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Spinal Cord Stimulation Modalities and Charging Systems for Optimizing Chronic Pain Management

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Abstract. Chronic pain, notably in conditions like failed back surgery syndrome (FBSS), challenges healthcare systems, prompting a search for effective therapies. However, pharma treatment triggers human body's resistance which disfunction in long-term treatment. Therefore, spinal cord stimulation (SCS) offers a promising avenue. According to the gate control theory of pain control, it is possible to control the pain signal by sending new electrical waves through spinal cord to the brain. In this paper, three SCS modalities (TCS, BURST, HF) will be introduced and evaluated according to previous studies, which mainly focus on user-friendly and nerve pain control. Besides the efficacy of SCS modalities (TCS, BURST, HF), wearable charging systems warrant scrutiny. Different charging strategies (magnetic induction, magnetic resonance coupling, radio reception) will be introduced and analyzed in detail. This paper offers a concise overview of these modalities and charging strategies, aiming to inform clinical decision-making and enhance patient outcomes in chronic pain management.

Keywords: Failed back surgery syndrome (FBSS); Spinal cord stimulation (SCS); Wearable charging systems; TCS; BURST.

1. Introduction

Chronic pain, particularly in conditions such as failed back surgery syndrome (FBSS), poses a significant challenge to both patients and clinicians. Traditional pain management approaches often fall short in providing adequate relief, leading to a search for alternative therapies. Spinal cord stimulation (SCS) has emerged as a promising intervention for chronic pain, offering a non-pharmacological method to modulate pain signals and improve patient outcomes. However, the effectiveness of different SCS modalities, including tonic conventional stimulation (TCS), burst stimulation (BURST), and high-frequency stimulation (HF), remains an area of active investigation.

In addition to the implantable components of SCS systems, the wearable charging systems play a crucial role in ensuring the sustained functionality of these devices. The portability and convenience afforded by wearable charging systems, coupled with their ability to utilize replaceable batteries, contribute significantly to the overall utility and usability of SCS devices. Understanding the different charging strategies available for SCS systems is essential for optimizing patient outcomes and improving the overall quality of care.

In this paper, we aim to provide a comprehensive overview of three primary charging strategies employed in SCS devices. By examining the characteristics and advantages of each approach, we seek to elucidate the potential implications for clinical practice and patient management in the realm of chronic pain treatment.

2. Stimulation Protocol

SCS stimulator has basically two parts, the implantable part and the wearable part, the implantable part involves one or more electrical leads located in the epidural space of spinal cord, leading to the action potentials in the peripheral afferent fiber. According to the gate theory of pain, the A-β fibers, the big nerve fiber, respond to the sensing part of human body in fast transmission while the C fibers

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control the pain sensing part in slow transmission. By stimulating A-β fibers, the pain signal will be blocked, which is the mechanism of SCS stimulator for pain control.[1]

2.1. Tonic conventional stimulation (TCS)

Tonic conventional stimulation (TCS) is the first adapted SCS treatment, which is widely used therapeutic approach for managing chronic pain, particularly in conditions like failed back surgery syndrome (FBSS). This method involves the delivery of continuous electrical pulses to the spinal cord, aiming to modulate pain signals before they reach the brain, thereby reducing the perception of pain. Conventional tonic SCS typically employs low-frequency stimulation with parameters such as pulse width, frequency, and amplitude tailored to individual patient preferences and pain characteristics, which frequency is around 10-150 Hz, and its amplitude is around 0.1-0.25 mA. [2]

For SCS stimulation protocol, tonic conventional stimulation (TCS), burst stimulation (BURST) and high-frequency stimulation (HF) are the most common strategies. A MULTIWAVE test by Bordeleau is conducted to compare the effects of traditional, burst, and high-frequency spinal cord stimulation in pain relief in patients with chronic back pain. By comparison and double-blind testing of 28 patients, the most suitable stimulation will be selected, where patients will be given a 3-month combination of TCS, BURST and HF while using different stimulation per month and changing the modality combinations.[2] This study is still ongoing while a series of trials illustrate the beginning of widespread research and application of spinal cord stimulators.

In 2007, Kumar and colleagues reported findings from the PROCESS trial, a multinational randomized controlled study.[3] This trial investigated the efficacy of combining spinal cord stimulation (SCS) with conservative management versus conservative management alone for adults diagnosed with failed back surgery syndrome (PSPS). The primary goal was to assess the percentage of patients achieving at least 50% relief from leg pain. Secondary measures included improvements in back and leg pain, quality of life, functional capacity, medication and non-drug pain treatment usage, patient satisfaction, and adverse effects incidence. In the intention-to-treat analysis at 6 months, 48% of patients in the SCS group versus 9% in the conservative group achieved the primary outcome ($p < 0.001$). By 12 months, 30 conservative group participants had switched to SCS treatment. A subsequent analysis, considering crossover treatment failures according to initial randomization, revealed only 3 patients in the conservative group and 17 in the SCS group achieving the primary outcome. Despite its effectiveness, traditional tonic SCS may have drawbacks such as potential paresthesia and suboptimal long-term pain management.[2]

2.2. Burst SCS

Therefore, newly introduced stimulations, BURST and HF are used in clinical field. BURST SCS, or Burst Spinal Cord Stimulation, is an innovative therapeutic approach for managing chronic pain, particularly in patients with failed back surgery syndrome (FBSS). This cutting-edge technology involves delivering high-frequency electrical pulses to the spinal cord, which modulate pain signals and provide relief to patients suffering from debilitating chronic pain conditions. Unlike traditional spinal cord stimulation (SCS) techniques, which typically utilize low-frequency stimulation, Burst SCS employs bursts of stimulation pulses followed by periods of rest, mimicking the natural firing pattern of neurons in the dorsal column of the spinal cord. This unique stimulation pattern has been shown to offer superior pain relief and improved patient outcomes compared to conventional SCS methods. Studies including 117 patients have demonstrated the effectiveness of Burst SCS in providing long-term pain relief, reducing opioid consumption, and improving quality of life for patients with chronic pain.[4] In Schu’s study, randomized, active-control experiment including 20 patients was conducted using Burst treatment.[5] During the short term (12 months) test period, patients who received burst therapy experienced pain relief. However, after more than twelve months, the pain relief lapsed. Without paresthesia and other side effects comparing to tonic SCS, Burst SCS works as an powerful and potential approach for short-term pain reduction, however its sustainability is the main limitation.

2.3. High-Frequency Spinal Cord Stimulation (HF SCS)

High-Frequency Spinal Cord Stimulation (HF SCS) represents a contemporary therapeutic strategy designed to alleviate chronic pain, particularly in patients diagnosed with conditions like neuropathy and failed back surgery syndrome (FBSS). HF SCS delivers electrical pulses at a higher frequency than traditional spinal cord stimulation (SCS) methods. The aim of this approach is to interfere more effectively with pain signals, providing enhanced relief to individuals suffering from debilitating chronic pain. A randomized, parallel arm, noninferiority study by Kapural aims to evaluate the long-term safety and efficacy of HF SCS in patients with FBSS, involving a cohort of 171 participants. Sustainability of HF outruns the conventional SCS in 12 months of leg and back pain control($P<0.001$).[6] To find out HF longer period performance, another study by Kapural lasted 24 months contained 198 patients was conducted. At the 24-month mark, HF10 therapy demonstrated superior outcomes compared to traditional SCS. In the HF10 group, response rates were higher for low back pain (76.5 versus 49.3 percent, difference 27.2 percent, 95% CI 10.1 to 41.8 percent, $P < .001$) and for leg pain (72.9 versus 49.3 percent, difference 23.6 percent, 95% CI 5.9 to 38.6 percent, $P < .001$) [7]. In addition, reductions in low back pain (66.9% ± 31.8% vs. 41.1% ± 36.8%, $P <.001$) and leg pain (65.1% ± 36.0% vs. 46.0% ± 40.4%, $P <.001$) were also greater in the HF10 group [7]. These findings highlight the significant efficacy of HF10 therapy in chronic pain management and its potential as a superior alternative to traditional SCS approaches. These studies have indicated that HF SCS may offer superior pain management outcomes, including improved pain relief without experience paresthesia and enhanced overall quality of life. The use of higher frequencies in HF SCS is a significant advancement in neuromodulation technology, providing a promising option for individuals seeking effective and sustainable pain relief.

By comparison of these three stimulation, Burst and HF are recommended for long-term treatment and high quality of life. However, HF's energy consumption is future improvement while Burst as a newly introduced treatment still requires more experiment and data.

3. Wearable charging system

For SCS wearable charging system, it contains pulse generator to generate electrical pulses, waveform generator for generating several different types of current waveforms
and electrode array concluding electrodes that can be used to stimulate specific areas
and possibly programmer to program and adjust implantable part. Briefly, there are different charging ways, the most common ones are magnetic induction, magnetic resonance coupling and radio reception.

3.1. Magnetic induction charging

Magnetic induction charging, also known as wireless charging, is a cutting-edge technology that enables the wireless transfer of power to electronic devices using electromagnetic fields. This process involves the use of an induction coil to create an alternating electromagnetic field, which induces a voltage in a receiver coil within the electronic device, thereby charging its battery without the need for physical connectors.[2] Magnetic induction charging has the convenience of wireless power transfer and the potential for increased water and dust resistance which leading to charger dysfunction due to the absence of physical charging ports. However, drawbacks of this technology may include slower charging speeds compared to wired charging methods, the need for precise location between the charging pad and the device, and potential energy inefficiencies associated with the conversion and transmission of electromagnetic fields.[7] As magnetic induction charging continues to evolve, ongoing advancements aim to address these limitations and further enhance the convenience and efficiency of wireless charging.

3.2. Magnetic resonance coupling

In magnetic resonance coupling, a significant advancement in mid-range energy transfer has emerged. Colombo conducted a study employing self-resonant coils in a strongly coupled regime, achieving efficient nonradiative power transfer over distances approximately eight times greater than the coil's radius. Their experimentation successfully transmitted 60 watts with around 40% efficiency at distances exceeding 2 meters, marking a breakthrough for mid to long-range power transfer capabilities.[8]

Resonant coupled Wireless Power Transfer (WPT) systems operate by establishing a robust magnetic coupling between two objects tuned to resonate at the same frequency, as shown in Fig. 1.

The emission part includes the power supply, the resonant circuit, and the emission coil. The power supply provides energy to the resonant circuit, which converts the energy into electromagnetic waves of a specific frequency and emits them through the emitting coil. The receiving part includes a receiving coil, a resonant circuit, and a rectifier circuit. The receiving coil receives the electromagnetic waves emitted by the transmitting coil and converts them into electrical signals, the resonant circuit converts the electrical signal into a voltage of a specific frequency, and the rectifier circuit converts the voltage into a DC voltage for the load.

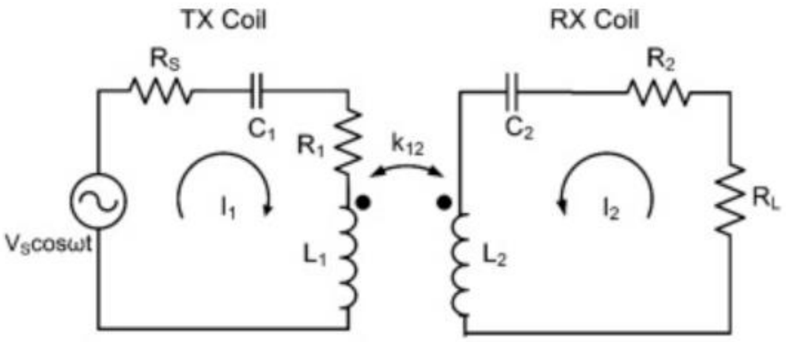

Fig. 1 Mechanism of magnetic resonance coupling [11]

This phenomenon arises due to the interaction of current-carrying coils through their changing or oscillating magnetic fields. The quality factor (Q) measures the performance of a coil, a capacitor, or an inductor in terms of its losses and resonator bandwidth. In magnetic resonance coupling, superior performance is associated with higher Q factors and reduced capacitance, as the equation shown [9].

$$Q_C = \frac{-X_C}{R_C} = \frac{1}{\omega_0 C R_C}$$

The characteristics of magnetic resonance coupling are high power over long distance. Comparing to magnetic induction, magnetic resonance coupling’s power can reach to kilowatt. Therefore, its biggest limitation is amplitude control, for its high-power can-do damage to the human body.

3.3. Radio reception charging

Radio reception charging works by transmitting power from a transmitter to a receiver via radio waves. The transmitter converts electrical power into radio waves, which are then transmitted through the air. The receiver converts the radio waves back into electrical power, which can then be used to power the device.[10] Radio reception’s biggest benefit is that it can be charged automatically, which convenience outruns the others. Besides, low-power-transfer guarantee the human body safety while using radio reception charging implantable stimulator. However, its low power and long transfer distance leading to slow and long charging period. The efficiency of radio reception charging is not as high as other wireless charging. This means that it takes longer to charge devices using radio reception charging than it does using wired charging.

In conclusion, comparing the previous three charging methods, magnetic resonance coupling is recommended as a charger for SCS stimulator. It outruns in high efficiency and long range for convenience and good quality of life, also its cost is relatively low.

4. Conclusion

In conclusion, the management of chronic pain, particularly in conditions like failed back surgery syndrome (FBSS), necessitates a comprehensive approach that integrates both conventional and cutting-edge therapeutic interventions. Spinal cord stimulation (SCS) has emerged as a valuable tool in the armamentarium against chronic pain, offering patients a non-pharmacological option for pain relief and improved quality of life. However, the selection of the most appropriate SCS modality and charging system is crucial for optimizing treatment outcomes and patient satisfaction.

This paper has provided a thorough examination of three primary charging strategies used in SCS devices: magnetic induction, magnetic resonance coupling, and radio reception. Each approach offers distinct advantages and limitations, and careful consideration of these factors is essential in clinical decision-making. While magnetic resonance coupling emerges as a promising option due to its high efficiency and long-range capabilities, further research and technological advancements are needed to address its limitations and optimize its performance.

Additionally, the discussion of stimulation protocols, including tonic conventional stimulation (TCS), burst stimulation (BURST), and high-frequency stimulation (HF), underscores the importance of tailoring treatment approaches to individual patient needs. The MULTIWAVE study exemplifies the ongoing efforts to compare and evaluate the efficacy of these SCS modalities, providing valuable insights into their respective benefits and limitations. By incorporating evidence-based stimulation protocols into clinical practice, healthcare providers can enhance the precision and effectiveness of SCS therapy, ultimately improving patient outcomes and satisfaction.

As we continue to explore the complexities of chronic pain management, collaboration between researchers, clinicians, and industry partners remains paramount. By fostering interdisciplinary dialogue and innovation, we can advance the field of SCS and develop novel solutions that address the diverse needs of patients with chronic pain conditions. Through concerted efforts and a commitment to evidence-based practice, we can strive towards a future where chronic pain is effectively managed, and patients experience improved quality of life and well-being.

References

[1] Khelemsky Y., Malhotra A., Gritsenko K. Academic Pain Medicine A Practical Guide to Rotations, Fellowship, and Beyond. Cham: Springer International Publishing, 2019.

[2] Billot M., Naiditch N., Roy-Moreau A. Comparison of conventional, burst and high-frequency spinal cord stimulation on pain relief in refractory failed back surgery syndrome patients: study protocol for a prospective randomized double-blinded cross-over trial (MULTIWAVE study). Trials, 2020, 21(1).

[3] Kumar K., et al. The Effects Of Spinal Cord Stimulation In Neuropathic Pain Are Sustained. Neurosurgery, 2008, 63(4): 762-770.

[4] Hou S., Kemp K., Grabois M. A Systematic Evaluation of Burst Spinal Cord Stimulation for Chronic Back and Limb Pain. Neuromodulation: Technology at the Neural Interface, 2016, 19(4): 398-405.

[5] Schu S., Slotty P. J., Bara G., von Knop M., Edgar D., Vesper J. A Prospective, Randomised, Double-blind, Placebo-controlled Study to Examine the Effectiveness of Burst Spinal Cord Stimulation Patterns for the Treatment of Failed Back Surgery Syndrome. Neuromodulation: Technology at the Neural Interface, 2014, 17(5): 443-450.

[6] Kapural L., et al. Novel 10-kHz High-frequency Therapy (HF10 Therapy) Is Superior to Traditional Low-frequency Spinal Cord Stimulation for the Treatment of Chronic Back and Leg Pain. Anesthesiology, 2015, 123(4): 851-860.

[7] Suh I-S. Chapter 5: Wireless Power Transfer Technical Issues and Challenges. In: Wireless Charging Technology and the Future of Electric Transportation. [Online] Available: ieeexplore.ieee.org, 2015, Jun. 08.

[8] Colombo C. G., Miraftabzadeh S. M., Saldarini A., Longo M., Brenna M., Yaici W. Literature Review on Wireless Charging Technologies: Future Trend for Electric Vehicle?. In: Proceedings of the 2022 Second International

Conference on Sustainable Mobility Applications, Renewables and Technology (SMART), Cassino, Italy, 2022: 1-5.

[9] Barman S. D., Reza A. W. Renewable and Sustainable Energy Reviews, 2015, 51: 1525-1552.

[10] Lu X., Wang P., Niyato D., Kim D. I., Han Z. Wireless Charging Technologies: Fundamentals, Standards, and Network Applications. IEEE Communications Surveys & Tutorials, 2016, 18(2): 1413-1452.

[11] Li W., et al. Review on Reinforcement Learning Controller in Soft Manipulator. [Online] Available: ieeexplore.ieee.org, 2022.