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Spinal cord stimulator electrode materials and electrode displacement issues: current status, challenges and future developments

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Abstract:

Spinal cord stimulation (SCS) is a key technology for the treatment of chronic pain and neurological dysfunction, and its effectiveness relies heavily on the selection and design of electrode materials. This paper reviews the electrochemical properties and biocompatibility of several commonly used electrode materials, including platinum-iridium alloys (PtIr), iridium oxides (IrOx), carbon nanotubes (CNTs), conductive polymers (PEDOT/PSS), and boron-doped diamonds (BDDs). The role of liquid crystal polymer (LCP) encapsulation technology in the long-term stability of electrodes is then discussed. Despite significant progress in the application of these materials in SCS devices, complications such as electrode migration and material degradation are still open issues. This paper analyzes the advantages and disadvantages of different electrode materials, discusses the possibility of improving electrode performance through emerging technologies such as nanotechnology and smart electrode systems, and proposes future research directions to reduce surgical complications and enhance treatment outcomes. With intelligent electrode systems and personalised treatment plans, electrical nerve stimulation technology provides greater precision, adaptability and long-term efficacy in the treatment of neurological disorders.

Keywords: Spinal cord stimulator (SCS), electrode materials, electrode displacement

1. Introduction

With the continuous advancement of medical technology, neuroelectric stimulation technology has shown great potential in treating chronic pain, neurodegenerative diseases, and motor dysfunction. Spinal Cord Stimulation (SCS) has become one of the effective means of treating intractable pain by transmitting electrical signals through implanted electrodes and interfering with pain transmission in the nervous system. However, despite the remarkable progress of SCS technology, there are still many challenges in its

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device implantation procedures, especially electrode-related complications, such as electrode displacement, device malfunction, and degradation of electrode materials. These problems not only affect the therapeutic outcome but may also lead to the need for secondary surgery for patients, increasing medical risks and costs.

Electrodes are the core components of SCS devices, and their material selection plays a crucial role in the long-term stability and biocompatibility of the devices. Traditional electrode materials such as platinum-iridium alloys (PtIr), iridium oxides (IrOx), and silver-silver chloride (Ag/AgCl) perform well in terms of electrochemical performance and biocompatibility, but they still face problems such as performance degradation and biotoxicity after prolonged implantation. Meanwhile, novel materials such as conductive polymers (e.g., PEDOT/PSS) and carbon nanotubes (CNTs) are potential choices for improving electrode performance due to their excellent flexibility and electrical conductivity. In addition, the encapsulation technology of liquid crystal polymers (LCPs) shows great application prospects in reducing the degradation of electrode materials and extending the service life of devices.

This study aims to investigate the selection and design of SCS electrode materials and their application in implantable devices, analyze the advantages and disadvantages of different electrode materials, and examine the role of technological improvements in reducing electrode-related complications. By reviewing existing studies and discussing future directions, this paper hopes to provide theoretical support for the optimization of electrode materials and the further development of SCS technology, as well as to bring safer and more efficient solutions for clinical applications.

2. Electrode materials

In neuroelectric stimulation and other biomedical fields, the selection and design of electrode materials directly affect the function and therapeutic effect of medical devices. With the development of medical technology, higher requirements have been placed on electrode materials, especially in implantable medical devices, and these materials not only need to have good electrochemical properties but also need to meet stringent requirements such as biocompatibility and mechanical strength. Although no side effects directly caused by spinal cord stimulator electrodes have been identified, allergic reactions and electrode failures have been reported [1,2]. The goal of future materials is to reduce foreign body reactions while providing durable and sensitive electrodes [3]. Conventional electrode materials such as platinum, iridium, and silver offer good performance in charge transfer but may face problems with biodegradation or tissue damage in long-term implantation. With the advancement of nanotechnology, researchers have greatly improved the mechanical and conductive properties of electrodes by combining conductive polymers (e.g., PEDOT/PSS) with materials such as carbon nanotubes (CNTs) and graphene oxide (rGO). Meanwhile, new electrode materials like boron-doped diamond (BDD) and Injectrode® have demonstrated good biocompatibility and conductivity and are gradually being used in neurostimulation devices. These advances not only promote the innovation of medical monitoring and treatment devices but also provide new ideas for the future development of neuroscience and regenerative medicine.

2.1 Artificial Skins as Electrodes.

The development of artificial skin electrode materials has benefited from advances in medicine, materials science, and electrical engineering. As an emerging technology, artificial skin electrodes are mainly used to monitor physiological signals and are gradually being applied in the field of neurostimulation. The development process encompasses from simple flexible sensors to complex multifunctional systems designed to achieve a high degree of compatibility and conductivity with human tissues.

Artificial skin electrodes were initially used primarily to monitor physiological parameters such as temperature, pressure, and strain. These flexible sensors are capable of capturing and transmitting small physiological changes in the human body, and application areas include health monitoring, clinical disease diagnosis, and sports and fitness [4]. However, early materials focused on achieving basic sensing functionality, making it difficult to balance long-term conductivity, flexibility, and biocompatibility.

The most commonly used electrode materials include graphene oxide (GO), reduced graphene oxide (rGO), carbon nanotubes (CNTs), and polymeric materials such as poly(3,4-ethylenedioxythiophene)/polystyrene sulfonate (PEDOT/PSS). The introduction of these materials significantly improves the electrical conductivity and mechanical flexibility of the electrodes, especially in electrophysiological signal monitoring such as electroencephalography (EEG) and electromyography (EMG), demonstrating comparable or even superior performances to those of conventional electrodes [5,6]. Through nanostructuring, artificial skin electrodes can significantly increase the surface area, which reduces the interfacial impedance and improves the signal quality [6]. Structurally, hydrogels have been shown to bind GO to form stretchable conductive materials, which strike a balance between flexibility and conductivity [5].

The introduction of nanomaterials has driven the development of artificial skin electrodes, particularly through the use of graphene oxide and carbon nanotubes to enhance conductivity and mechanical properties. It has been shown that reduced GO can combine with flexible hydrogels to form a composite with good mechanical properties and electrical conductivity [5,6]. This composite material solves the problem of uneven conductivity caused by early GO aggregation and significantly improves the mechanical durability of flexible electrodes. Recent studies have further expanded the application of artificial skin electrodes by integrating pressure, temperature, and bioelectrical signal sensors on the same platform to form a multifunctional skin electronic system [6]. This multifunctionality not only helps to improve the flexibility of the electrodes but also enables continuous monitoring of different physiological signals in the human body, which significantly enhances the utility of medical devices. By introducing the nano-mesh structure, the artificial skin electrodes perform well in the monitoring of electrophysiological signals. In particular, the low impedance and high conductivity of nanoweb electrodes significantly enhance signal stability in EMG and EEG measurements [5]. In addition, the introduction of new fabrication techniques such as organic transistors have enabled the electrodes to maintain stable electrical properties even under stretching and bending [7].

One of the biggest challenges facing artificial skin electrode materials is how to ensure their long-term biocompatibility while maintaining high electrical conductivity. Although materials such as hydrogels and nanomesh provide excellent flexibility and breathability to prevent skin overhydration and eczema, the degradation of these materials in long-term use needs to be further addressed [7,8]. Future research will continue to develop self-repairing materials and nanocomposites to extend the service life of electrodes and reduce biological rejection. Large-scale production of artificial skin electrodes still faces the problems of high cost and production complexity. Although the use of organic transistors and nanomaterials has significantly improved electrode performance, ways to reduce manufacturing costs and increase production efficiency remain key to future development [7]. By improving the design of the sensing system and simplifying the production process, high-throughput manufacturing technology will lay the foundation for the popularization and application of these devices.

The future development direction of artificial skin electrodes will focus on the development of intelligent systems. These systems can automatically adjust electrode parameters according to the user's physiological state to achieve personalized medical treatment and health monitoring [6]. For example, combined with artificial intelligence algorithms and big data analysis, the electrodes will be able to make adaptive adjustments based on real-time feedback information to provide more precise treatment results.

2.2 Implantable Electrode Material:

2.2.1 Platinum-Iridium Alloy (PtIr)

PtIr is one of the main choices for neuroelectric stimulation electrodes due to its excellent electrochemical stability and mechanical strength. The material transfers charge via the Faraday reaction and possesses efficient charge injection capability, making it suitable for long-term implantation applications. However, it has been shown that under certain conditions, PtIr electrodes may generate toxic platinum compounds that lead to damage to the surrounding tissues, a phenomenon that limits their use in some cases, as shown on Fig.1 [9,10].

2.2.2 Iridium Oxide (IrOx)

IrOx is commonly used for neuroelectric stimulation due to its excellent charge injection ability and good biocompatibility. IrOx has pseudo-capacitive properties and can form a stable oxide layer on the electrode surface with the electrolyte, thus reducing side reactions. However, the long-term stability of IrOx is still problematic, especially under prolonged high-intensity stimulation, and material degradation may occur. This phenomenon may lead to device failure or tissue damage in practical clinical applications.

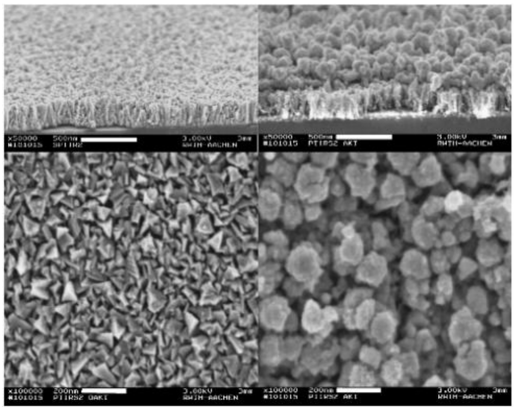

Fig. 1 SEM pictures of the PtIr films on soda-lime substrates before activation (left) and after partial activation (right). The upper image shows the cross-section and the lower part shows the top view [9].

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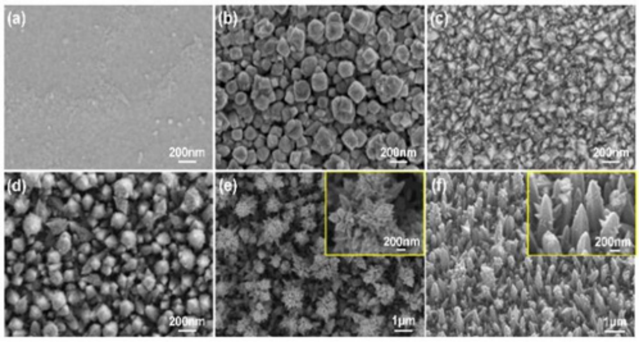

Fig. 2 SEM images of coated microelectrodes with different deposition processes. (a) Bare Pt electrode. Morphology of nanostructured Pt deposited in electrolytes containing (b) PtCl4, (c) PtCl4 + (NH2CH2)2·2HCl,(d) PtCl4 +NH4Cl,(e)(NH4)2PtCl6 and(f)PtCl4 +(NH4)2PtCl6 respectively. The insets in (e,f) show the enlarged images of Pt nanocluster and nanocone respectively [11].

2.2.3 Nanocone array-based platinum-iridium oxide (Pt-IrOx) neural microelectrodes

By controlling the ratio of ammonium ions (NH4+) to platinum ions (Pt4+) in the electrolyte, a team of researchers prepared nanocone-shaped platinum coatings on bare platinum substrates. The nanocone structure provided a large surface area, which significantly reduced the electrode impedance and improved the electrode's charge storage capacity (CSCc) and charge injection capacity (CIC). Iridium oxide (IrOx) was used to further improve the electrode performance due to its high pseudo-capacitance properties. The nanocone array electrodes coated with iridium oxide exhibit lower impedance and higher capacitance. The nanocone array structure not only improves the mechanical stability of the coating but also enhances the contact between the neuroelectrode and the tissue and reduces possible foreign body reactions during long-term implantation. Extremely low impedance, high charge storage capacity, and good biocompatibility make it a potentially preferable material for future neuroimplantable devices, as shown on Fig.2 [11].

2.2.4 Carbon nanotubes (CNT)

Carbon nanotubes are widely used to improve electrode performance due to their unique nanostructures and high electrical conductivity.CNTs can significantly increase the surface area of electrodes, thereby improving charge storage and injection capabilities. In addition, functionalized carbon nanotubes improve their biocompatibility and reduce tissue rejection. However, the long-term stability and potential biotoxicity issues of CNTs still need to be further investigated [12,13]. Fig. 3 shows the schematics of zigzag, armchair, chiral SWCNT [12].

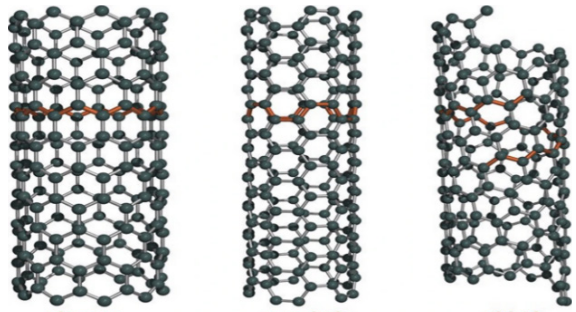

Fig. 3 Schematics of zigzag, armchair, chiral SWCNT [12]

2.2.5 Conductive polymers (PEDOT/PSS)

PEDOT/PSS is a conductive polymer with high electrical conductivity and flexibility, which can reduce the mechanical mismatch problem between electrodes and tissues. The material not only has good electrochemical properties but also can load bioactive molecules through the coating to reduce post-implantation inflammatory responses. However, the stability of the conductive polymer under long-term DC stimulation still needs to be further verified to ensure its safety in the clinic, as shown on Fig. 4 [14].

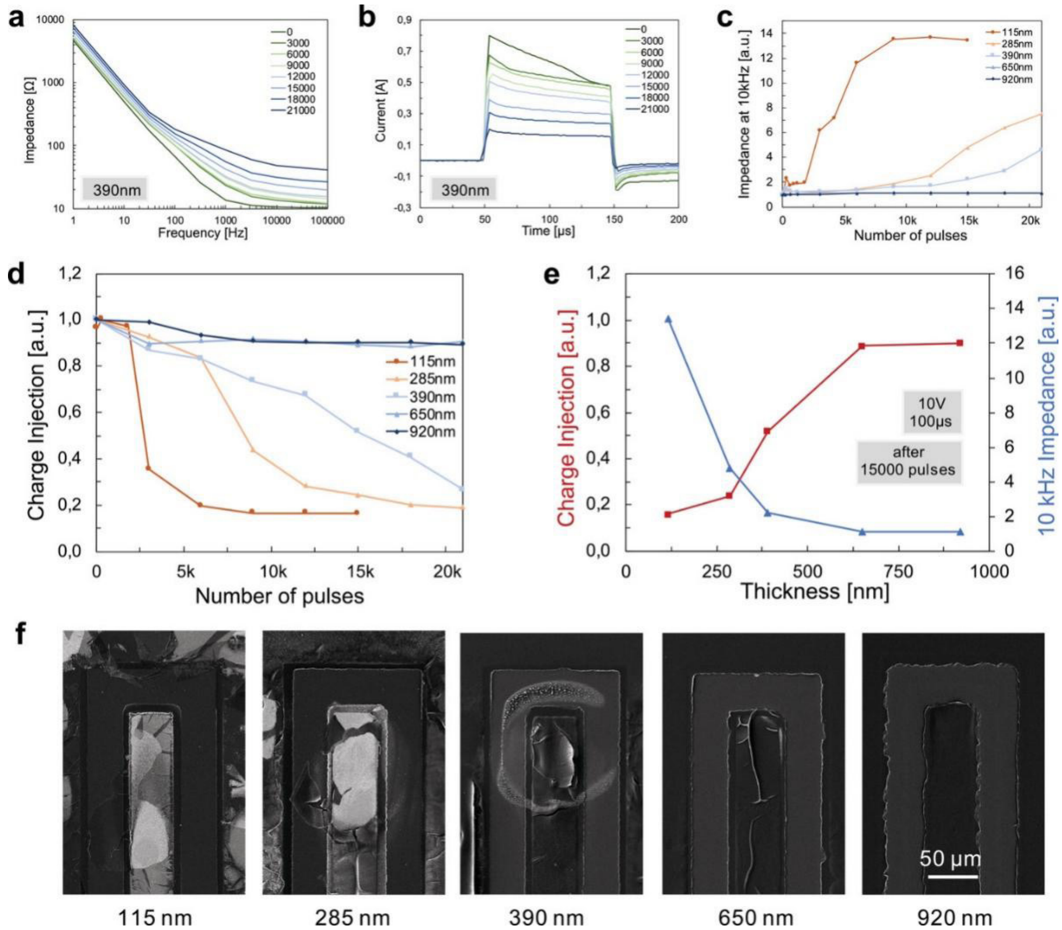

Fig. 4 Electrode stability for repetitive 10 V, 100 μs, 10 Hz pulses. Change in a) impedance and b) current for a 390 nm PEDOT: PSS coating during prolonged application of pulses. Impedance and current were measured after every 3000 pulses. c) Normalized 10 kHz impedance and d) charge injection as a function of number of pulses for various coating thicknesses. e) Normalized charge injection and 10 kHz impedance as a function of coating thickness after 15 000 pulses. f) SEM images after 21 000 pulses for various coating thicknesses [14].

2.2.6 Silver-Silver Chloride (Ag/AgCl) and Stainless Steel

Although silver-silver chloride electrodes are capable of efficiently transferring charge through the Faraday reaction, the release of silver ions may trigger cytotoxicity problems, limiting their long-term use. Stainless steel is used in some low-demand applications due to its low cost, but it is less biocompatible and prone to triggering inflammatory reactions and tissue damage during long-term implantation.

2.2.7 Graphene/rGO-CNT composite electrode materials

Graphene and rGO have significant advantages in electrode materials due to their high electrical conductivity and large specific surface area, but graphene is prone to stacking, resulting in impeded charge transfer.CNT, as a one-dimensional material, prevents this stacking and improves the stability and electrical conductivity of the electrode, making it an efficient composite electrode material [15]. The electrochemical properties of graphene, rGO, and CNT composites can be significantly enhanced by nitrogen doping and the addition of conductive polymers such as polypyrrole and polyaniline.

The ability of these composites to exhibit both electrochemical double-layer capacitance (EDLC) and pseudocapacitance properties allows them to gradually transition from capacitive energy storage behavior to battery-type behavior, which makes them not only capable of fast charging and discharging but also provide higher energy density. Although composites show great potential for energy storage, practical applications still face challenges

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such as long-time cycling stability and conductive path optimization. Future research needs to further improve the structural design and fabrication process of the materials to achieve higher performance and large-scale applications.

2.3 Boron doped diamond (BDD)

Boron-doped nanostructured diamond (BDD) electrodes are very promising electrode materials for neural interface technology due to their excellent chemical stability, biocompatibility, and wide electrochemical window.BDD materials have excellent chemical stability and maintain their structural integrity even in complex in vivo environments. The corrosion resistance and the wide electrochemical window of the BDD materials allow for long-term use without harmful reactions, especially in neuro implantable devices that require electrical stimulation [16,17]. It has been shown that the electrochemical performance of BDD electrodes can be significantly enhanced by nanostructuring them.3D nanostructured BDD electrodes have a larger surface area, which effectively reduces the interfacial impedance of the electrodes, thereby enhancing their charge storage capacity (CSC) and charge injection capacity (CIC). These improvements have led to better performance in capturing weak neural signals and providing more efficient neural stimulation [17,18].

BDD electrodes have significant advantages in neural signal recording and neurostimulation applications. It has been found that BDD electrodes exhibit high sensitivity and low noise in capturing low-amplitude neural signals (e.g., 10-20 μV), as well as excellent mechanical strength, which keeps their performance stable under prolonged implantation conditions. This makes BDD electrodes ideal for neuroimplantable devices and neuroprostheses [16,17]. Compared to conventional electrode materials such as titanium nitride (TiN), BDD electrodes exhibit better biocompatibility in vivo. Studies have shown that the thinner fiber capsule formed around BDD electrodes triggers a less inflammatory response, which is crucial for long-term implantable device applications. This implies that BDD electrodes have very low biological rejection and long-term stability in neuroimplantation applications [17,18].

2.4 Injectable Electrodes

Injectable electrodes are an emerging electrode technology designed to enable better adaptation of electrodes to neural tissue through injection techniques, reducing the complexity and cost of the procedure. Injectrode is an injectable, pre-polymerized electrode material that is injected and then cured in vivo to form a soft neural electrode. It is characterized by its ability to form electrodes in vivo that conform to the neuroanatomy, reducing mechanical stress and mechanical mismatch between the device and the surrounding anatomy. The material has a Young's modulus of less than 100 kPa, which is much lower than currently used materials for neural interface electrodes, making it more flexible after implantation.

Injectrode consists of platinum-cured silicone rubber and thin silver metal sheets. This combination creates an electrode that is much softer than conventional neural interface wires. Flexible electrodes reduce mechanical stress, which in turn reduces the inflammatory response due to stress and stretching between the device and nerve tissue [19].

A team of researchers evaluated fiber recruitment and resistance to electrical stimulation thresholds by comparing the performance of the Injectrode with stainless steel electrodes in the L6 and L7 spinal ganglia (DRG) of cats. The results showed that Injectrode's thresholds in all major sensory neurons were comparable to those of the stainless steel electrode. This implies that it can effectively stimulate major sensory neurons, showing its potential for clinical applications [19].

Despite its excellent performance in early experiments, the long-term biocompatibility of the material needs to be further investigated due to the known toxicity of silver. Researchers are looking for alternative materials to replace silver to minimize its potential toxicity issues. In the meantime, further biocompatibility and long-term stability testing remain a critical step in moving Injectrode toward clinical application.

In recent years, as nanotechnology and coating technology continue to advance, researchers have begun to explore the possibility of improving electrode performance through nanostructured materials and bioactive coatings. Nanostructures can significantly increase the surface area of electrodes, thereby increasing charge storage capacity, while bioactive coatings can reduce post-implantation tissue reactions by adsorbing anti-inflammatory drugs. For example, PEDOT/PSS-doped carbon nanotube coatings have demonstrated good electrochemical stability and biocompatibility in experiments and have become a potential direction for improving electrode performance. In addition, LCP-encapsulated electrodes and the introduction of IrOx nanocoatings have also improved the efficiency of the electrode interaction with neural tissues, thus reducing the impedance of the electrodes [20]. Also compared to other polymer materials such as polyimide and Parylene-C, LCP showed better tissue tolerance during long-term implantation and was able to reduce post-implantation-induced inflammation and tissue reactions [21].

Despite significant progress, the long-term stability and biocompatibility of electrode materials are still the focus of future research. To reduce post-implantation complications, researchers need to further optimize the surface coating and structural design of the materials to improve their durability in physiological environments. Meanwhile, the development of smart electrode systems that can adaptively adjust electrical stimulation is also an important direction for the future. These smart electrode systems can automatically adjust the charge injection according to the real-time state of the tissue, thus improving the therapeutic effect and reducing unnecessary tissue damage. In addition, the development of LCP encapsulated electrodes and composite electrodes is also expected to further enhance electrode performance by combining the advantages of multiple materials.

3. Complications of electrode displacement

Spinal Cord Stimulation (SCS) is one of the effective treatments for chronic neuropathic pain and has been widely used in refractory pain management [22]. Its main principle is to interfere with the transmission of pain signals by emitting electrical signals through electrodes implanted near the spinal cord. However, complications after SCS device implantation surgery, especially electrode displacement, have been a problem for clinicians and patients. Electrode displacement not only affects the effect of pain management but also may lead to increased pain in patients and even require secondary surgical repair [23]. With the rapid development of SCS technology, how to reduce electrode displacement, improve the long-term stability of the device, and optimize surgical operation has become an important current research direction.

3.1 Incidence and impact of electrode displacement

Among the early complications after spinal cord stimulation surgery, electrode displacement is one of the most common device-related problems. Study data showed that electrode displacement occurred in approximately 88.5% of patients after surgery, with 86.3% of the electrodes moving caudally and the average displacement distance being 12.34 mm. Longitudinal or lateral displacement of the electrode results in a change in the range of stimulation and the patient may no longer feel the desired pain relief. Although some mild displacements can be corrected noninvasively by adjusting the stimulation parameters, severe displacements usually require reoperation to reposition the electrode to restore its original function. Electrode displacement not only increases patient pain, but also raises the cost and risk of surgery [24]. However, with advances in surgical techniques and equipment, this incidence has decreased significantly. For example, using modern hardware and surgical techniques, the rate of electrode displacement has been reduced to 2.1% [23]. Modern 10 kHz SCS devices have also reduced electrode migration with new anchoring techniques, with no cases requiring surgical correction at 6-month follow-up [25].

3.2 Risk factors for electrode migration

The causes of electrode migration are related to a variety of factors, including the experience of the surgeon, the location of lead implantation, the site of the implanted device, and postoperative recovery activities. The cervical region is more susceptible to lead displacement due to its greater mobility. In addition, premature resumption of strenuous activity can also affect the formation of fibrous tissue around the wire and increase the risk of displacement [22]. In one study, the patient's body mass index (BMI) significantly affected the risk of displacement. It was found that patients with higher BMI were more likely to have problems with electrode migration, possibly due to thicker subcutaneous tissue, increased difficulty of the procedure, and instability of the device during fixation [24].

3.3 Surgical Improvements and Treatment Outcomes

To reduce electrode displacement, researchers have continued to optimize surgical techniques. Since 1998, longer and stronger anchors have been used to secure the electrodes, and the stability of the electrodes has been further enhanced by methods such as injecting adhesive into the silicone rubber anchors. These improvements include the incorporation of fascial incisions to minimize displacement of the electrode from the tissue, increased strength and durability of sutures, and other measures. With effective anchoring, especially in high-mobility areas such as the lower lumbar region, the rate of lead displacement decreased significantly, reducing the need for secondary surgery [26]. For example, out of 291 patients, only 1.37% (4 patients) experienced electrode displacement and required repair surgery. With further improvements in the technique, the incidence of electrode displacement was zero in another study that included 142 patients [24]. In addition, the 10 kHz SCS device was able to correct deviations in the area of pain coverage caused by minor displacements by reprogramming, thus avoiding further surgical corrections [25]. The study showed a 23% shift rate for percutaneous wire implantation and a 24% shift rate for open-window surgery. Although the difference was not significant, electrode displacement with open win-

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dowing was more easily detected by imaging. In addition, the use of open windowing has demonstrated the benefits of reduced displacement in certain clinical scenarios [23]. Although there is no significant difference in the rate of displacement between percutaneous implantation and windowing, windowing allows for more precise detection of displacement by imaging, giving clinicians more options to respond to specific pathologic needs [27].

4. Challenge and future trends

Despite the remarkable progress that has been made, further optimization of electrode materials and improvement of implantation methods are still key issues to be addressed in the future.

4.1 Application of smart electrodes

With the continuous development of medical technology, smart electrode systems are becoming one of the key directions for future research. Intelligent electrodes can monitor the patient's tissue changes and electrode position in real-time and automatically adjust the electrical stimulation parameters according to this information, thus reducing the risk of electrode displacement after surgery. This intelligent technology not only improves the accuracy of treatment but also reduces patient pain and the possibility of secondary surgery.

4.2 Advances in material science

The choice of electrode materials is critical to the long-term stability of SCS devices. Advances in nanotechnology have opened up possibilities for the design of novel materials. Nanostructured electrodes and bioactive coatings can improve the biocompatibility and electrochemical properties of the electrodes, and reduce the friction and displacement of the electrodes from the surrounding tissues. For example, carbon nanotube coatings doped with conducting polymers (e.g., PEDOT/PSS) have shown good electrochemical stability and biocompatibility, and have become a direction for future research on electrode materials. Further research could be devoted to optimizing the surface properties of these materials to enhance the binding of the electrodes to the surrounding tissues and to reduce degradation problems in long-term use.

4.3 Individualized Surgery and Treatment Options

Considering individual patient differences (e.g., BMI, gender, age, etc.), the development of personalized surgical protocols for SCS will also be an important trend for future development. By combining imaging techniques, customized devices, and material selection preoperatively and intraoperatively, surgeons can better predict and control the risk of electrode displacement. For patients with higher BMI, more sophisticated fixation techniques or enhanced design strength of the electrodes may be required to ensure their stability in long-term use. In addition, postoperative rehabilitation and follow-up should be more individualized to monitor changes in electrode position for timely intervention.

5. Conclusion

The selection and design of electrode materials play a crucial role in biomedical applications such as electrical nerve stimulation. With the continuous development of medical technology, implantable devices place higher demands on the biocompatibility, electrochemical stability, and mechanical strength of electrode materials. Commonly used electrode materials such as platinum-iridium alloys, iridium oxides, carbon nanotubes, and conductive polymers have shown their respective advantages and limitations. In addition, liquid crystal polymers (LCPs) are emerging as an important material choice in implantable devices due to their excellent encapsulation properties and stability.

Electrode migration is one of the most common complications after spinal cord stimulator surgery, especially in patients with high body mass index. Studies have shown that the incidence of electrode displacement can be significantly reduced by technological improvements, such as the use of longer anchors, more robust fixation methods, and the application of adhesives. Meanwhile, the development of smart electrode systems, the application of nanotechnology, and the implementation of personalized surgical protocols have provided new directions for improving the long-term stability and therapeutic efficacy of devices.

In the future, researchers should continue optimizing the surface coating, structural design, and implantation techniques of electrode materials to ensure their durability and safety in vivo. By developing intelligent electrode systems and personalized treatment plans, neural electrical stimulation techniques can be further enhanced, offering improved precision, adaptability, and long-term efficacy in treating neurological disorders.

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