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J. Vis. Commun. Image R. xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

J. Vis. Commun. Image R.

journal homepage: www.elsevier.com/locate/jvci

Intermediate multimedia node: Implantable spinal cord stimulator

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ARTICLE INFO

Article history:
Received 26 January 2016
Revised 21 June 2016
Accepted 3 September 2016
Available online xxxx

Keywords:
Intermediate
Multimedia node
Implantable device
Stimulator
Wireless communication

ABSTRACT

Advanced wireless technology in multimedia devices that is used widely in daily life can be applied to medical devices, such as spinal cord stimulator (SCS), for functioning as a multimedia node. This paper describes a SCS prototype that functions as a sensor and actuator for scientific research and potential clinical applications. The SCS is able to generate voltage/current outputs in 4 channels (with 16 electrodes selection) and has the capacity to sense tissue impedance in real-time. Furthermore, the SCS allows for wireless communication with high power efficiency at a long range (up to 2 m). Benefiting from its novel designs for high power efficiency and wireless signal/power transmission, the SCS also satisfies the long-term animal/clinical test requirements for maintaining multimedia link. Our experiments also indicate that the SCS has better performance, such as in electrical parameters and versatility, to relevant studies.

1. Introduction

The current technological advancements in multimedia networks, which include software platforms and hardware instruments, have an important role in daily living of people in the developed countries. An important aspect of the multimedia network is signal-processing technology, which is becoming more robust and reliable. An example of this advancement is the ability to process pattern recognition in a real-time manner [1–6]. While it is simple to search or recount complicated signals in multimedia networks [7–9], decoding the signals of the nervous system remains a challenge. For example, scientists require sensors to detect information and transmit these valuable data into multimedia networks. The rapid developments in implantable medical devices combined with advancements of multimedia networks may allow the relay of information with specific neurons in the nervous systems of the human body [10–12]. As such, the potential use of intelligent implantable nodes, may improve clinical diagnosis from the multimedia and multimodal observations made available [13–16].

Chronic neuropathic pain is a refractory disease. Ever since Melzack presented the "gate control" stimulation theory in 1965 [17], spinal cord stimulator (SCS) methods were developed to reduce pain [18]. Later in 1971, the analgesic effects of SCS were reported in the first clinical trial [19]. Thereafter, SCS developed into a popular method for treating chronic neuropathic pain.

SCS treatment is based on the induction of functional electrical stimulation (FES) i.e. injection of electrical currents directly into tissue. During surgery, the SCS is placed under skin. The activation of the device causes a relay of a mild electric current to the nerve fibers of the spinal cord, which is carried by extension wires and electrodes produced from pulse generator. The effect of reduced pain is thought to be caused by electrical currents interrupting pain signals from reaching brain [20] (see Fig. 1).

In recent years, commercial companies and research institutes have focused on the development of SCS devices. The SCS market is growing rapidly and is estimated to reach $2.3B by 2016 [25]. Medtronic, St. Jude, and Boston Scientific, the market leaders in neuronal modulation, have developed several SCS products to treat neuropathic pain (e.g. Medtronic RestoreSensor Model 37714 [21]). To date, several of these devices have wireless rechargeable function, with short-range wireless communication. In addition, the SCS could also be used to treat angina and asthma in the future, extending its market use remarkably [25].

SCS devices are required to meet several critical functions in order to maintain connection with a multimedia network. Long-range wireless communication is a fundamental feature, along with bi-directional neuronal signal transfer (neuronal stimulation and measurements in tissue's impedance) [21]. It is important that the transmission rate of interaction is high enough to satisfy the requirements for neuronal recordings [22,23]. For meeting such requirements, it is necessary for implantable devices to have efficient power consumption, which requires not only wireless charge function but also circuit efficiency.

Unfortunately, the commercial and academic SCS devices have several known shortcomings. These include the lack of both

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http://dx.doi.org/10.1016/j.jvcir.2016.09.001
1047-3203/

Please cite this article in press as: Y. Hu et al., Intermediate multimedia node: Implantable spinal cord stimulator, J. Vis. Commun. (2016), http://dx.doi.org/10.1016/j.jvcir.2016.09.001

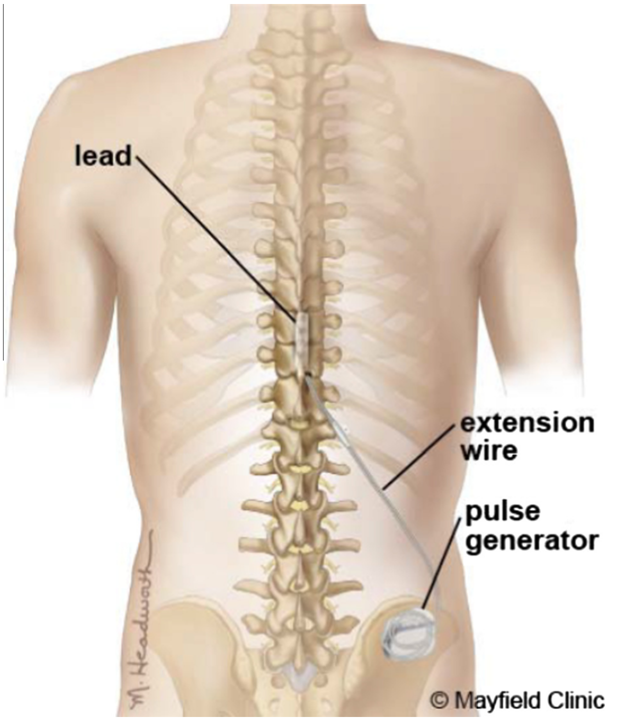

Fig. 1. Implantable SCS (including pulse generator, extention wire, and lead): The pulse generator, which generates the current, is implanted under the skin in the abdominal region. The current pulse is transferred through the extension wire into the lead, activating the spinal cord to disrupt the pain. At the same time, physiological signals can be acquired by the lead, which can be sent to the pulse generator through the extention wire. All three parts of the SCS are implanted inside the human body.

voltage and current output functions, which are valuable for clinical applications. For example, voltage output function is power efficient but remains limited by accuracy, while current output function is relatively accurate but is not power efficient. Furthermore, for the current output function, the devices developed to date are unable to efficiently adjust the supply voltage to different impedances, which causes the problem of power consumption control. In addition, the currently available SCS devices have wireless communication function that is limited to a short range with low speed.

In this study, we present an implantable spinal cord stimulator as a multimedia node, which has been designed to overcome the limitations of currently used devices.

The SCS methods are presented in Section 2, which reports system overview and submodules' design strategy. We then present the test results in Section 3, mainly representing measurement results for functions including wireless charge, voltage/current output, and wireless communication. In Section 4, we conclude that SCS has a powerful function as a multimedia node, which has the potential to be further improved.

2. SCS prototype methods

2.1. System overview

The SCS prototype system was designed to improve specific features in currently used devices for application in scientific research and clinical testing. These included the development of:

(1) Wireless rechargeable function to prolong its battery life.
(2) The output module for power efficiency i.e. long usage time per battery charge.
(3) Programmable SCS's outputs (voltage or current output) with impedance test function. In addition, to accommodate to the long length of the spinal cord, the module was designed with 4 channels, composed of 16 electrodes.
(4) The wireless communication module for interaction with a multimedia network.

The design of the SCS (Fig. 2) consists of (i) a wireless recharge power management module (ii) a control center (iii) a voltage/current output module with impedance test function and (iv) a wireless communication module.

The wireless recharge power management module was designed to receive wireless power through inductive transmission, changing AC into DC power to charge battery. This module provides electricity to the whole system. The control center manages the voltage/current output module according to wireless communicating information. The voltage/current output module generates high voltage for outputs, delivering power to the electrodes in 4 channels. This output module also comprises of an impedance measurement function. For all blocks, except for electrodes and part of wireless communication (antenna), these were sealed inside a titanium alloy shell.

2.2. Wireless recharge power management

As shown in Fig. 3, under the action of the resonance capacitor, the internal coil receives electromagnetic energy from the external coil. The received energy is in the AC form under a specific frequency. Using a rectifier and capacitor, the AC energy is rectified to DC form. The linear dropout regulator (LDO) assists by reducing the ripple and glitch of this DC waveform, realizing buffer's function at the same time. The charge management controls battery

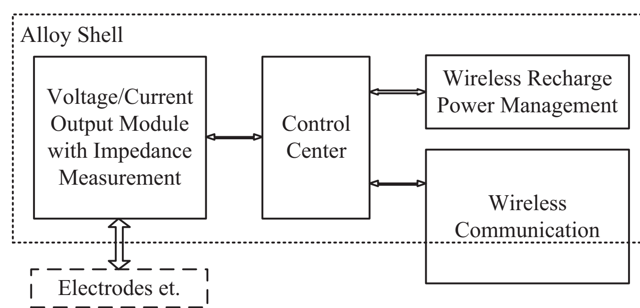

Fig. 2. Diagram of SCS system: blocks and interact connection. The wireless recharge power management module receives wireless power through inductive transmission, providing electricity to the whole system. The control center sends/receives the instructions through wireless communication module and then it controls the output module.

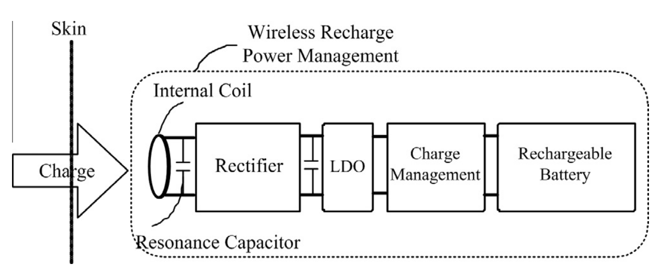

Fig. 3. Diagram of wireless recharge power management: interact connection and position. The internal coil receives AC from electromagnetic energy with help of the resonance capacitor. The rectifier transfroms AC to DC. The LDO and the charge management module controls the charging of the rechargeable battery.

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