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Novel wireless measurement system of pressure dedicated to *in vivo* studies

DOI 10.1515/cdbme-2016-0030

Abstract: This paper reports on the development of a wireless system to monitor the thoracic cavity pressure in mammals. This project seeks to open a new field using the radio frequency (RF) technology in the studies of the interaction between breathing and locomotion in mammals. Furthermore, this study embodies the first step to develop a method of telemetry and remote monitoring based on implantable devices. In addition, it can be modified with other sensors to measure different physiological parameters.

Keywords: implantable device; locomotor-respiratory coupling; pressure sensor; wireless.

1 Introduction

Over the last 30 years, implantable wireless devices have been used in many applications, becoming valuable biomedical tool for telemetry *in vivo*. Based on this approach, the purpose of this paper is to present an implemented wireless communication system, as an alternate method to study the interaction between locomotion and breathing in mammals. The core system consists of a transmitter and a receiver. In addition, this project seeks for a versatile and reliable telemetry system for future applications, such as monitoring and collecting data of other physiological parameters.

The remainder of the paper is organized into five sections: Section 2 gives a brief review on the coupling of locomotion and breathing in mammals, an overview of implantable pressure devices, and describes the challenges of their design. Section 3 presents the description of the system developed. Experimental results concerning the system are reported in Section 4. Finally, Section 5 presents the discussion and conclusions.

2 Overview of the interaction between the breathing and locomotion in quadrupeds mammals

Human being and their phylogenetic relatives (quadrupedal and bipedal mammals) use the sucking type of breathing. As well for a functio-morphological understanding of that kind of breathing as for the development of technical devices to study thoracal mechanics in human beings, median-sized quadrupedal mammals form a reference.

In literature, several theories have been proposed to explain mechanical interactions between locomotion and breathing in mammals. Bramble and Carrier [1] made a valuable study on quadruped mammals. This research describes the differences between horse and human locomotion cycles in states as trotting and galloping. These studies introduce the concept of Locomotor-respiratory coupling (LCR).

Alexander [2] in a study on wallabies and horses described three coupling mechanisms for running and hopping particularly in mammals: (1) The thorax receives an impact when the forelimbs hit the ground, (2) lumbar flexion considering the contraction in the abdominal muscles and, (3) the inertial movements of the visceral mass in each stride called the “visceral piston”. In recent years, researches on the locomotor-respiratory coupling considered modern technology to support these studies. One example was presented by Simons [3], a hypothesis of visceral displacement in rabbits was developed, based on results of synchronized videographic, cineradiographic and pneumotachographic measurements.

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2.1 RF implantable devices and design challenges

Some consideration must be taken into account in the design of implantable devices. The main item to be considered is the choice of a radio frequency (RF) band for the communication. The Federal Communications Commission (FCC) established the Industrial, Scientific, Medical (ISM) bands with the basic frequency of 433 MHz. These bands have become a reliable alternative for short-range and low power communications systems.

On the other hand, other requirement should be considered during the design of implantable devices, such as minimal size and weight, low power consumption and minimization of pain sensation and discomfort to the host. Furthermore, whereas advances in semiconductor and microelectromechanical systems have developed rapidly in recent decades, the antenna and battery size are still a challenge to overcome. The system presented here was designed based on the implantable device features mentioned above, and the commercial components were selected mainly considering the low power consumption and the high reliability, including a pressure sensor accredited for possible future medical applications.

Nowadays, any physiological parameters could be monitored by a telemetry tool like an implantable device. In particular, for pressure monitoring *in vivo*, researchers have proposed various methods for different applications. Tan et al.[4] developed a pressure device for use in short-term urological studies and patient monitoring. Lin et al. [5] also developed a device to measure pressure changes in the upper urinary tract per degree of obstruction. It is worth mentioning that all the devices presented have the flexibility to connect other sensors, as Valdastri [6] suggested.

This work also takes into account the possibility to connect more pressure sensors in parallel or another type such as an accelerometer to measure diaphragm velocity and acceleration during breathing.

3 Development of wireless system

The structure of the system is based on three basic circuits ensuring proper functioning. This structure is implemented for the transmitter and receiver each. The main component is a microcontroller, which manages and controls all the data flow via the wireless interface. The second component is the transceiver; this module manages the radio frequency communication, allowing data transmission and reception. In the system presented, the design of the device includes a microcontroller and a transceiver coupled in the same chip called System on Chip (SoC). It allows programming the RF communication and the data acquisition in the same chip.

Particularly, the transmitter contains a sensor signal conditioner (SSC), the main function of which is to adapt the sensor signal before microcontroller processing. The SSC in the transmitter is a ZSC31014; the main advantage is the internal CMOS circuit for highly accurate amplification and analog to digital conversion of the signals of the differential piezoresistive sensor. The data output is transmitted to the SoC by SPI channel as is shown in Figure 1.

Finally, the piezoresistive pressure sensor belongs to the series NPC-100, designed specifically for medical applications. Further, the catheter is wrapped with a biocompatible silicone Nusil MED-4011.

The evaluation board (EB) SmartRF®04EB with a RF module based on the SoC was chosen as a receiver. Further, this EB in connected with the PC, where the Graphic unit interface (GUI) implemented in Matlab®(R2013a, The MathWorks, Inc.) decodes and shows the data received.

As was mentioned above, the focus of this paper is on the proper functioning of the wireless system with pressure data acquisition as a first step of a future implantable device. For practical operation, this system also includes other connectors for power supply and additional headers to monitor the principal signals. All characteristics of the transmitter are illustrated in Figure 1 and 2.

3.1 Electrical features of the transmitter

The power supply board hosts mainly the coin cell lithium battery (CR1216) of 3.0 Vdc. Additionally, it includes a reed switch, activated by an external electromagnetic field. Thus, the devices inside the thoracic

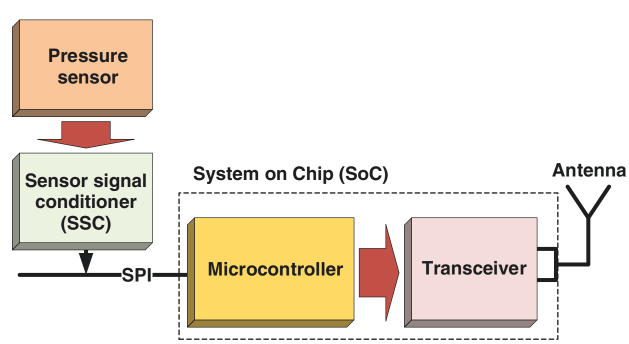

Figure 1: Transmitter blocks diagram.

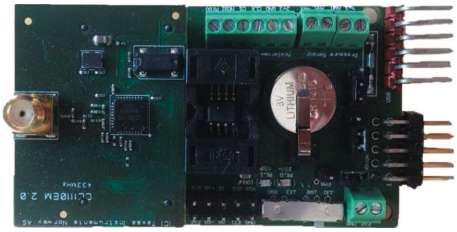

Figure 2: Developed module of the transmitter.

cavity can be switched on exclusively during the data transmission.

The total current consumption of the device in the transmission mode is around 35 mA. This value references when the device is programmed at 10 dBm. The total power consumption with 3 Vdc. of power supply is 1068 mW.

4 Experimental results and analysis

The main goals in our experiments were to test mainly three characteristic of our system: (1) The performance of the pressure sensor catheter, (2) the data wireless communication (protocol) between the transmitter and the receiver, (3) the graphic unit interface connected with the receiver, showing and processing the data in the computer in real time.

To test the sensor catheter and the transmitter, we used a container filled with a bio-material such as pork meat. Externally, a rubber bulb was connected to change the pressure inside the container. The experiment structure can be seen in Figure 3.

In addition, the transmitter was located outside the container and sent the pressure data wirelessly using the frequency of 433 MHz. Finally, a digital manometer measured the pressure inside the container to provide a pressure reference. Figure 4 shows the pressure sensor and the silicone catheter. The wires were connected to the transmitter through a flexible medical tube (Tygon ND 100-65), which protected and isolated the wires from the material inside the container.

The first results confirmed the sensor linearity mentioned in the data sheet. This is important to consider due to the demand that the system needs to assure that the sensor is linear in the pressure range required (–40 mmHg to +40 mmHg), as shown in Figure 5. This test was made in the container without any material, the sensor was located on the bottom of the container and the data was compared with that of the manometer. Figure 6 illustrates the second test, the container was filled with pork meat, and the sensor was placed inside the meat. To generate pressure variations inside the container, via the bulb we introduced small amounts of air. The hermetic lid released the air slowly and the digital manometer measured the data in real time. On the other hand, the sensor measured the pressure changes and the transmitter processed and sent the data wirelessly. The communication between the

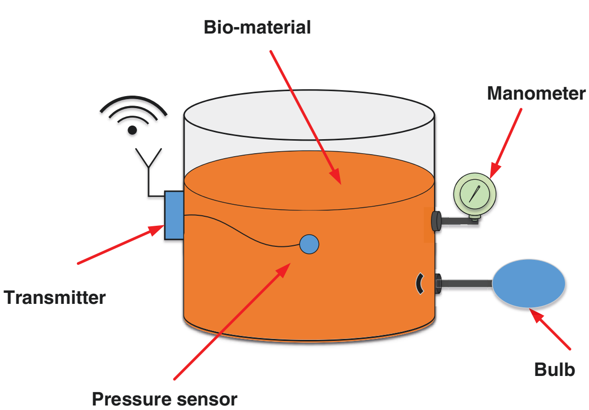

Figure 3: Graphical illustration of experimental test

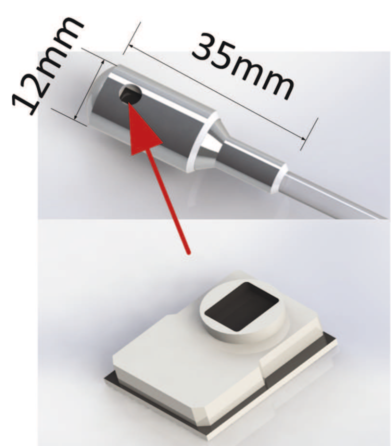

Figure 4: Piezoresistive sensor NPC-100 and catheter.

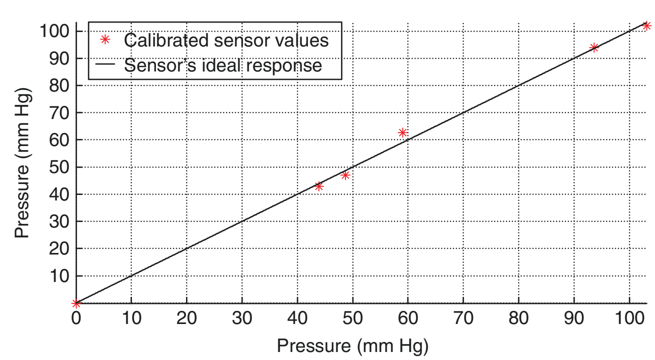

Figure 5: Calibrated values of the sensor compared with the sensor ideal response.

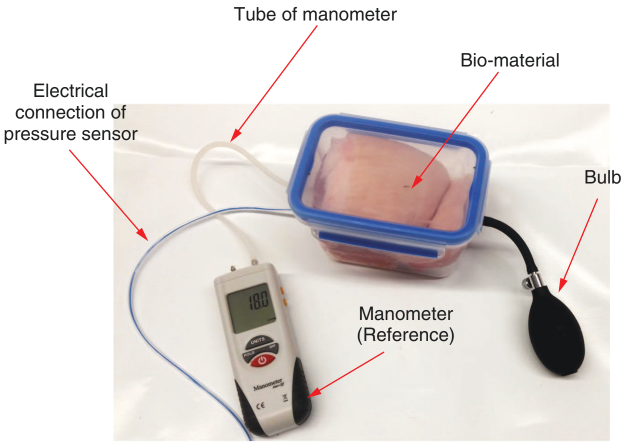

Figure 6: Implemented test bench.

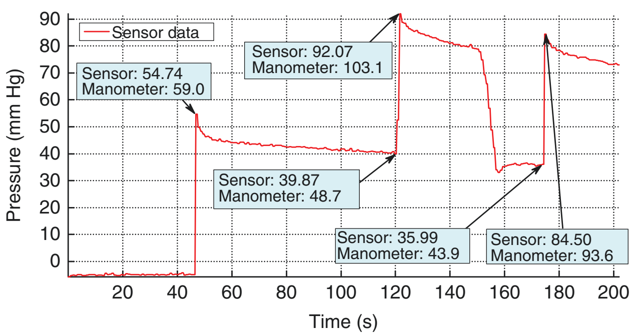

Figure 7: Response of the sensor after an air impulse inside the container. Reference is the m pressure reported by the manometer.

transmitter and receiver worked without any interference and continuously.

Figure 7 presents the rapid pressures changes detected by the sensor. The differences between the data measured by the manometer and the sensor basically responds to two factors: (1) the calibration parameter of the sensor needs to be adjusted, (2) the digital value of the manometer was measured visually.

5 Discussion and conclusion

In summary, we developed a wireless device to measure in future the pressure *in vivo* within the thoracic cavity of a medium size quadruped mammal. Next step has to be an *in vivo* evaluation of its functions in animal experiments.

The system was designed considering the technical specification of implantable devices, such as low power consumption, standard communication protocols, biocompatible material to reduce any kind of infection in the animal and the flexibility to extend the device using other sensors.

The RF technology used in this application, responses to the commercial frequency range (433 MHz) for medical devices according to the international standards bands (ISM). However, the device supports also the frequency band for implantable devices.

Concerning the experiments and results, we could test the sensor performance in a simulated bio-environment. The linearity of the NPC-100 sensor guarantees a correct measurement of the pressure. However, it is necessary to test other sensor with similar technical conditions in order to make more reliable devices. Finally, this device was developed to measure pressure. However, it can be expanded to additional sensing modalities, such as accelerometry to measure the position and speed of the diaphragm during breathing, or a thermistor for measurements of thoracic temperature.

Acknowledgment: The authors of this paper would like to thank Dr.-Ing. Ralf Stephan and his team in the Microwave Technology Group of Technische Univesität Ilmenau for the help provided during this work. We also thank the Peruvian institution "Fincyt" for the financial support of the Peruvians researchers.

Author's Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to animal use complies all the relevant national regulations and institutional policies for the care and use of animals.

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