33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

A Fully Implantable Stimulator with Wireless Power and Data Transmission for Experimental Use in Epidural Spinal Cord Stimulation

Qi Xu, Jun Li, Wenjuan Han, and Houlun Zhou

Abstract—**Epidural spinal cord stimulation (ESCS) combined with partial weight bearing therapy (PWBT) has been reported to facilitate recovery of functional walking for individuals after chronic incomplete spinal cord injury. This paper describes a low cost, fully implantable, advanced ESCS stimulator that can be manufactured in a research laboratory for use in small animals. The system is composed of four main parts: an external personal digital assistant (PDA), an external controller, an implantable pulse generator (IPG), lead extension and electrode. The PDA allows the experimenter to program the stimulation parameters through a user-friendly graphical interface. The external controller placed on the rat back communicates with PDA via RF telemetry. The IPG generates the biphasic charge-balanced voltage-regulated pulses, which are delivered to the bipolar electrode by the lead extension to achieve chronic ESCS in freely moving rats. A RF carrier from the Class-E amplifier in the external controller provides both data and power for the implanted circuitry through a closely coupled inductive link. The IPG is hermetically packaged using a silicon elastomer and measures 22mm×23mm×7mm with a mass of ~3.78g.**

Keywords— Class-E amplifier; epidural spinal cord stimulation; incomplete spinal cord injury; inductive link; rat

I. Introduction

RECENTLY, it is reported that the combination of ESCS and partial weight bearing therapy (PWBT) can induce significant functional gains in over-ground gait from individuals with chronic, incomplete spinal cord injury (ISCI) who have very low motor scores in their lower limbs [1]–[2]. Specifically, the study participants exhibited quantifiable improvements in functional gait measures during the application of nonpatterned ESCS, including increased walking speed and distance, improved gait kinematics and kinetics, enhanced metabolic fuel consumption, and reduced reliance on gait assistive devices for balance and weight support. While the mechanism underlying these improvements is not well understood, ESCS influences motor unit excitability, induces muscle twitches, and modulates phasic patterns of muscle activity in prior studies [1]–[2].

Animal experiments can be employed to test a wide range of stimulation protocols, to identify effective interventions, and to study the basic biological mechanisms of the cellular and tissue response to various protocols. Animal studies in parallel with clinical studies enhance overall understanding of the effect of ESCS on the locomotion performance [3].

The effectiveness of ESCS to improve locomotion performance after an incomplete spinal cord injury in chronic adult rats is unknown. The study of the neural control of locomotion is often performed using the rat as a model considering the fact that in some ways the anatomical organization of the human spinal cord rostro-caudally is more similar to that of the rat than the cat, e.g. number of spinal segments and segments in the lumbar enlargement. In addition, humans and rats are plantigrade animals, whereas cats are digitigrade. The commercialized devices for spinal cord stimulation have been widely used in human clinical studies [1]–[3].

The purposes of the current study were (1) to develop a radio-frequency controlled implantable stimulator, and (2) to test it in an acute rat model. In this paper, we describe a low cost, fully implantable stimulator used for ESCS in rats to enable the investigation of the ESCS mechanisms on the improvement of the locomotion performance. The implanted stimulator receives power and data transcutanuously through an inductive coupled link, so that the stimulation parameters can be reprogrammed after implantation. Moreover, the implant contains no battery or external wire to reduce its size and avoid the infection at the site of entry through the skin.

II. Materials and Methods

A. System Overview

The design of the programmable ESCS system incorporates three important features. First, the implantable pulse generator (IPG) contains no battery or external wire and is enough small to be implanted in rats. Second, the voltage pattern delivered to the stimulating electrodes can be reprogrammed after implantation. Third, an external personal digital assistant (PDA) can control multiple external controllers constituting a star network, where the PDA could transmit the stimulation parameters to multiple IPGs implanted in grouped rats. The key specifications of the system are listed in Table I. For a chronic stimulation, pulses

Manuscript received April 15, 2011. This work was supported by the Natural Science Foundation of China under Grant 60874035,and in part by the Fundamental Research Funds for the Central Universities under Grant HUST: 2010JC012).

Qi Xu and Jun Li are now with the Key Laboratory of Image Processing and Intelligent Control, Department of Control Science & Engineering, Huazhong University of Science & Technology, Wuhan, P.R. China. (phone:86-27-87557284; fax: 86-27-87543130; e-mail: xuqi@mail.hust.edu.cn).

Houlun Zhou is now with the Department of Anatomy, Tongji medical college, Huazhong University of Science & Technology, Wuhan, P.R. China (e-mail: zhouhl@mails.tjmu.edu.cn).

TABLE I
THE KEY PARAMETER ITEMS AND HARDWARE CAPABILITIES OF THE STIMULATOR

Stimulation parameters	Range (Resolution)
Number of channels	2
Output characteristics	Constant voltage
Waveform type	Monophase, square wave
Voltage output	50mV~3.0V (0.01V or 0.1V or 1V step)
Current output	35 mA per channel max (load dependent)
Pulse frequency	0~200Hz (1 Hz or 10 Hz or 100Hz step)
Pulse width	400~1200μs (400μs step)
Stimulation duration	10s~60min (1s or 10s or 1min step)
Spinal cord segments	L2-L4

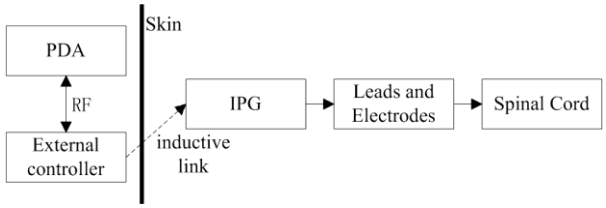


Fig. 1. Block diagram of the ESCS system.

should be charge-balanced to prevent corrosion and irreversible electrolyte reactions. In many cases, biphasic waveforms are symmetric with equal pulse amplitudes and pulsewidth. However, asymmetric, charge-balanced waveforms allow better control of electrochemical reactions at the electrodes and may suppress undesired physiological reactions, e.g. increase of excitation thresholds in comparison with monophasic pulses [4].

The block diagram of the ESCS system is shown in Fig. 1, which consists of an external PDA, an external controller placed on the rat back, an IPG, extension leads and stimulation electrode. The experimenter uses the external PDA to set or program the desired stimulation parameters by a user-friendly interface consisting of a keyboard and LCD display. Then the PDA transmits the control commands corresponding to the waveform parameters to the external controller by RF telemetry. Next, the external controller will transfer transcutanuously the data and power to the IPG by inductive link. The IPG generates the voltage-regulated pulse to stimulate the spinal segments through the electrode placed in the epidural space.

There are two wireless communications in this system. The first one exists between the PDA and the external controller based on a RF transceiver chip CC2500 (Chipcon, Oslo, Norway). The CC2500 is a low cost, true single chip 2.4GHz transceiver for very low power wireless applications, which is intended for the ISM (Industrial, Scientific and Medical) applications and has a short range device (SRD) frequency band from 2400MHz to 2483.5MHz. The second one between the external controller and the IPG is achieved by an inductively coupled link. While a high-efficiency Class-E

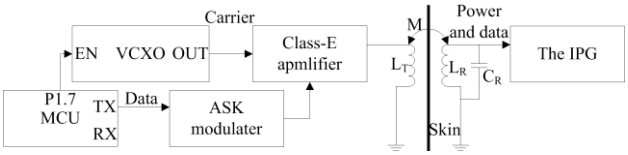


Fig. 2. Block diagram of the external controller powering and controlling the IPG through an inductive telemetry link driven by a class-E power amplifier.

amplifier drives the transmitter coil in the external controller, the voltage induced in the receiver coil is amplified by the LR-CR parallel resonant tank in the IPG.

B. External Controller

There are two external control units in the advanced ESCS system. The first one is the battery-powered PDA built around the MCU of C8051F411 (Silicon Laboratories, Boston, USA). The keyboard and LCD display in PDA will provide a user-friendly interface for the experimenter to modify stimulation parameters in convenience. The second one is a portable external controller placed on the rat back to achieve the RF data communication with IPG. By a transceiver CC2500-based RF telemetry, the microcommands for the ESCS parameters is delivered from PDA to the external controller on the rat back. The PDA is fabricated using surface mount devices (SMD) on a small double-layer printed circuit board (PCB) with a size of 5.9cm×8.8cm.

On the other hand, the RF signal, 4MHz amplitude modulated (AM) carrier, is used to transfer power and data to the implanted stimulator. The choice of the carrier frequency is dictated by a tradeoff between adequate miniaturization of the components (mainly, receiver coil and tuning capacitors) in the implant and tissue absorption of the electromagnetic energy. The RF telemetry link is a pair of transformer-like coupled coils that has been previously used in implantable telemetry applications [5].

As shown in Fig.2, the external controller is built around MCU to power and control the implantable pulse generator (IPG) through an inductive link driven by a class-E power amplifier. The class-E amplifier is chosen because of its simplicity and very high efficiency. This efficiency in the active device is necessary because the efficiency of the link is quite poor due to the very low coupling between the transmitter and receiver coils (with the implanted system receiving 1% of the average emitted RF energy). This low coupling results from the fact that the transmitter coil is essentially a relatively large air-core inductor, while the receiver coil is a much smaller coil with a cross section that does not capture a very large portion of the magnetic flux. On the other hand, different modulation strategies can be used to send information through an inductive link, such as the amplitude shift keying (ASK) or the frequency shift keying (FSK). An ASK modulation is used to transmit information in this work. If no data are transmitted, then the efficiency is high because all the time is transmitting this level. All components are assembled on a small PCB (3.8cm×7.4cm) and powered by a 9V lithium battery.

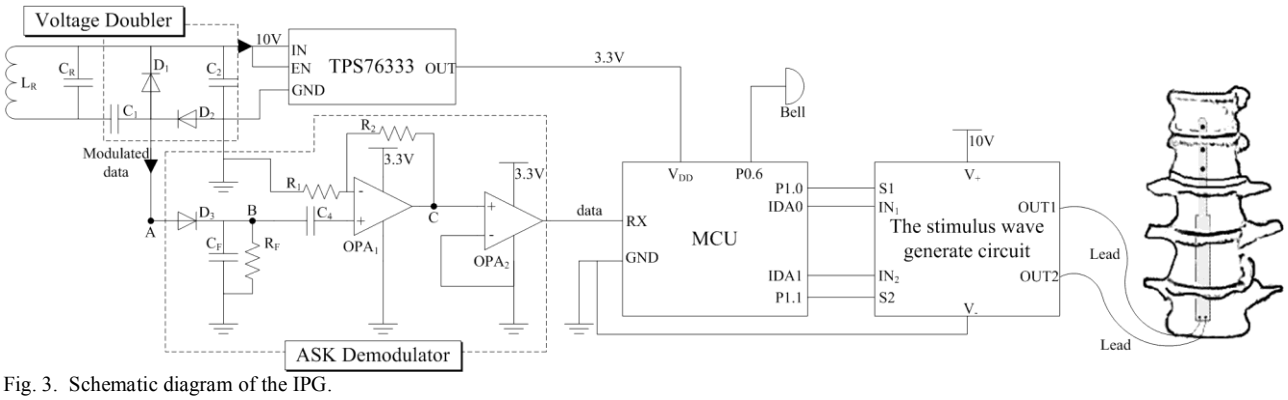


Fig. 3. Schematic diagram of the IPG.

C. Implantable Pulse Generator

Fig.3 shows the overall diagram of the IPG, which consists of four major blocks: (1) a voltage regulator circuitry; (2) a data detection circuitry (ASK demodulator); (3) a microcontroller; and (4) a constant-voltage output stage. The received signal after being picked up by a resonant tank consisting of receiver coil (LR) and parallel tuning capacitor (CR), goes through a voltage regulator in order to generate the required supply voltages. The voltage doubler provides good DC regulation from the 4-MHz carrier and permits high voltage up to 10V for the output stage. The DC-DC convertor (TPS76333) is used to supply the microcontroller. Moreover, the LRCR parallel resonant circuit is also used to receive the ASK-modulated carrier for data transfer from the external controller. By means of the ASK demodulator, the data including specification of the required pulse parameters (pulse width, pulse amplitude) and stimulation sequence parameters (duration of sequence) are extracted and stored in the onboard memory in the microcontroller.

In order to ensure charge balancing at the electrode site, the output stage generates two monophasic constant-voltage pulse signals applied to a pair of electrode contacts, which forms a current pulse flowing in one direction and then it is reversed as a current in the opposite direction.

Although the application of the integrated circuits enables the miniaturization of the implantable device, the off-the-shelf components is used to build the IPG at a low cost in a research laboratory. Micropower design is essential for any implantable device. Many design choices are driven by the effort to minimize power consumption. The C8051F411 microcontroller was selected because it uses less power than other functionally identical microcontrollers. A general principle of micropower design is to use the largest values of resistors and the smallest values of capacitors as possible to minimize power consumption. Any unused I/O pins of the microcontroller were set to INPUT mode during initialization of the software, and the pins were pulled to ground in hardware using 1 MΩ resistors.

D. Leads and Electrodes

The leads carry the stimulus current to the electrode, which provides the electrochemical interface to the spinal cord. In the ESCS system the Teflon coated stainless steel wire (Cat No.793500, A-M Systems Inc, http://www.a-msystems.com/) connects the stimulating electrode to the IPG. After the distance from the surgical site of the IPG to the spinal segment of interest is measured, all stainless steel leads are at least 30% longer than the distance to reduce the axial and bending stress encountered by the lead in the freely moving rats, thus increasing its ability to resist fractures due to either high transient loads or cyclic fatiguing loads [7].

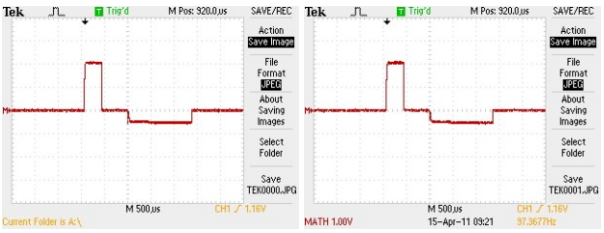
The ESCS electrode, manufactured by the flexible circuit board technique, consists of the gold contacts on the polyimide substrate. Three round gold contacts with the diameter of 1 mm are separated at 7 mm distance on the electrode.

E. Test and Hermetic Packaging

The IPG was fabricated using surface-mount devices assembled on a small two-layer PCB. The ability of the implantable stimulator to receive the stimulation parameters from the external controller and to stimulate resistive loads was extensively examined in laboratory conditions.

It is important to remove any contaminates produced during manufacture prior to encapsulation of the implants. The PCB is cleaned with detergent followed by isopropyl alcohol. Once dried and cleaned, the PCB is only handled using clean plastic tweezers. Then the PCB is coated with conformal coating (Electrolube DCA SCC3) [8]. After the conformal coating has been cured, the assembled board is coated with a silicone elastomer, taking care not to cover the electrode connection pads. The size of encapsulated IPG was 22 mm×23 mm×7 mm with a mass of ~3.78 g.

After encapsulation, the function was verified again by observing the voltage waveform between the two electrode contacts using an oscilloscope. As shown in Fig.4, the biphasic asymmetric charge-balanced waveform had a positive phase V1 (dominant rectangular stimulation pulse) followed by a negative phase V2, while a load of 1.5 kΩ was placed between the electrode contacts to simulate tissue impedance. Finally, the IPG was tested in vitro for the leak tightness. The encapsulated IPG was submerged in the 0.9% saline at the temperature of 37°C in a constant-temperature container for seven days. The prototype of the ESCS system for experimental use in rats is shown in Fig.5.



(a) (b)

Fig. 4. Measured biphasic asymmetric charge-balanced waveform via (a) no load resister, and (b) a 1.5kΩ load resistor placed between the electrode contacts to simulate spinal cord impedance.

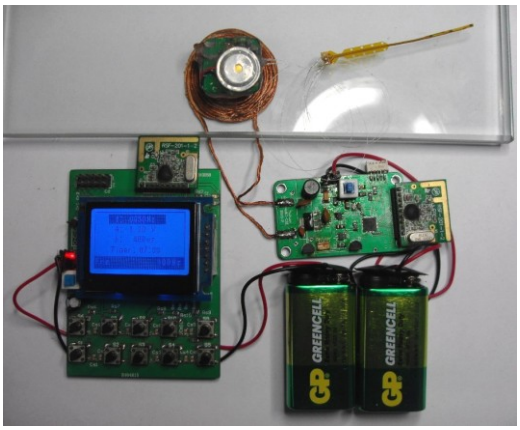


Fig. 5. The ESCS system for rats can be manufactured in a research laboratory, where the magnetic coupled link is used to pass data and supply power from the external device to the implant.

III. Conclusion

In order to investigate the mechanism of the ESCS therapy, we developed an advanced ESCS system that can be used to chronically stimulate a target spinal segment in small animals using charge-balanced biphasic pulses. Moreover, the external controller provides both data and power for the implanted circuitry through a closely coupled inductive link.

Future works of these fully implantable, magnetically coupled stimulators is to develop the multichannel stimulators for experimental use. Moreover, it is necessary to verify its function by implanting stimulators into rats.

Acknowledgment

The work has been supported by the Natural Science Foundation of China (Grant Number 60874035), and in part by the Fundamental Research Funds for the Central Universities (HUST: 2010JC012).

References

[1] M. R. Carhart, J. He, R. Herman, S. D'Luzansky, and R. Knight, "Epidural spinal-cord stimulation facilitate recovery of functional walking following incomplete spinal-cord injury," *IEEE Trans. Neural Syst. Rehabil. Eng.,* vol. 12, no. 1, pp.32-42, 2004.

[2] H. Huang, J. He, R. Herman, and M. Carhart, "Modulation effects of epidural spinal cord stimulation on muscle activities during walking," *IEEE Trans. Neural Syst. Rehabil. Eng*., vol. 14, no. 1, pp. 14-23, 2006.

[3] R.M. Ichiyama, Y. P. Gerasimenko, H. Zhong, R.R. Roy, and V.R. Edgerton, "Hindlimb stepping movements in complete spinal rats induced by epidural spinal cord stimulation," *Neurosci. Lett.*, vol. 383, no. 3, pp. 339-344, 2005.

[4] Q. Xu, J. He, Y. Wang, T. Xu, and J. Huang, " A versatile microprocessor-based multichannel stimulator for experimental use in epidural spinal cord stimulation," in *Proc. 1st Int. Conf. Neural Interface and Control*,Wuhan, China, May, 2005, pp. 205-208.

[5] N. Chaimanonart and D. J. Young, "An adaptively RF-powered wireless batteryless in vivo EKG and core body temperature sensing microsystem for untethered genetically engineered mice real-time monitoring," in *2009 6th Int. Conf. Networked Sensing Systems (INSS)*, Pittsburgh, PA, June, 2009, pp.1-6.

[6] W. D. Memberg, P. H. Peckham, and M. W. Keith, "A surgically-implanted intramuscular electrode for an implantable neuromuscular stimulation system," *IEEE Trans. Rehab. Eng.*, vol. 2, no. 2, pp. 80-91, 1994.

[7] R. G. Dennis, D. E. Dow, and J. A. Faulkner, "An implantable device for stimulation of denervated muscles in rats," *Medical Engineering and Physics*, vol. 25, no. 3, pp. 239-253, 2003.

[8] R. E. Millard and R. K. Shepherd, "A fully implantable stimulator for use in small laboratory animals," *Journal of Neuroscience Methods*, vol. 166, no. 2, pp. 168-177, 2007.