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An implantable radio-telemetry system for detecting multiple bio-parameters of a small animal based on wireless energy transmission

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ABSTRACT

Background and problem: The bio-parameters such as the blood pressure, the core body temperature and the biopotential are very important clinical clues to evaluate the physiological and psychological conditions of an animal. And these bio-parameters are also important for other clinical application. However, it is difficult to get the bio-parameters of a small animal for the long term under its normal state. It is a challenge for researchers to propose a method to acquire the bio-parameters of a small animal for the long term under its normal state. *Method*: This paper proposes an implantable radio-telemetry system to simultaneously detect long term blood pressure, temperature and biopotential of a small animal under its normal state. This system comprises an implantable capsule, a data logger and wireless energy transmission system. Three sensors are integrated into the implantable capsule. A pressure sensor is designed to detect the blood pressure, a temperature sensor to detect the inside body temperature, two tiny soft silver wires as the third sensor to detect the biopotential. The analog outputs of the three sensors are conditioned by their respective amplifiers. The three amplified bio-parameters are digitalized by an AD7683 (a 16-bit, charge redistribution, successive approximation, PulSAR analog-to-digital converter). Microprocessor PIC16F690 reads the digital data and sends it out of the animal's body through a wireless communication chip. A data logger can receive the data and save it with time stamps into a SD card. The data in the SD card can be processed with a computer. Curves of three bio-parameters can be used for evaluating physiological and psychological conditions of the animal. Wireless energy transmission system provides energy to the implantable capsule under the animal's normal conditions. A 3D secondary coil of the wireless energy transmission system enables itself to receive enough energy in an arbitrary position and posture. *Results*: In vivo experiment results show that the implantable radio-telemetry system can detect the blood, the temperature and biopotential of a rabbit. It meets the expected requirements.

1. Introduction

The bio-parameters such as the blood pressure, the core body temperature and the biopotential are very important clinical clues to evaluate the physiological and psychological conditions of an animal. These bio-parameters are also crucial clues for evaluating the effects of some new medicines in animal's clinical trials before these medicines are applied to human finally. However, it is very difficult to detect long term bio-parameters of animals under its normal condition. Numerous research work and efforts have been made to acquire long term bio-parameters of animals under its normal condition. Peng [1,2] and Young [3] proposed a microsystem for measuring the blood pressure of a laboratory mouse. This microsystem was powered by an external RF power source in a batteryless manner. An implantable device could measure the blood pressure of a mouse for the long term. However, this microsystem can only detect the blood pressure. It cannot detect the core body temperature and the biopotential at the same time. Park [4] developed a cuffless and noninvasive measurement technique of blood pressure using nanometric pressure sensor. The authors figured out MAP (Mean Arterial Pressure) based on the physiological characteristic including the elasticity of wrist tissue and the depth of blood vessel. However, this method was also only designed to get blood pressure. There are many other researches on the blood pressure acquiring [5–8]. These methods are also only designed for blood pressure acquiring at the same time. Nag [9]

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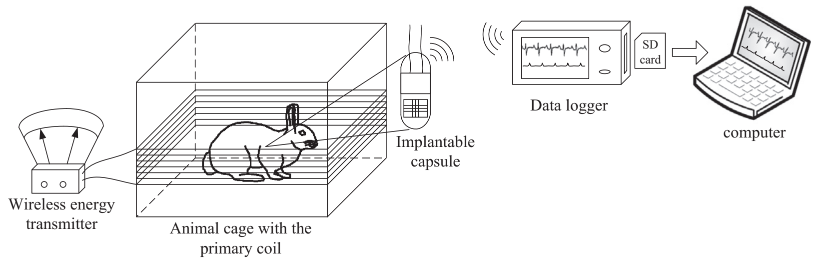


Fig. 1. Overview of the implantable radio-telemetry system.

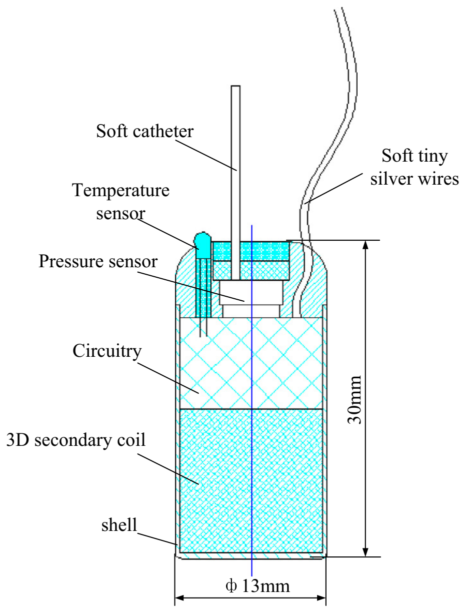


Fig. 2. Structure of the implantable capsule.

presented an e-jacket of a smart clothing system with multiple bio-parameter acquisition of electrocardiogram (ECG), pulse oximetry, body motion/tilt and skin temperature. This method could acquire the multiple bio-parameters at the same time. It is obvious that the e-jacket cannot be used in animal experiments. Risstamma [10] proposed an implantable wireless, inductively powered ECG-monitoring device. However, this device could only detect ECG, and cannot detect the blood pressure and the core body temperature. Tomasic [11] measured the charge generated due to triboelectric effect between one of the lead conductors and the inserted stylet. In order to get enough power from wireless energy transmitting system, Wenhui [12] developed a three-dimensional receiving coil. By the aid of this receiving coil, the secondary coil can get enough power in a random position. RamRakhyani [13] discussed thoroughly resonance-based wireless power delivery systems for biomedical implants. Wireless power delivery is an efficient technology to be used in biomedical implants. Russel [14] proposed a prototype of a wireless power delivery system for mouse telemeter. Four overlapped planar primary coil is designed to transmit energy to the pickup. The primary coil is driven by a full bridge series resonant inverter. This system can enable the pickup to receive the minimal power up to 20 mW. Dissanayake [15] proposed a transcutaneous energy transmission (TET) system for an implantable biomedical device. Temperature rise was considered in the TET system. The results of sheep studies showed that the efficiency of TET system was up to 82.1% and a temperature rise was up to 2.7 °C. Si [16] proposed a method to regulate the power transferred over a wireless link by adjusting the resonant operating frequency of the primary converter. This method is important on condition that the load, coupling and circuit parameters of the secondary coil are variable. Dowling [17] proposed the vivo experiment of the AbioCor Implantable Replacement Heart powered by TET system. Experiment results showed that the device worked normally. The TET system could provide energy to the implantable artificial heart. Patents [18–22] involve inventions about the transcutaneous energy transmission system for artificial heart. All the above research work and efforts prove that wireless energy transmission system is widely used in implantable biomedical devices. In this paper, wireless energy transmission system is also designed to provide energy to the implantable radio-telemetry system.

This paper develops an implantable radio-telemetry system without the aforementioned disadvantages. The system is composed of an implantable capsule, a data logger and wireless energy transmission system. The implantable capsule is designed to be implanted into an animal's body. It detects three bio-parameters of the animal simultaneously and sends the acquired bio-parameters data out of the animal body through wireless communication. The data logger can receive and save the data into an SD card. The data can be read and curves of three bio-parameters can be drawn for evaluating the animal's physiological and psychological conditions. Wireless energy transmission system can provide enough

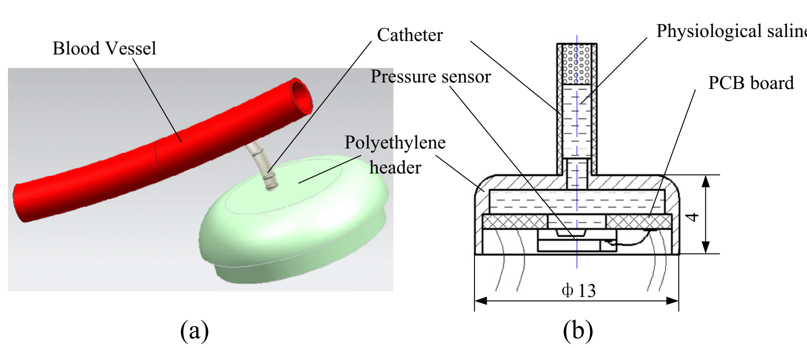


Fig. 3. Schematic of the pressure sensor and the detailed structure of the pressure sensor. (a) 3D structure of pressure sensor and (b) detail structure of pressure sensor.

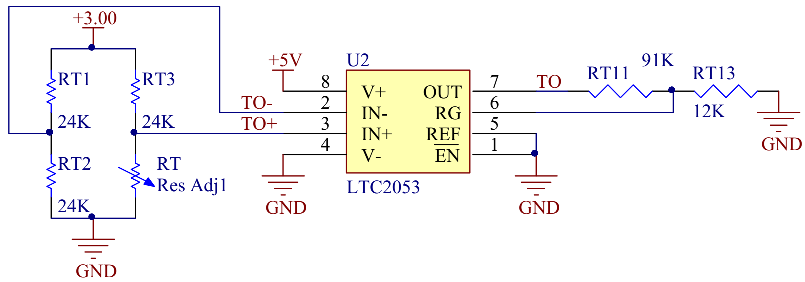


Fig. 4. Temperature resistor bridge.

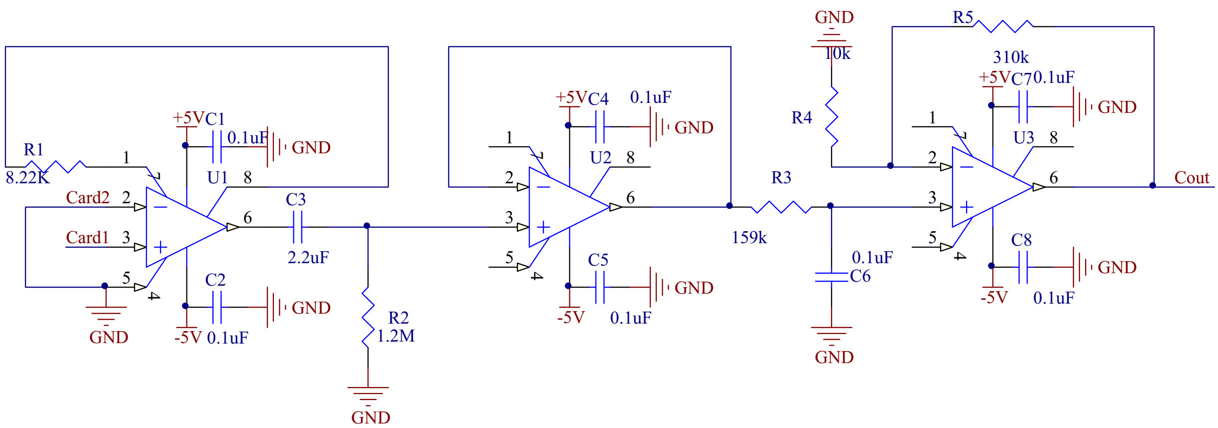


Fig. 5. Structure of the biopotential sensors circuitry.

energy to the implantable capsule under the animal's normal condition. In vivo experiment results verify the performance of the developed implantable radio-telemetry system.

Topics presented in subsequent sections include the outline of the implantable radio-telemetry system, the design of the implantable capsule, the design of the data logger, the design of wireless energy transmission system and in vivo experiment results. The paper ends with a discussion of the future work of the system.

2. Material and methods

2.1. Overview of the implantable radio-telemetry system

The implantable radio-telemetry system is composed of an implantable capsule, a data logger and wireless energy transmission system. The overview of the implantable radio-telemetry system is in Fig. 1.

The implantable capsule is designed to be implanted into the body of a small animal. In order to get the minimal invasion, the size of the implantable capsule should be as small as possible. Three sensors are integrated into the implantable capsule so that it can simultaneously detect the blood pressure, the temperature, and the biopotential of the animal. The analog outputs of the three sensors are preconditioned by their respective circuits. Then the preconditioned outputs go into an analog-to-digital chip to get digital data. The digital data of the three bio-parameters can be sent out through a wireless communication chip. The data logger is designed to receive the data from the implantable capsule. The received data is saved into an SD card with time stamps. And curves can be drawn on the LCD display of the data logger according to the received data in real time. Computer can also read the data from the SD card in the data logger and draw the curves of the three bio-parameters. These curves are used to evaluate the physiological and psychological conditions of the animal. Wireless energy transmission system is designed to provide energy to the implantable capsule from outside without end. In order to enable the implantable capsule to receive enough energy in an arbitrary position and posture, a 3D secondary coil is designed for the wireless energy transmission system.

The design of the implantable capsule will be investigated thoroughly as follows.

2.2. The implantable capsule

The implantable capsule is designed to be implanted into the body of an animal. The structure of the capsule is in Fig. 2.

The implantable capsule is cylindrical with 13 mm in diameter and 30 mm in height (the tiny wires for biopotential and the catheter of the pressure are not included). A thin shell of the capsule holds a 3D secondary coil, a circuit board, a pressure sensor and a temperature sensor. A catheter and two tiny soft silver wires are fixed on one end of the implantable capsule. The two tiny soft sliver wires will be implanted into the muscle to detect the biopotential. In order to keep the size of the implantable capsule to be small, special attention should be paid upon the miniature structure design of every part in the implantable capsule.

2.3. Pressure sensor

The pressure sensor used in this system is made by EPCOS Corp., a member of TDK-EPC cooperation. It is 2.2 mm in width, 2.7 mm in length and 0.8 mm in height. It is a die and should be bonded in a PCB before its application. In order to detect the blood pressure with a minimal invasion, the pressure sensor is packaged into a special form in Fig. 3. The pressure sensor die is fixed and bonded on a PCB board. There are four tiny wires from the PCB board with

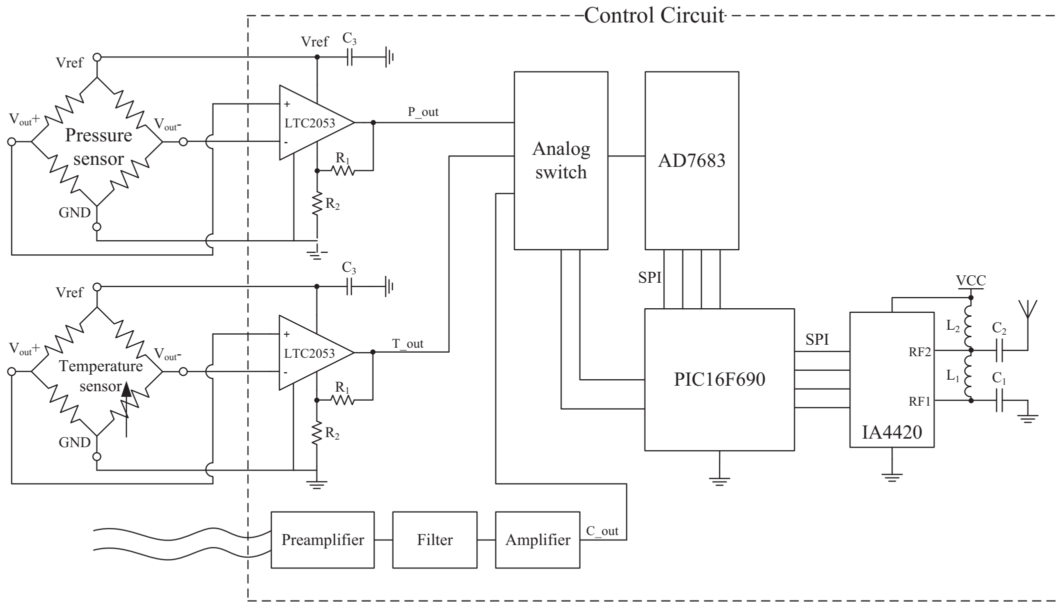


Fig. 6. Circuitry of the implantable capsule.

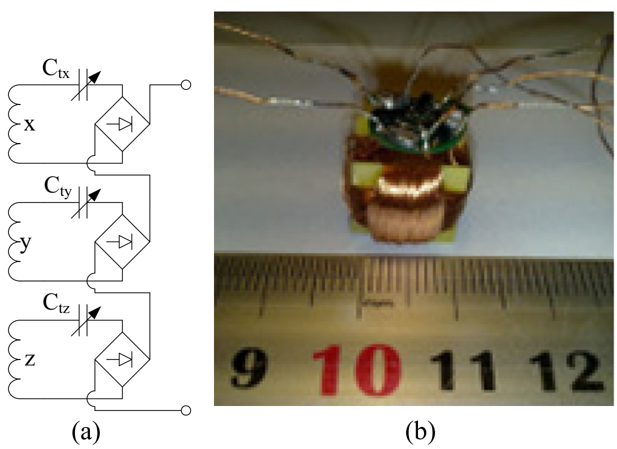


Fig. 7. Rectified circuit of 3D secondary coil and actual 3D secondary coil. (a) rectified circuit of 3D secondary coil and (b) actual 3D secondary coil.

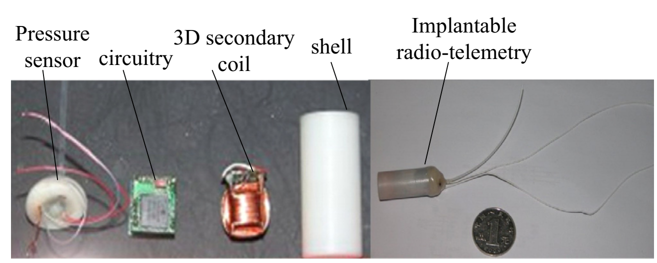


Fig. 8. Actual implantable capsule.

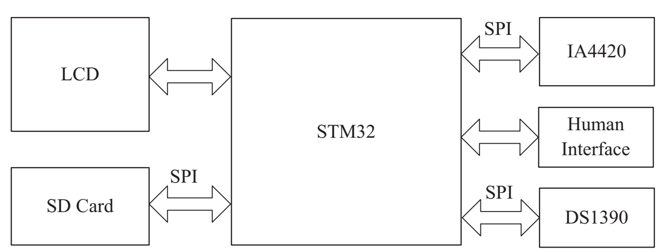


Fig. 9. Schematic of data logger.

0.4 mm in diameter. The PCB board is fixed in a hole of a polyethylene header with 13 mm in diameter and 4 mm in length. There is an empty chamber in this part. The sensitive surface of the pressure is exposed to the chamber of this part. A catheter with 0.61 mm in diameter is fixed on the convex end of the header. Physiological saline is full of the chamber and the catheter. In its application the other end of the catheter would be led to the blood vessel through a small incision. Then this end of the catheter would be pasted into this small incision in Fig. 3a. As soon as the catheter is pasted into the small incision of the blood vessel, the pressure in the blood vessel can be transmitted into the pressure sensor through the physiological saline. The pressure sensor can detect the blood pressure in the blood vessel in real time.

2.4. Temperature sensor

The temperature sensor is a negative temperature coefficient (NTC) resistor. It is designed to detect the temperature of an animal. In order to improve the temperature resolution, a resistor bridge is designed. The circuit of the resistor bridge is in Fig. 4.

The voltage fed into the resistor bridge is a reference voltage. The output of the resistor bridge changes with the NTC resistor's change. The output of the resistor bridge will be fed into an instrument amplifier LTC2053 to amplify the amplitude of the output. Then the amplified output is fed into an analog-to-digital chip for digitizing. After the digital output is calibrated, this thermal resistor can be used to detect the temperature in real time. The thermal resistor is spherical and is only 1.4 mm in diameter. It is very suitable to be packaged into the convex surface of the polyethylene header.

2.5. Biopotential sensor

The size of the traditional electrode for detecting the biopotential is too large for an implantable capsule to get a minimal

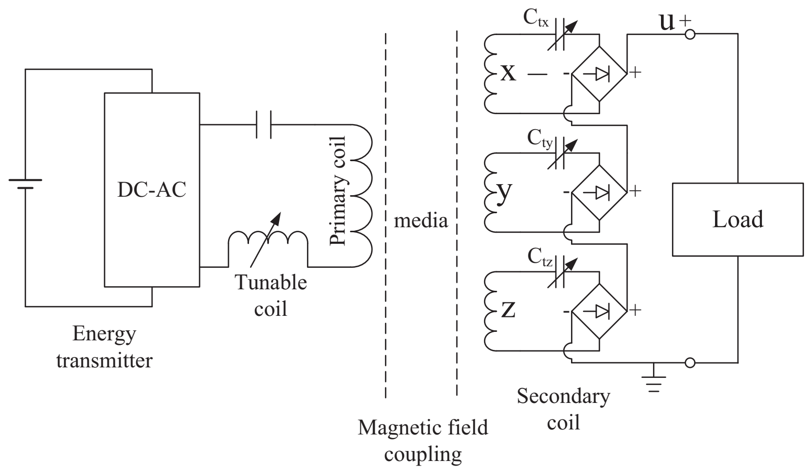


Fig. 10. Schematic of wireless energy transmission system.

invasion during its implantation. The potential electrode for detecting the biopotential should have the good conductivity performance. Moreover the electrode should be soft enough to be implanted into the tissue of an animal. Due to the two requirements, two tiny soft silver wires are designed to detect the biopotential. The amplitude of the biopotential between the two wires is determined by their positions of the two wires. One wire is fixed in the tissue near the heart of the animal and the other is fixed in the tissue near to the front leg of the animal. The voltage difference between the two ends of the two wires is fed into a preamplifier, a filter and an amplifier to get a suitable voltage for digitalizing. Fig. 5 depicts the structure of the biopotential circuitry.

2.6. Circuitry

The circuitry schematic of the implantable capsule is in Fig. 6. The conditioned analog outputs of three sensors should be digitalized before they are sent out through a wireless communication chip. There is an analog converter chip with 16 bits resolution. A PIC microprocessor controls an analog switch to feed the conditioned analog outputs of three sensors into the analog converter chip in sequence. The digitalizing output of the analog converter is read by the PIC microprocessor. The digitalizing outputs of three sensors forms one data packet. The PIC microprocessor sends one data packet out of the animal body through the wireless communication chip IA4420 [23] which is a single chip, low power, multichannel FSK transceiver. The bio-parameter data sent by IA4420 is received by the data logger with an IA4420. IA4420 can work in the 315, 433, 868 and 915 MHz bands. In this design, IA4420 works in 433 MHz band, which covers the frequency band used by the capsule camera such as PillCams [24]. It proves that the wireless signal can be sent out effectively with less degradation by the body of the small animal. It also has many good features for implanted devices such as low power consumption, low cost and compact size.

Fig. 12. Prototype of the wireless energy transmitting system.

2.7. A 3D secondary coil

Wireless energy transmission system is an optimal solution to provide energy to implantable capsule from outside without wire connections. Once the implantable capsule is implanted into the body of a small animal, the position and the posture of the implantable capsule in the animal's body is changeable. In order to enable as many magnetic field lines as possible to travel through the secondary coil in an arbitrary position and posture, the secondary coil is designed to be three dimensional. In a 3D secondary coil, there are three coils whose orientations are perpendicular. There is at least one coil of the three coils to couple the magnet field any time. The 3D secondary coil enables that the energy from outside to be transferred to the implanted capsule effectively. Since it will be

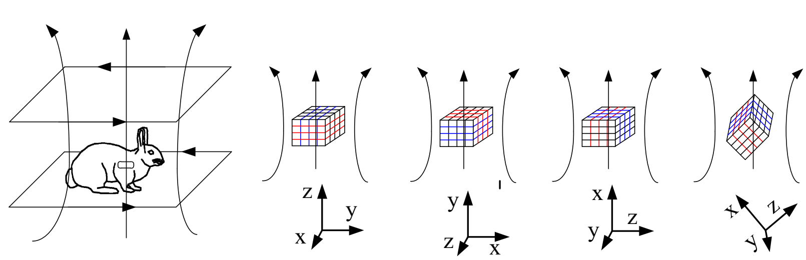
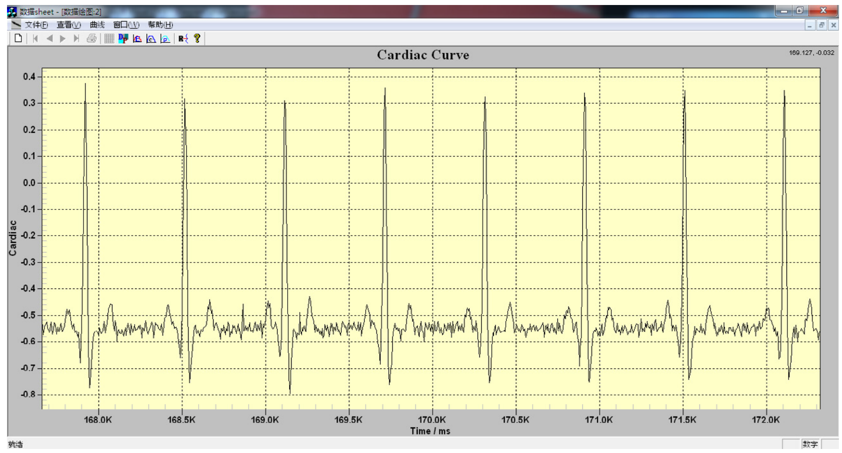
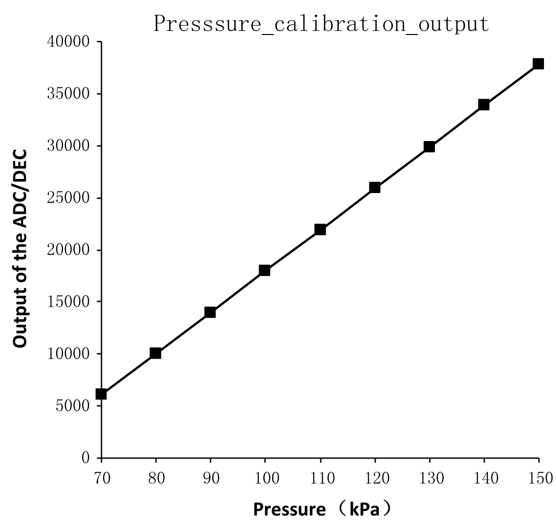


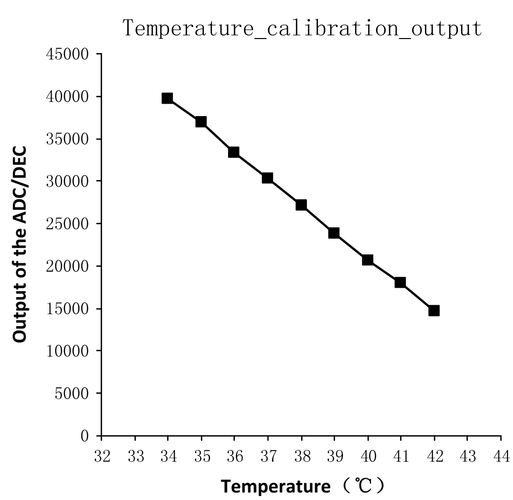
Fig. 11. Coupling link between the primary coil and the secondary coil.



(a) Biopotential sensor calibration output



(b) Pressure sensor calibration output



(c) Temperature sensor calibration output

Fig. 13. Calibration outputs of three sensors.

integrated into the implantable capsule, the size of the 3D secondary coil will be less than 13 mm in diameter. To reduce the alternating current loss in high frequency, litz wires are chosen to be the winding of the 3D secondary coil. In order to strengthen coupling the magnetic field, a cubic ferrite core is designed to be a base. Litz wires are winded along the core's three mutually perpendicular planes. The final structure of the 3D secondary coil is in Fig. 7. Once the 3D secondary coil is in an alternating magnetic field, the induced voltage generates in at least one of the three coils at an arbitrary position and posture. The induced voltage is rectified into a direct current source and the direct current source should be serialized together and fed into all electrical components in the implantable capsule.

The pressure sensor, the temperature sensor, the biopotential sensor, the circuitry and the 3D secondary coil should be packaged into the implantable capsule. The packaged implantable capsule is 13 mm in diameter and 30 mm in length. The actual implantable capsule is in Fig. 8.

2.8. A data logger

A data logger is designed to receive data from the implantable capsule. There are an arm microprocessor (STM32F103), a wireless communication chip (IA4420), an SD card, a LCD display, a time module and several control buttons. The arm microprocessor controls all the other components. The wireless communication chip is designed to receive data from the implantable capsule and transfer data to the microprocessor. The SD card is designed to save the data. The LCD display is designed to depict the three bio-parameters in real time. The arm microprocessor reads the current time from the time module and adds a time stamp to every data packet received from the wireless communication chip. Control buttons select different communication channels in accordance with the implantable capsule. The data in the SD card can be read and the curves can be drawn in the computer for evaluation. Fig. 9 is the schematic of data logger.

2.9. Wireless energy transmission system

Considering that the objective of this research is to detect the bio-parameters of a small animal under its normal state for the long term, it is very important to choose a suitable powering method. There are two imperfections to power the implanted capsule from outside with tiny wires. One will increase the likelihood of infections since the skin is perforated to allow a cable to connect the implanted capsule to the outside for the long term. The other will increase the likelihood of interference with the normal state of the small animal since there is a cable to connect a power source for the long term. Using cell battery for the implanted capsule cannot meet the long term requirement. Compared with other power methods, wireless energy transmission is a promising method. It is a widely used technology to provide energy without wire connections and is an optimal solution to provide energy for the implanted medical device such as artificial heart. The energy is transmitted from the primary coil to the secondary coil through inductive power link. Fig. 10 is the schematic of wireless energy transmission system. DC current is inverted into alternating current through the DC–AC inverter. As the alternating current flows through the primary coil, the alternating magnetic field generates. The secondary coil couples the magnetic field and in turn induces alternating voltage in itself. The alternating voltage is rectified into direct power source. The direct power source is fed into all electrical components of the implantable capsule.

As shown in Fig. 10, there is a tunable coil in the energy transmitter. The tunable coil is designed to get the resonance from the energy transmitter. The frequency of the alternating current fed into the primary coil is determined by the frequency of the driving square wave of the DC–AC inverter. The frequency of the circuitry is determined by the following equation.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

In the equation, L is the total inductance and C is the total capacitor of the circuitry. The tunable coil is designed to change the total inductance of the energy transmitter to get the resonance in the energy transmitter.

There are three tunable capacitors to get the resonance in the energy receiver. After the 3D secondary is winded, every coil in the 3D secondary coil should be configured with a suitable capacitor to get the resonance according to the frequency of the energy transmitter. In order to get the suitable capacitor, an impedance analyzer is used to implement the configuration.

The 3D secondary coil has 3 coils whose orientations are perpendicular with each other. This structure is helpful to simplify the design of the primary coil. The primary coil is designed to be only one dimension. When the magnet field is generated by the primary coil, the magnet field penetrates the 3D secondary coil as shown in Fig. 11. At least one coil effectively couples the magnet field in an arbitrary position and posture. An induction voltage generates in the coupled coil of the secondary coil. Then the power is transferred from the outside to the secondary coil through the coupling link between the primary coil and secondary coil. In order to reduce alternating current loss of the primary coil in high frequency, litz wires are chosen to be the winding of the primary coil. To keep the normal state of the animal, the wind of the primary coil is along the cage of the animal. In this design, the magnetic field generates along the animal's cage. The animal stays freely in the cage and the magnetic flux lines cut cross the 3D coil in the body of the animal. The induced alternating voltage generates in the 3D secondary coil meanwhile the animal is under its normal condition. Fig. 12 shows the actual animal's cage, the primary coil and the energy transmitter.

2.10. Sensor calibration

Before the prototype is used in vivo experiment, three sensors are calibrated in simulation input. A function generator (Agilent 33120A, Agilent Corporation) is used to calibrate the cardiac sensor of the prototype. It generates a cardiac function. The amplitude of the cardiac function is degraded to millivolt level to meet the input of the biopotential sensor. A pressure conditioner (DHI 7250, Fluke Corporation) is used to calibrate the pressure sensor of the prototype. A temperature sensor (5618B, Fluke Corporation) is used to calibrate the temperature of the prototype. Fig. 13 shows the outputs of three sensors.

As shown in Fig. 13, the biopotential sensor, the pressure sensor and the temperature sensor can detect the inputs respectively and get linear amplification. The calibration outputs prove that the three sensors can be used to detect the biopotential input, the pressure and the temperature.

3. Results

The prototype of the implantable radio-telemetry was conducted in vivo experiment. A rabbit was chosen to be a subject. The catheter of the pressure was inserted into the aortic near the

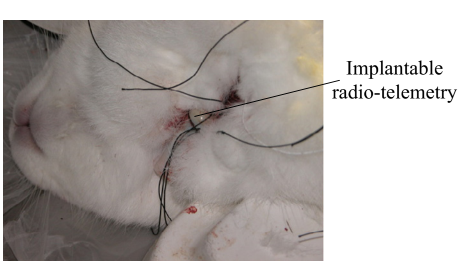
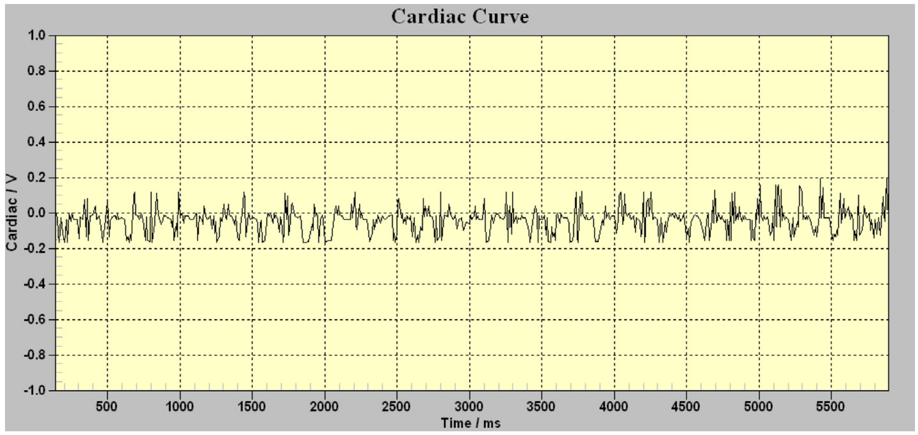
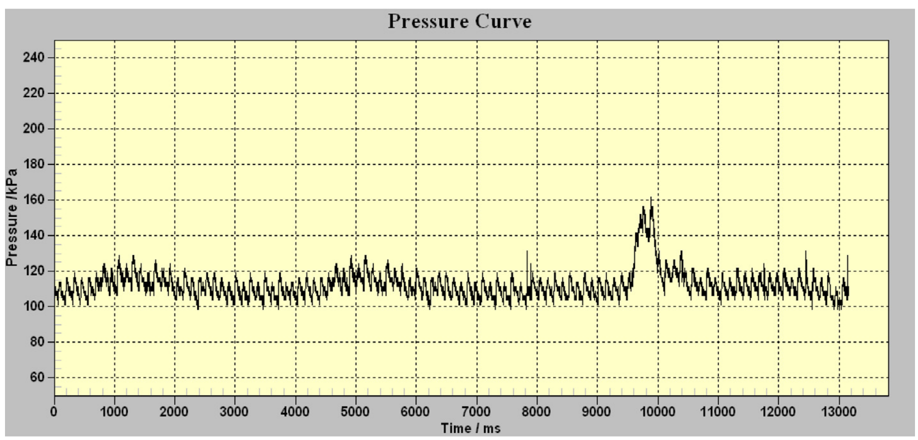


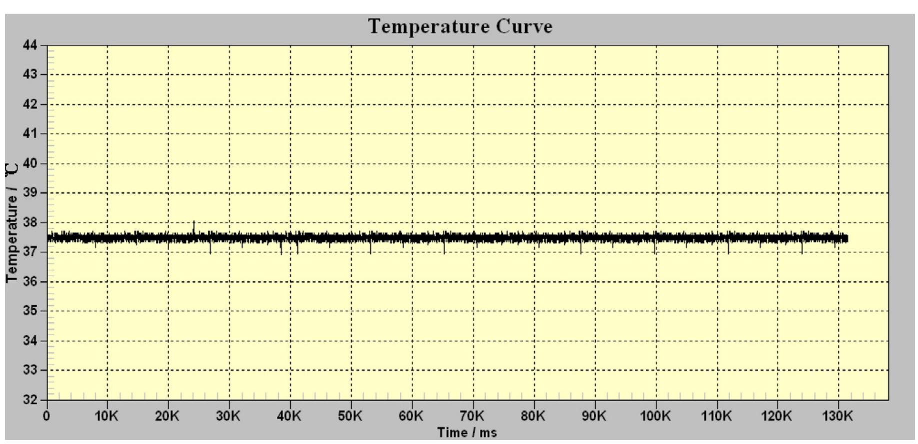
Fig. 14. The procedure of the implantable radio-telemetry.



(a) biopotential curve



(b) Pressure curve



(c) Temperature curve

Fig. 15. In vivo experiment results.

front leg of the rabbit. One end of one tiny silver wire was placed in the muscle near to its heart. The other end of the other tiny silver wire was placed in the muscle near to the front leg. The farther of the two ends between the two tiny silver wires is, the stronger the biopotential signal is. Fig. 14 shows the implantable radio-telemetry during the implantable procedure.

Fig. 15 shows the biopotential curve, the pressure curve and the temperature curve of the received data from the implantable radio-telemetry.

As shown in Fig. 15, the biopotential, the blood pressure and the temperature can be detected. Plot a in Fig. 15 proves that biopotential between the heart and the leg of the rabbit is very close to the ECG. Plot b in Fig. 15 depicts the blood variation of the aortic of the rabbit. Plot c in Fig. 15 shows the body temperature of the rabbit. The temperature is detected from the body of the rabbit and kept stable. In this design the three above curves were drawn according to the raw data. Considering that the raw data is received from wireless communication, there is few noises in the raw data. The

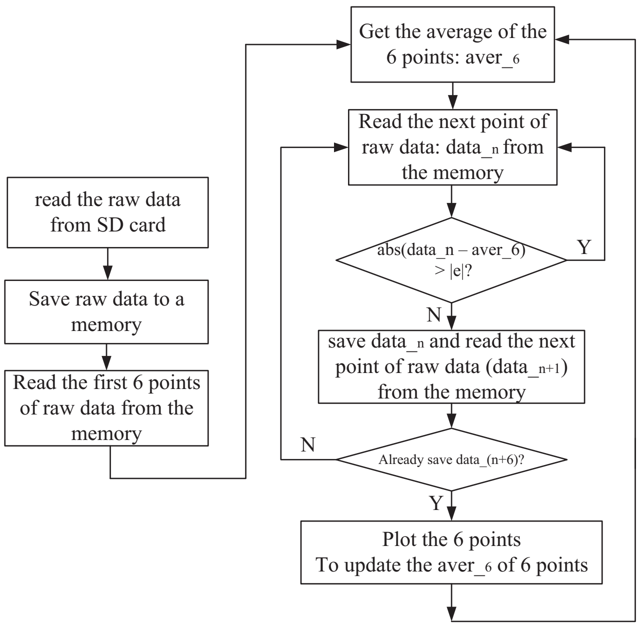


Fig. 16. Algorithm of filtering.

place of the data logger should be more close to the subject animal to get fewer noises. In order to remove the noises in the raw data, a moving average based on a moving window is proposed. The detected parameters data is continuous and relative to time. The variations of the detected parameters are continuous. The size of every package during wireless communication is 6 points. The moving average is from 6 points. The next data is compared with the average to eliminate the noise. Once another 6 points are valid, the average should be updated by the 6 valid points. The algorithm is as follows (see Fig. 16).

The results in Fig. 15 prove that the performance of the radio-telemetry meets the expected requirements.

4. Discussion

This paper investigates a novel implantable radio-telemetry system to detect the three bio-parameters of a small animal simultaneously under its normal condition for the long term. The design of this system is investigated thoroughly. The prototype system is tested in vivo experiment. The experiment results demonstrate that this system meets the expected requirements of the system. Future research work will focus on vivo experiments for confirming the long-term bio-compatibilities between the implantable radio-telemetry and the tissues.

Acknowledgment

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References

[1] Peng C, Chaimanonart N, Ko WH, Young DJ. A wireless and batteryless 10-Bit implantable blood pressure sensing microsystem with adaptive RF powering for real-time laboratory mice monitoring. IEEE J Solid-State Circuits 2009;44(12):3631–44.
[2] Peng C, Ko WH, Young DJ. Wireless batteryless implantable blood pressure monitoring microsystem for small laboratory animals. IEEE Sens J 2010;10(2):243–54.
[3] Young DJ. An RF-powered wireless multi-channel implantable bio-sensing microsystem. In: Presented at the 32nd annual international conference of the IEEE EMBS; 2010. p. 6413–6416.
[4] Park M, Kang H, Huh Y, Kim KC. Cuffless and noninvasive telemetry mean arterial pressure measurement by physiological characteristics and applied pressure. In: Presented at proceedings of the 28th IEEE EMBS annual international conference; 2006. p. 6418–6421.
[5] Fiala J, Bingger P, Foerster K, Heilmann C. Implantable sensor for blood pressure determination via pulse transit time. In: Presented at IEEE SENSORS 2010 conference; 2010. p. 1226–1229.
[6] Zhang Yuan-Ting, Xiang XY, Poon CCY. The evaluation of nodes of body sensor networks: wearable blood pressure measuring devices. In: Presented at proceedings of the international workshop on wearable and implantable body sensor networks (BSN'06); 2006. p. 161–64.
[7] Shriram R, Wakankar A, Daimiwal Nivedita, Ramdasi D. Continuous cuffless blood pressure monitoring based on PTT. In: Presented at 2010 international conference on bioinformatics and biomedical technology; 2010. p. 51–5.
[8] Gamini DS, Shastry PN. Design and measurements of implantable chip radiator and external receptor for wireless blood pressure monitoring system. In: Presented at microwave symposium digest; 2009. p. 1681–1684.
[9] Nag S, Sharma DK. Wireless E-Jacket for multiparameter biophysical monitoring and telemedicine applications. In: Presented at proceedings of the 3rd IEEE-EMBS international summer school and symposium on medical devices and biosensors MIT; 2006. p. 40–4.
[10] Riistama J, Vaisanen J, Heinisuo S, Lekkala J, Kaihilahti J. Evaluation of an implantable ECG monitoring device in vitro and in vivo. In: Presented at proceedings of the 29th annual international conference of the IEEE EMBS; 2007. p. 5703–5706.
[11] Tomasic D, Ferek-Petric B, Brusich S, Accardo AP. Acute animal and human study of a tensiometric pacing lead sensor based on triboelectricity. IEEE Trans Biomed Eng 2011;58(8):2290–6.
[12] Wenhui X, Guozheng Y, Wenxin W. Wireless energy transmitting system for capsule endoscope. In: Presented at the 9th international conference on electronic measurement & instruments; 2009. p. 1820–1824.
[13] RamRakhyani AK, Mirabbasi S, Chiao Mu. Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants. IEEE Trans Biomed Circuits Syst 2011;5(1):48–64.
[14] Russell D, McCormick D, Taberner A, Nielsen P, Hu P, Budgett D, et al. Wireless power delivery system for mouse telemeter. In: Presented at biomedical circuits and systems conference; 2009. p. 273–76.
[15] Dissanayake TD, Hu AP, Malpas S, Bennet L, Taberner A, Booth L, et al. Experimental study of a TET system for implantable biomedical devices. IEEE Trans Biomed Circuit Syst 2009;3(6):370–8.
[16] Si Ping, Hu AP, Malpas S, Budgett D. A frequency control method for regulating wireless power to implantable devices. IEEE Trans Biomed Circuit Syst 2008;2(1):22–9.
[17] Dowling RD, Etoch SW, Stevens KA, Johnson AC, Gray Jr LA. Current status of the AbioCor implantable replacement heart. Ann Thoracic Surg 2001;71(3 suppl):147–9.
[18] Transcutaneous Energy Transfer System with Vibration Inducing Warning Circuitry, by ABIOMED INC. Patent US 20120154143 A1. <http://www.google.com/patents/US20120154143>; 28 June, 2012.
[19] Transcutaneous Energy Transfer System with Multiple Secondary Coils, by ABIOMED INC. Patent US 20120157753 A1. <http://www.google.com/patents/US20120157753>; 28 June, 2012.
[20] A Compact Battery and Controller Module for a Transcutaneous Energy Transfer System, By ABIOMED INC. Patent US 20120157754 A1. <http://www.google.com/patents/US20120157754>; 28 June, 2012.
[21] Method and Apparatus for Accurately Tracking Available Charge in a Transcutaneous Energy Transfer System, By ABIOMED INC. Patent: US 20120157755 A1. <http://www.google.com/patents/US20120157755>; 28 June, 2012.
[22] Transcutaneous Energy Transfer Coil with Integrated Radio Frequency Antenna, by ABIOMED INC. Patent US 20120265003 A1. <http://www.google.com/patents/US20120265003>; 18 October, 2012.
[23] Silicon Labs Inc. <http://www.silabs.com/products/wireless/ezradio/pages/default.aspx>.
[24] Thoné J, Radiom S, Turgis D, Carta R, Gielen G, Puers R. Design of a 2 Mbps FSK near-field transmitter for wireless capsule endoscopy. Sens Actuators, A 2009;156(1):43–8.