Dean&Francis
ISSN 2959-6157

Review of power supply for wearable medical devices

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Abstract:

Various medical equipment has been invented and used, and the power sources used to power them have improved and progressed from the traditional metal batteries to the current bio-batteries. More sophisticated equipment requires higher demands on battery structure and performance. New technologies have led to a broader range of energy sources for batteries. This paper will describe and analyze the structure of energy power sources and their characteristics from the perspective of power sources, divided into those that derive energy from external sources and those that derive energy from the body's biochemical reactions and movements. As technology advances, the battery's energy source will become more versatile. Initially, rigid metal batteries were unsuitable for flexible implantable devices, but research has improved the structure of metal batteries and better-sealed packaging to avoid harming the human body. It has also developed remote power supply and human chemical energy batteries. The characteristics of these batteries are designed to serve the patient better and alleviate subsequent pain, which is also the direction of development.

Keywords: Energy supply, medical devices, wearable device.

1. Introduction

Advances in biomedicine and materials science have led to the invention and use of wearable or implantable medical devices, which monitor the health of the human body and provide treatment to specific patients. The power supplies invented for these devices are critical to their proper installation and long-term use.

Energy harvesting sources for medical devices vary, ranging from power supply through external metal batteries (lithium batteries, etc.) to research into harvesting and converting the body's internal energy to generate energy, including bioelectricity, heat, mechanical energy, and biochemical energy. Externally replaced batteries still power mainstream medical products. Medical devices have different battery requirements depending on their use, but all power sources should fulfill the essential characteristics.

The power supply must be installed and used in a way that is not detrimental to human health, which means it needs to be biocompatible. It needs to ensure long-term reliability, reduce the number of follow-up appointments and the frequency of patient surgeries, and avoid secondary damage. In addition, to ensure that the patient's daily life is not affected, the device has strict requirements for the power supply size, which needs to be small and able to meet the power supply requirements. Finally, the power supply should be easily recyclable and not pollute the environment at the end of its useful life.

This paper will describe and analyze the structure of energy power sources and their characteristics from the perspective of power sources, divided into those that derive energy from external sources and those that derive energy from the body's biochemical reactions and movements. It will then review representative applications of power supplies in medical devices. Finally, some of the challenges facing power sources for medical devices are discussed, and the possible future energy of new batteries is envisioned.

2. Power Supplies for Harvesting Energy from Outside the Human Body

2.1 Lithium-based batteries

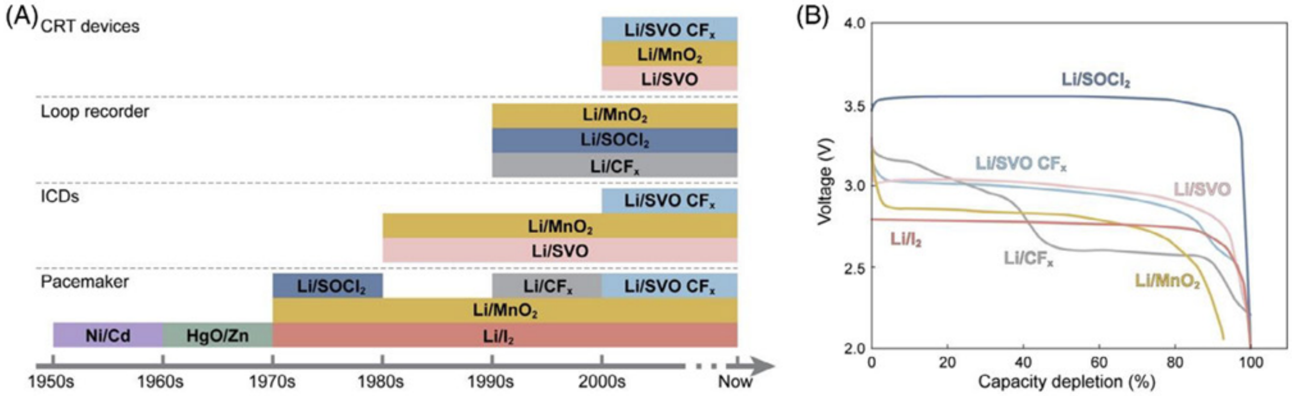

Fig. 1.The development of biomedical electronics (A) recounts the development of metal battery materials for cardiac implantable devices, and (B) shows the capacitance properties of the different materials currently in use [1].

Batteries have significantly influenced the development of biomedical electronics, particularly in medical devices such as pacemakers and defibrillators shown on Fig 1. Lithium-based batteries, a metal battery, have emerged as the preferred choice for powering medical devices.

Lithium battery systems all use lithium metal as the anode. The lithium/iodine battery uses a lithium/iodine-polyvinyl pyridine (PVP) system [2]. It is widely used as a power source for pacemakers, as it can stably provide current in the microamp range. The LiI layer is formed in the battery reaction, acting as an electrolyte and a diaphragm, improving the battery's reliability. The system can also judge the decrease in battery life by the increase in impedance. Lithium-iodine batteries have a high energy density, and their battery size can be tiny. Clinical medicine has also proven the safety of lithium-iodine batteries. Lithium/manganese dioxide (Li/MnO2) batteries have a low self-discharge rate and high stability and can deliver milliwatts of power consistently [2]. Adding chromium oxide and lead oxide can assess lower battery capacity. A dual cell design and series structure can enhance high-speed discharge performance and is suitable for devices with high pulse demands, such as implantable defibrillators. Other cathodes with more applications include fluorocarbons, silver vanadium oxides, or hybrid cathodes of fluorocarbons and silver vanadium oxides. These batteries combine lithium and other metal ions and have high energy density and good capacitance characteristics. The metal's properties also determine the battery's long service life.

Due to the strong reactivity of pure lithium metal, lithium batteries are disposable batteries that cannot be reused after their life is exhausted, and damage to the battery will also cause severe damage to the human body. Lithium-ion batteries can be continuously charged as rechargeable after the device is implanted in the human body, which is suitable for devices with high power output. Lithium-ion batteries use lithium ions as the cathode, which is superior to pure lithium metal in terms of stability. Lithium cobalt oxide, lithium manganese oxide, and manganese cobalt oxide are used for the anode. Lithium-ion batteries have excellent capacitive properties with low self-discharge rates, and they do not require replacement, which reduces subsequent maintenance costs and ensures a long-term pa-

ISSN 2959-6157

tient experience [2]. Leakage of lithium ions and battery destruction can be equally damaging to human health, and safety can be improved by adding protective circuitry.

In addition to lithium-based batteries, other metals have been used as batteries to power medical devices. Silver oxide batteries have properties similar to lithium batteries but relatively low energy density. It has the advantage of continuous and stable operation in thermal environments. Typical applications are powering enteral endoscopic capsules, and it has also been chosen as a battery power source for ingestive and implantable electronic devices. Zinc-air batteries have the highest energy density but lack airflow inside the body, making them suitable for external devices such as hearing aids. Nickel-cadmium batteries are characterized by high discharge rates, thermal stability, and the ability to recharge quickly [2]. However, its disadvantages are apparent: cadmium metal harms the human body and the environment. NiMH batteries have a higher energy density than NiCd batteries and are less harmful to the human body and the environment. But it has a shorter life cycle. Nickel-cadmium batteries also have memory effects and high self-discharge rate defects. Other non-lithium batteries in medical equipment are also used. However, because of their apparent defects or performance, they are not as good as lithium-based batteries; the most widely used battery is still lithium-based.

2.2 Remote wireless power supply

The advantage of a remote wireless power supply system is that it dramatically simplifies the subsequent maintenance of medical equipment so that patients do not have to go through the surgical pain of changing batteries and ensure patients' comfort. Compared with a battery power supply, the energy density is lower, but it can also meet the needs of the equipment. Wireless medical devices can be smaller, easy to carry, and can ensure biosafety. Nowadays, remote wireless power supply is mainly done through induction, radio frequency, ultrasound, photovoltaic, and other ways to complete the remote power supply.

The principle of induction power supply is based on Faraday's law. Wireless energy transmission is achieved by electromagnetic induction between two coils. The components are a transmitting coil and a receiving coil. When an alternating current passes through the transmitting coil, an alternating magnetic field is generated, which connects with the nearby receiving coil and induces an induced current in the receiving coil [3]. To improve energy efficiency, the system needs the coils to be in resonance, i.e., both coils have the same resonant frequency, and the self-inductance of both coils should be high. This can also be achieved by improving the structure to increase the power density and operating range [4]. An inductively powered device avoids the surgical risks associated with changing batteries, reduces the risk of corrosion, has a longer life, etc. Typical applications now are for cochlear implant power supply; millimeter-scale medical devices will have a more comprehensive application in the future.

RF power supply is the wireless transmission of energy through externally emitted RF radiation, the reception of RF signals through the antenna, the rectifier converts the electromagnetic wave into electrical energy, and then the storage of electrical energy by the storage. The distance of the RF power supply is the key to affecting the new energy according to the distance divided into near-field, mid-field, and far-field. Near-field transmission distance is short, and energy transfer efficiency is high [3]. As the distance increases, the efficiency of far-field energy transfer decreases significantly. RF power supply is suitable for low-power devices and small electronic equipment needs. Its system is relatively simple, easy to maintain, and can provide long-term stable energy. The disadvantages of an RF power supply are that it is limited by the environment and frequency band, has limited use scenarios, and still needs to be optimized regarding biocompatibility and output power. Typical applications in medical devices include neurostimulators and pacemakers.

Ultrasonic power conversion converts external ultrasound waves into electrical energy for devices and is also a technology used to power implantable devices wirelessly. The two main methods of conversion are piezoelectric and capacitive. Piezoelectricity utilizes the piezoelectric-semiconductor coupling effect, whereby ultrasound waves propagating through a medium are converted into electrical energy after passing through a piezoelectric converter [5]. On the other hand, the capacitive type converts energy through electrostatic induction and friction electric effect. The main characteristic of ultrasonic power supply is that it will not cause harm to the human body, and there will be no electromagnetic interference. Ultrasound energy can penetrate conductive materials, making it suitable for implantable devices. It has excellent directionality and penetration in human tissues, and the energy does not diminish easily and, therefore, travels long distances and is theoretically very efficient at specific frequencies. It also has excellent energy density and can be designed for small devices. Its drawback is that ultrasound loses energy by reflection in the medium, and prolonged use can cause tissue heating, leading to damage. System design needs to be optimized to mitigate the heating benefits, and studies have been done to maximize the power of energy transmission through multilayer piezoelectric materials or structures. Currently, ultrasonic power supply has limited transmission efficiency and is suitable for low-power devices, which are widely used in implantable medical devices, such as neurostimulators and pacemakers.

Photovoltaic cells can convert light and solar energy directly into electricity through the photovoltaic effect. It mainly comprises p-n diodes, which can use the electron-hole pairs generated by semiconductor materials after absorbing photons to generate electric current [6]. Also, it includes unique light-trapping structures that can maximize the absorption of incident photons. Photovoltaic cells can have high energy transfer efficiency and energy density, wireless charging characteristics, and low maintenance costs. Its drawback is that light conditions limit it. Light penetration of tissue is limited; near-infrared light has a strong tissue penetration ability but also cannot reach a depth of less than 2cm, so the implantation of photovoltaic cells in the location of the requirements of the implantation of the device is only applied to the surface implantation of the device [7]. Currently under-development photovoltaic cells are flexible, easy to carry around, and self-powered, with good biocompatibility and mechanical stability, typical medical devices such as neurostimulators and retinal prostheses, etc., and can also be used to detect vital signs in wearable devices.

3. Power collected from the human body

The human body produces and consumes a lot of energy daily, which can be used to power medical devices. The heat and mechanical energy generated by the body's movements can be converted into electrical energy using devices, and the glucose and lactic acid formed in the body can also be converted into electrical energy through a reaction. The connection and interaction between these different energies are also crucial for the balance and health of the person himself.

3.1 Mechanical energy supply

Mechanical energy powering converts mechanical energy into electrical energy through body movements and organ vibrations, such as daily running, bending joints, and heartbeats. These devices are lightweight and small, making them easy to carry around. In flexible medical devices, energy can be harvested during daily walking and joint activity, allowing the device to determine potential risks to human health through the data collected and allowing for real-time monitoring. The movement of the human body and the activity of the organs is persistent and constant, which makes the source of mechanical energy power supply long-term stability; it can work autonomously for a long time to maintain normal function, eliminating the need for subsequent patient surgery. The two modes of mechanical energy supply are piezoelectricity and friction electricity.

Piezoelectric nanogenerators are based on the properties of piezoelectric materials, which cause an imbalance of charge when the material is subjected to mechanical stress, thus generating electrical energy [6]. It works on the principle of the piezoelectric effect, and the materials used for piezoelectric devices are polyvinylidene fluoride and zinc oxide. When these materials are subjected to mechanical changes such as bending, twisting or stretching due to human activity, the internal charge distribution will change, and the corresponding voltage and current will be output. Piezoelectric generators have a high energy conversion efficiency and flexibility, making them easy to stretch. They are also used in medical, wearable small, and health monitoring devices. The nanostructured design of the device significantly increases the output voltage, current, and power density during low-frequency mechanical motion, allowing the device to harvest energy efficiently.

The friction nanogenerator is a power supply model based on the friction electric effect and electrostatic induction. It works on the principle that when two different materials come into contact and separate, the surfaces undergo a charge transfer, resulting in one surface being positively charged and the other negatively charged [6]. These charges flow through an external circuit, resulting in a continuous current. The device efficiently converts mechanical energy into electrical energy to power the materials as they separate on contact. Frictionally powered devices are lightweight and flexible with few installation constraints. They are used in various applications, such as medical wearables and sensors. Both modes of power supply devices have excellent biocompatibility, stability, and environmental protection, and they do not pollute the human body and the environment. They also have great potential in the future direction of power supply research.

3.2 Thermal power supply

A thermoelectric nanogenerator is a power supply device based on the Seebeck effect, whereby a temperature gradient is converted into an electrical potential. It works on the principle that when a temperature difference exists, charge carriers within P and N-type semiconductor materials flow from the high-temperature end to the low-temperature end, generating a voltage [3]. The unique advantage of this type of power supply is that it can directly utilize the temperature difference that exists within the entire body itself. Thermally powered devices are also lightweight, stable, long-lasting, biocompatible and can

ISSN 2959-6157

eliminate the need for subsequent surgical maintenance treatments. According to theoretical analyses, the most considerable temperature difference in the human body is near the skin surface. This is because there is a significant temperature difference between the body's internal organs and the skin's surface, with the internal organs having a higher temperature and the surface temperature being similar to that of the external environment [8]. The apparent gradient between the two temperatures makes the vicinity of the skin surface an ideal location for the implantation of thermal power devices. Thermal power is also used in areas such as wearable sensors.

3.3 Biofuel power supply

Biofuel cells are an excellent alternative to using human tissue for power supply, using body fluids such as blood and sweat as fuel, and converting chemical energy into electrical energy through microbes, enzymes or non-enzymatic catalysts that can accelerate the oxidation of the fuel and the reduction of oxidants. Biofuel cells can continuously extract chemical energy from the human body and generate hundreds of milliwatts of power, making them suitable for long-term power supply. Standard fuels include glucose and lactic acid. Lactic acid, which has a high concentration in body fluids after strenuous exercise, can simultaneously meet the needs of people's daily exercise and power supply and is currently a significant direction in the research of power supply for medical devices [9].

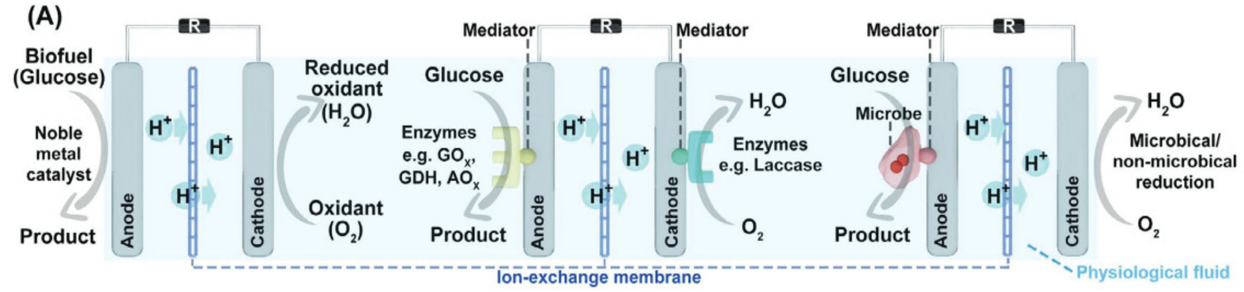

Fig. 2. The process by which biofuels power batteries [10].

Byproducts of the breakdown of glucose reactions can be reintroduced into the body's metabolism shown on Fig 2.

Enzymatic biofuel cells use an enzyme-catalyzed glucose oxidation reaction to generate electrical energy, which is very promising as a feedstock that can be naturally generated within the human body. The introduction of inorganic nanomaterials has significantly enhanced its power density. The power density of a small biofuel cell prepared using AuZn electrodes in glucose solution can reach more than ten times the density in human serum [10]. In addition, increasing the enzyme-loaded area and the electrode active area can allow for improved cell performance. Optimizing the structure of the bioelectrode can further enhance the power supply, e.g. designing enzyme/polymer composites with a porous structure to improve enzyme immobilization. The disadvantages of enzymatic batteries are their weak stability, the high cost of the materials used for catalysis, and the current more limited power output. With experimental development and optimization, it has been shown that enzymatic batteries have great potential for generating electricity in vivo and will be used more often in the future to power medical implants.

A non-enzymatic fuel cell is a type of biofuel cell that utilizes inorganic materials as catalysts, which is accessible from the disadvantages of biological enzymes, such as instability in the operating environment and low electron transfer efficiency when compared with conventional enzyme-catalyzed fuel cells based on them [11,12]. Applying inorganic nanomaterials (e.g., metal nanoparticles, metal oxides, and carbon-based materials) enhances its catalytic performance with good chemical tolerance and high thermal stability. Its composition and structure are tunable and more flexible. Inorganic catalysts are less environmentally demanding and operate over a broader range of temperatures and pH values, thus increasing the lifetime and energy density of the fuel cell. Non-enzymatic batteries similarly utilize fuels such as glucose in the body to generate electricity and reintegrate the metabolites into the biological system. It is an excellent mode of powering future implantable devices.

4. Conclusion

This article reviews power supplies used in wearable medical devices, including in vivo and ex vivo power supplies. They have advantages and disadvantages due to differences in material properties or structural design. Common characteristics of good power sources for human medical devices include but are not limited to, high energy density, small size for portability, flexible construction, good biocompatibility, and harmlessness to the human body and the environment. Medical devices should have the flexibility to select power sources in conjunction with the function of use and the site of implantation and abrasion, so that a combination of the strengths of each power source of the device can be combined in the design. The updated iteration of the medical power supply shows that the future trend of medical power supply is self-powered, wireless power, or to use the body's energy to recharge. Medical equipment should be designed with the patient's needs in mind, and batteries are part of that. It is also essential to consider the patient's condition to control costs, extend lifespan, and avoid subsequent maintenance surgery.

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