efficient drug delivery system or solely rely on the stimulation to trigger the tissues. Meanwhile, G. Rodrigues et al and the teammates took advantage of a mm-sized wireless system to monitor the encapsulation of active implants. Successfully addressing the difficulties of powering and communicating with an implant the size of a millimeter, the suggested system successfully converted the power and modulated the backscattered signals [12]. This ability might be further utilized to enhance the durability of the devices while reducing its size. The data produced could be used for in vivo studies to offer some ideas for the new design of such devices just as the microregulator system could be used as well. As for the research about cancer, Robinson, A. J. et al and the team focus on the use of tumor treating fields and try to find the way to disrupt cancer cell division. The use of direct current electric field helps with the delivery to further develop the understanding of the mechanisms of the tumor [13]. The bioelectronic devices have the possibility to be better used to target the cancer cells and some neural pathways to deal with those chronic issues and improve the treatment of it.

#### 3.2. Military monitor

Military is also a field that bioelectronics would be frequently applied as both wearable and implantable devices could be used in military to monitor the performance of each soldier and create a database for them. Bio- batteries is one of the applications. In the sci news, this new kind of battery could indeed offer people an eco-friendlier way to store energy and generate power in order that soldiers who rely on electronic devices could have better performance on the battlefield [14]. Taking advantage of 3D printing in bioelectronics, Kong, Yong Lin tried to create ingestible bioelectronic device so that they would reside in the stomach and monitor the health conditions, which was proved to be a success. With high durability, functionality and biocompatibility, the devices were capable of operating within the stomach environment without abnormal neural interface [1]. Such achievement could possibly be used in soldiers to enhance the health monitor by integrating additional sensors to detect the biomarkers like some pathogens. This provides soldiers with a more comprehensive health assessment to ensure the health condition of each people in the army. Meanwhile, if this technique is mature enough, personalizing specific device and medicine might be also applicable. With the real-time data collected from the monitor, experts could analyze that and offer them best-fitted therapy or even use the devices themselves to deliver the target drug. Furthermore, based on the 3D printing materials mentioned in Kong, Yong Lin's essay, it could be further developed and experimented to find better materials with improved biocompatibility and functionality. Using this material to integrate other wearable devices might be an efficient usage as well. Another consideration could be the practicability of putting these devices in mass production to allow all soldiers having access to these devices. In sum, bioelectronics have the potential of being a key component of the future military technology with further development and research.

### 3.3. Environmental monitor

Detecting pollutants in water, air and soil, bioelectronic devices could also be used to monitor the environment. Gavrilas, S. and their team summarize the different types of biosensors used in the detection of the environmental conditions, including enzyme-based biosensors, whole cell biosensors, antibody-based biosensors, aptamer-based biosensors and finally the biomimetic sensors, a type of sensor that mimic biological recognition elements to detect pollutants. The team emphasizes the high sensitivity of those types of biosensors as they could detect a wide variety of pollutants such as pesticide and heavy metals [15]. These biosensors could possibly be further used with different digital technology to improve the process of data collecting and analyzing. Based on its current sensitivity, it still has space for improvement to ensure reliable performance in different scenarios with distinct environmental conditions. By using different materials, these sensors have the chance to provide a greener application of bioelectronics as they would be placed in the nature. Having similar research, Justino, C.I.L. and their team mainly focus on different types of pollutants in the environment such as pesticides, toxic elements [2]. The further development might include enhancing the capabilities of these biosensors to detect various kinds of pollutants mentioned in the paper simultaneously to have a better assessment of environmental indicators such as water quality and air quality. Meanwhile, since these sensors are used outdoor, the durability while operating in wild field. Ensuring that these sensors are robust enough is essential for the use of these sensors to avoid some damage caused to them from wild creatures and might even lead to data loss. By fully utilize bioelectronics devices, any contamination could be easily detected in the water and air, ensuring people's health. This detection on environment could also be treated as a vital indicator of soil quality during farming. This agricultural usage facilitates the improvement on the adjustment made to the soil for higher productivity to grow crops of higher quality.

## 4. Challenges and expectation

### 4.1. Challenges

Several challenges are faced currently for the development of bioelectronics. As mentioned above, the application of bioelectronics in medication takes advantage of the neural interface in order that some target hormones or chemicals could be released to treat certain disease. Since these devices needed to be implanted into human body to get involved in these interactions, people should place a great emphasis on the biocompatibility to ensure that immune responses could be avoided, which means that the choice of material is of vital importance. The chosen material should be non-toxic so that the cells and the organs would not attack the devices, and the devices would not hurt the body. Meanwhile, the lifespan of the devices is also a problem. They need to be stable enough to maintain their functions in the body's environment. Their durability is important because some chemicals in the body fluid is acidic or basic, which might erode some parts of the devices if the material or the protection is not appropriate. Furthermore, how can people integrate the chips into a complete system to make sure that the devices would be small and tiny enough to be implanted into human body is another problem. This could not be easily solved as a compromise between the functionality and its size is difficult to find. The technical skills required still needs further exploration and research. Another challenge is the internal circuits of this devices. The mutual conversion between the biological data, such as the heartbeat and pulse rate, and the electronic signals could be extremely complicated. The accurate detection of abnormal data and the sensitivity to some weak signals could play a vital role in the diagnosis. The process and the interpretation of the data collected is also a key factor. Using well-developed algorithms and techniques is pivotal so that the analysis could be real-time. In addition, a reliable source of power and energy is still a problem. Since the devices are implanted inside human body, the charging problem should be emphasized. The method of wireless charging in this case, through people's skin, is essential to ensure the consistent power supply for operation.

## 4.2. Expectation

In the future, bioelectronics could further improve the materials of the devices. There are already some examples of integrating the nanomaterials into bioelectronic devices to improve their functionality and performance [8]. Some further experiment might be carried out to find out better material or just utilize the current material to improve the sensitivity and other aspects of the devices. Also, the improvement of the sensors used in the devices could be forecasted as the high level of effective neural interfaces is significant to trace the disorders and errors occurs in the neurons. Meanwhile, the future development might include the integration of the devices with a generator so that the devices could generate power inside human body without the need for charging. Specifically, it might use the chemical fluids inside the organs or utilize the thermal energy from people to generate electricity for the operation. Admittedly, this requires a very high level of the techniques to make the generator small enough for the integration and could produce power efficiently and continuously. As for the data interpretation, the artificial intelligence might be integrated into the system to process the large amount of data and offer some possible solutions. Based on the existing data, artificial intelligence might further use it for the prediction of a person's health condition, which could offer some preventive methods and suggestions. Meanwhile, these prediction and analysis could be used to personalize the amount of the pills to offer the best-fitted treatment.

## 5. Conclusion

In conclusion, this review introduces some basic types of devices in bioelectronics, mainly focusing on their application and the future development. Offering an innovative solution on treating diseases, bioelectronics use a way of stimulating the nerve system to release the desired chemicals with minimal side effects due to the precise signals sent to specific organs. Despite the limitation on the choose of materials and the neural interface, the bioelectronic devices could still be further utilized by finding better way of integration to improve the accuracy of the devices for the monitor of the body conditions. This integration could offer a personalized way to provide specific treatment along with the real-time measurement. Taking advantage of all these techniques, doctors could provide a more effective diagnosis and reduce the cost of different checks and medicine in long term.

Other challenges include the biocompatibility and the durability of devices. A high level of cooperation is required between multiple subjects including electrical and electronics engineering, biology and material engineering. Future research will concentrate on the improvement of the properties of the materials, the integration of small sensors, the stability of the whole devices and the effectiveness of the whole treating process. As the research gets further and this technique becomes more mature, this device has the potential to efficiently combine the biological systems and the electronic technologies, offering better indicator to detect disease, monitor the environment and for military use.

## References

- [1] Kong Y L. Transforming military medicine with 3D printed bioelectronics. *HDIAC journal*, 2019, 6 (2).
- [2] Justino C I L, Duarte A C, Rocha-Santos T A P. Recent progress in biosensors for environmental monitoring: A review. *Sensors*, 2017, 17 (12): 2918.
- [3] Perumal V, Hashim U. Advances in biosensors: Principle, architecture and applications. *Journal of applied biomedicine*, 2014, 12 (1): 1-15.
- [4] Heikenfeld J, Jajack A, Rogers J, et al. Wearable sensors: modalities, challenges, and prospects. *Lab on a Chip*, 2018, 18 (2): 217-248.
- [5] Xu K, Ko S H, Chen J. Advances in wearable and implantable bioelectronics for precision medicine. *Bio-Design and Manufacturing*, 2024: 1-5.
- [6] Anderson D, Siddharth K. An Implantable Device Could Enable Injection-Free Control of Diabetes. *MIT News*, 2023. <https://news.mit.edu/2023/implantable-device-control-diabetes-0123>.

- [7] Nagarkar K, Hou X, Stoffel N, et al. Micro-hermetic packaging technology for active implantable neural interfaces. 2017 IEEE 67th Electronic Components and Technology Conference (ECTC). IEEE, 2017: 218-223.
- [8] Raj P M, Spurnevy R G, Dwarakanath S, et al. Nanostructures for Enabling Implantable Bioelectronic Systems. 2018 IEEE 13th Nanotechnology Materials and Devices Conference (NMDC). IEEE, 2018: 1-5.
- [9] Ross A, Jain A. Biometric sensor interoperability: A case study in fingerprints. International Workshop on Biometric Authentication. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004: 134-145.
- [10] Chen S, Pande A, Mohapatra P. Sensor-assisted facial recognition: an enhanced biometric authentication system for smartphones. Proceedings of the 12th annual international conference on Mobile systems, applications, and services. 2014: 109-122.
- [11] Levine Y A, Simon J, Faltys M. Neurophysiologic and chronic safety testing of a miniaturized active implanted device with Integrated Electrodes for Bioelectronic Medicine Applications. 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2018: 3689-3692.
- [12] Rodrigues G, Neca M, Silva J, et al. Towards a wireless system that can monitor the encapsulation of mm-sized active implants in vivo for bioelectronic medicine. 2021 10th International IEEE/EMBS Conference on Neural Engineering (NER). IEEE, 2021: 981-984.
- [13] Robinson A J, Jain A, Sherman H G, et al. Toward hijacking bioelectricity in cancer to develop new bioelectronic medicine. *Advanced Therapeutics*, 2021, 4 (3): 2000248.
- [14] Cozier M. Bio-batteries Could Be Powering Military Electronics. *SCI News*, 2022. [www.soci.org/news/2022/3/bio-batteries-could-be-powering-military-electronics](http://www.soci.org/news/2022/3/bio-batteries-could-be-powering-military-electronics).
- [15] Gavrilaş S, Ursachi C Ş, Perța-Crișan S, et al. Recent trends in biosensors for environmental quality monitoring. *Sensors*, 2022, 22 (4): 1513.