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Application of Conductive Polymer in Medical Treatments

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Abstract. With the gradual integration of conductive polymer into the modern world in the form of organic photovoltaic cell, biosensors, and organic light-emitting diode, the importance and the huge influence brought by the conductive polymers became more conspicuous as it's uses became more ubiquitous. It's application in medical treatments is crucial and played an indispensable role in making such advancements in medical treatments in the past decades. Common conductive polymers like polypyrrole, polyaniline, and polythiophene are frequently employed in diverse aspects of medical procedures like drug delivery, nerve probes, and biosensors. The properties that made these organic polymers to be categorized as conductive polymers made them suitable for their application, for example, the property of high conductivity. Despite for some limitations of the conductive polymers-the social issue related to nerve probes, the brittleness of conductive polymers-in medical treatment field, progressing in a proactive way for the use and application of conductive polymer would make the problem to be a piece of cake.

Keywords: Conductive polymer, biosensors, nerve probes

1. Introduction

In the past decades, conductive polymers emerged as a brand-new technology and attracted a lot of chemists to explore its property and possible uses. In the mid of 1970s, many chemists discovered low ohmic resistivity, or high conductivity, in many simplest form of conductive polymer like Polypyrrole. The groundbreaking discovery made an obvious progress to the polymer Chemistry. The discovery seemed unprecedented to the chemists as they realized not all polymers are semiconductors. Subsequently, an array of new advanced technologies was fostered by this discovery. In the year of 1986, by using such good conductivity of conductive polymers, a team led by the Dr. Ching W.Tang at Eastman Kodak Research Laboratories invented the first organic photovoltaic solar cell. Organic photovoltaic cell made the solar panels accessible in curved surfaces as it is really flexible, not like the hard brittle property of the crystalline silicon solar cells. Notably, in the following year 1987, Dr. Ching W.Tang made the first organic electroluminescent diode, the first organic light-emitting diode. Despite these two inventions brought huge impacts even to the modern time, the most impressive and progressive one is the application of conductive polymer in the field of medical treatment. In 1988, a team led by Anthony P.F. Turner and Pavel J. Rezanka invented the first microbiosensor which is conductive polymer based. Due to the high bio compatibility and conductivity of conductive polymers, they are really suitable to be used as

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biosensors. In the early 19th century, doctors found it really hard to detect the detailed health condition of a patient or analyze the electronic signals from the patients' nerves. Using the metal rods to detect the nerve signals would be really risky due to the possibility of metal ion leaking of the metal electrodes, often called low bio compatibility. Also, the size of the metal rods would be unsuitable for detecting the complex nerve system in the brain. However, with the help of the conductive polymer, its high bio compatibility, flexibility, high conductivity, and softness made it a indispensable component for all the modern biosensors.

2. Common conductive polymers

As the well-known fact that conducting polymers in general are not conductive without doping, and doping of π-conjugated polymers results in a highly conducting state of the polymer according to a team of researchers [1]. The applications of doped conductive polymers in the field of medical treatment are wide, from drug delivery, biosensors, bio-actuators, tissue engineering, and neural probes. Three types of polymers are the one who are most frequently used and have the largest influence on the medical treatment. The first type of polymer is polypyrrole(Ppy), one of the most widely used type of conductive polymer. It is the essential components for many medical treatments procedure. For definition, polypyrrole is the polymer made from multiple single units pyrrole that has the chemical formula C_4H_5N. Polypyrroles are often made through the process of chemical polymerization or electrochemical polymerization. It is categorized as a conductive polymer due to its high conductivity because of its free electrons in the alternating single and double bond between carbon atoms. Also, it is definitely considered as bio compatible and is pretty easy to synthesis. Thus, by doping the polypyrrole, chemists could use it to detect some of the biological molecules in people's body. For a real life example, polypyrrole is often used in biosensors like the glucose detectors.

Secondly, polyaniline(PANI) is another typical conductive polymer used in biosensors, bio-actuators, and tissue engineering. Similar to the polypyrrole, it is made from numerous monomer units through the process of polymerization. It's monomer units is aniline, with chemical formula $C_6H_5NH_2$. As a conductive polymer, it also has high bio compatibility and high conductivity. However, unlike other conductive polymers, it has three fundamental oxidation states and the conductivity is depends on the extent on how much it is oxidized. The first state is called Leucoemeraldine when the polymer is fully reduced. It has a color of white and has poor electrical conductivity. In the next state Emeraldine, when the polymer is partially oxidized, the color is blue and it is electrical insulator, except the outlier that it can be highly electric conductive when doped with acids. The final state is Pernigraniline, with a color of violet or purple. This state is complete electrical insulator. Thus, what it means is that by controlling the degree for how much it is oxidized, chemists could control its conductivity accurately, therefore suitable for medical treatments applications.

The final example of common conductive polymer is polythiophene(PTh), linking monomer units thiophene C_4H_4S together. This polymer is specifically targeted to tissue engineering and biosensors. Surprisingly, due to its optical property, it is widely applicable in producing organic photovoltaic cell for the conversion of energy from solar energy. The other properties of this polymer like bio compatibility, high conductivity, and high sensitivity to the biological analytes could let it to play an important role in biological molecules detection by binding it with biological analytes to made detectable change in electrical resistance.

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3. Medical applications

3.1. Nerve probes

In the wide applications of conductive polymers in medical treatments, two of the applications are well-known and crucial, nerve probes and drug delivery.Firstly, for nerve probes, this technology is similar to the neuron implants technology that a conductive polymer are implanted into brain. Nowadays, neuron implants technology already had some real life examples. Some disabled people like people who have no arms or legs to think the action they wanted to do in the brain, so that the electric signal transferred in nerves could be captured and convert to commands to the machine arm or legs to help them move freely. Nerve probes are similar to the brain chips . The electrical properties of the nerve cells made it possible for human to use nerve probes to detect the signal with the help of conductive polymer.. According to the Matthews, An electrical voltage exists across the plasma membrane, while the inside of the cell remains more negative than the outside. By convention, the potential outside the cell is called zero; therefore, the typical value of the membrane potential is -60 to −100 mV [2]. Offered by Paul, this potential difference is maintained at a steady level when excitable cells are inactive and is called the resting potential [3]. Thus, by detecting the variation between the resting potential and the electric signals in the nerve cell when the nerve transferred signals, people would be able to detect such variation in order to analyze the patient conditions. According to Sanchvi, Polypyrrole (PPy) is a conductive synthetic polymer that has numerous applications in drug delivery and nerve regeneration and it has also been used in biosensors and coatings for neural probes . Polypyrroles and other conductive polymers like PANI has the properties like high bio compatibility to serve as the coating of nerve probes [4].Neural electrode functionality can be increased by modifying the surface of the electrode sites with low impedance conductive polymer coatings with nanoscale roughness or porosity and through the incorporation of cell adhesion peptides, proteins or anti-inflammatory drugs [5].

3.2. Biosensors

Moreover, Conducting polymers have attracted much interest as a suitable matrix of enzymes [6]. In general, for the fundamental mechanism of biosensors, according to Kapen, Skorupar, and Krukiewicz, The sensing substance reacts with the target analyte to produce a signal chemically which is transmitted to the transducer, which finally converts the input into an electrical signal [7]. Antibodies, enzymes, DNA probes, and cell receptors that interact with a particular analyte might serve as the biological sensing component. By encapsulating the sensing substances or analytes, the conductive polymer like polypyrrole could convert the input into numerical data of electrical signals. For this reason, conductive polymers often served as transducers in biosensors due to their great bio compatibility and high conductivity. Also, chemists could modified the conductive polymers by doping with other substances to made it widely applicable to diverse analytes, for example, the polypyrrole. Polypyrrole could served as a transducer to in the biosensors for detecting many kinds of biological molecules like glucose and urea.

4. Limitations and future expectations

Despite the suitable properties of conductive polymers to the application in many technologies of medical treatments, it still faced some serious challenges and limitations. Here are some of the limitations: the film made from the conductive polymers like polypyrroles for the use of neural

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probes or biosensors would be considerably fragile and have poor mechanical stability [8]; the extreme high level of bio compatibility needed for the neural probes and biosensors standard is still hard to achieve using conductive polymers; ethical issues appears due to the emergence of neural probes, and some laws needs to be considered thoroughly to further develop the neural probes and even make them into legal customer facing medical products for correct uses like curing disabled people. Distinct uses of conductive polymers would and will have different challenges and limitations for people to solve and handle. In the modern world, chemists and engineers already strive over and over on the improvements of the application of conductive polymers and aimed to amend the mistakes.

Looking ahead, the future of conductive polymers in medicine is poised to transition from diagnostic and supportive tools to fully integrated, intelligent therapeutic systems. The next frontier lies in developing self-healing, biodegradable conductive polymers that can safely dissolve after fulfilling their function, eliminating the need for removal surgeries and reducing long-term biocompatibility concerns. The emergence of "smart" neural interfaces capable of not only reading complex neural signals but also delivering precise, feedback-controlled neuromodulation to dynamically treat conditions like Parkinson's disease or depression can be anticipated. Furthermore, the convergence of conductive polymers with advancements in AI and nanotechnology will pave the way for advanced nanorobots or sophisticated organoids for drug delivery and tissue regeneration. These systems will be capable of autonomously monitoring physiological states, diagnosing anomalies, and administering therapies in real-time, heralding a new era of personalized and predictive medicine where the line between technology and biology becomes increasingly seamless.

5. Conclusion

In conclusion, conductive polymers have undeniably revolutionized the landscape of medical technology, marking a paradigm shift from rigid, inert materials to dynamic, biocompatible interfaces. As this essay has detailed, the unique confluence of electrical conductivity, biocompatibility, and versatile processability in materials like polypyrrole, polyaniline, and polythiophene has unlocked unprecedented applications. They form the critical backbone of modern biosensors, enable targeted drug delivery systems, and are indispensable in the development of advanced neural probes that restore function and mobility. By effectively translating biological signals into electrical data and vice versa, these materials have bridged a crucial gap between the electronic world of medical devices and the organic world of the human body.

However, the path forward is not without its challenges. Issues of long-term mechanical stability, achieving the highest echelons of biocompatibility, and navigating the complex ethical terrain of neural augmentation remain significant hurdles. These limitations necessitate continued interdisciplinary collaboration among chemists, material scientists, engineers, and ethicists. Despite these challenges, the trajectory is overwhelmingly positive. The ongoing research into polymer doping, composite material creation, and biodegradable formulations promises to address current shortcomings.

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