Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Intra-Abdominal Pressure Monitoring by Surface Bioimpedance Estimation

To cite this article: M David *et al* 2019 *J. Phys.: Conf. Ser.* **1272** 012013

Intra-Abdominal Pressure Monitoring by Surface Bioimpedance Estimation

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Abstract. Intra-abdominal hypertension (IAH) is produced by an accumulation of liquids in the abdominal cavity. In such case, the intra-abdominal pressure (IAP) increases, and the abdominal wall is stretched. Previously, an inverse correlation between the abdominal wall's thickness and the IAP was theorized. Since the abdominal wall can be modelled as a compound of parallel dielectric slabs, changes in their width have direct effect on its overall bioimpedance. Numerical analyses of the bioimpedance as a function of the compression of the abdominal wall were verified by an in-situ trial on a porcine model. In this work, we present the project of a medical grade bioimpedance spectroscopy system along with a summary of our findings.

1. Introduction

Intra-abdominal hypertension (IAH) affects at least one in every two patients in intensive-care units (ICU) [1]. IAH is defined as the pathological increase of Intra-Abdominal Pressure (IAP) and is directly associated with augmented morbidity and mortality [1-4]. IAP above 10 mmHg affects blood flow and organ perfusion. When high IAP is prolonged, abdominal decompression by surgical procedures is usually indicated [5-8]. Thus, the importance of continuous monitoring of IAP in critical patients is evident [3,4]. For such continuous measurement of IAP, several techniques have been proposed [5], spanning from direct measurement to non-invasive indirect monitoring.

Continuous direct measurement of IAP is intrinsically invasive. A system based on a solid microtransducer was proposed in 2007 by Pracca et al. [9]. Minimally invasive indirect measurements of IAP are performed using Kron's intravesical catheter as published by Iberti [10] and Cheatham [11], which, in 2013, was officially recommended by the World Society of the Abdominal Compartment Syndrome, as the standard [12].

Bioimpedance continuous indirect non-invasive IAP monitoring was originally proposed by our group [13,14]. Firstly, we developed a numerical model of the bioimpedance of the abdominal wall [13] and verified it on a pilot run on a porcine model [14], proving the feasibility of continuous monitoring of IAP using non-invasive bioimpedancemetry. In the present work we summarize our findings and describe the development of a medical grade low-cost bioimpedance measuring system based on AD5933 from Analog Devices.

2. Materials and methods

2.1. Structure of the abdominal wall

Based on mechanical properties of soft tissue [15,16], theory predicts a correlation between IAP and abdominal wall thickness [13]. These changes in the abdominal wall thickness will affect its electromagnetic characteristics over a broadband spectrum (from few kHz up to MHz); therefore, a link between IAP and the electromagnetic responses can be made.
The abdominal wall is mainly formed by five main tissue layers [17-19]:

1. Skin and subcutaneous tissue
2. Fascia
    a. Camper's fascia (fat)
    b. Scarpa's fascia (fibrous)
3. Muscle
4. Fascia transversalis
5. Peritoneum

Mechanical stress, such as IAP, may compress or decompress abdominal wall's soft tissues [13-16]. Therefore, an increase in IAP will cause compression of the abdominal wall, and its thickness will consequently decrease.

2.2. Bioimpedance modelling of the abdominal wall

The combined complex dielectric coefficient ε_T^* of two parallel biological layers with frequency-dependent properties can be considered a simple case of interfacial polarization (Maxwell-Wagner polarization [20,21]) when subject to an external electric field. The overall dielectric coefficient ε_T^* is described by equation (1) [22]:

$$\varepsilon_T^*(\omega) = (d_1 + d_2) \cdot \frac{\varepsilon_1^*(\omega)\varepsilon_2^*(\omega)}{d_2\varepsilon_1^*(\omega)+d_1\varepsilon_2^*(\omega)} \quad (1)$$

where d_1, ε_1^*, d_2, and ε_2^* are the width and complex dielectric coefficient of each layer, respectively.
The bioimpedance measured over the abdominal wall depends upon the overall dielectric coefficient and its separate layers components d_1, ε_1^*, d_2, and ε_2^* [20,23]. Due to the IAP-caused compression of the abdominal wall, it follows that the surface bioimpedance is a function of IAP [24,25]. Based on results published by Gabriel et al. [21,22], we estimate that maximum bioimpedance sensitivity to width changes can be found at frequencies between 80 kHz and 200 kHz [15].

2.3. Verification on sus scrofa domesticus

As reported previously [14], the procedure was performed on a cadaver of female s*us scrofa domesticus* (domestic pig), weighing 49.9 kg [14] in accordance with ethical standards. The cadaver was put in supine position. Over the *linea alba*, caudal and next to the umbilicus, a trocar was inserted across the abdominal wall, reaching the abdominal cavity. Through the trocar, the cavity was inflated to pressures of 4, 5, 6, 7, 8, 10, 12 and 14 mmHg. The whole procedure was done within one hour of the subject being sacrificed. The induced IAP was kept constant for 15 seconds before performing the measurements. The room temperature was held stable at 20 ◦C.
Two dry rectangular stainless-steel electrodes (5 cm length, 2 cm width), separated 0.4 cm from each other were placed over the abdomen of the subject. The electrodes were placed 7 cm caudal from the umbilicus and 7 cm left from the *linea alba*, and the surface electrical bioimpedance was measured in order to monitor the changes in the dielectric characteristics of the abdominal wall. Table 1 and Figure 1 present the absolute impedance values at 99.8 kHz, as reported by our group in [14]. Note that 99.8 kHz is the frequency at which the maximum sensitivity was achieved.

IOP Conf. Series: Journal of Physics: Conf. Series **1272** (2019) 012013 doi:10.1088/1742-6596/1272/1/012013

Table 1. Absolute impedance values for different IAP at 99.8 kHz

IAP [mmHg]	$\lvert Z_{AWTh} \rvert$ [Ω]
4	8383±42
5	8222±41
6	8151±41
7	8139±40
8	8138±40
10	8118±40
12	8116±40
14	8115±40

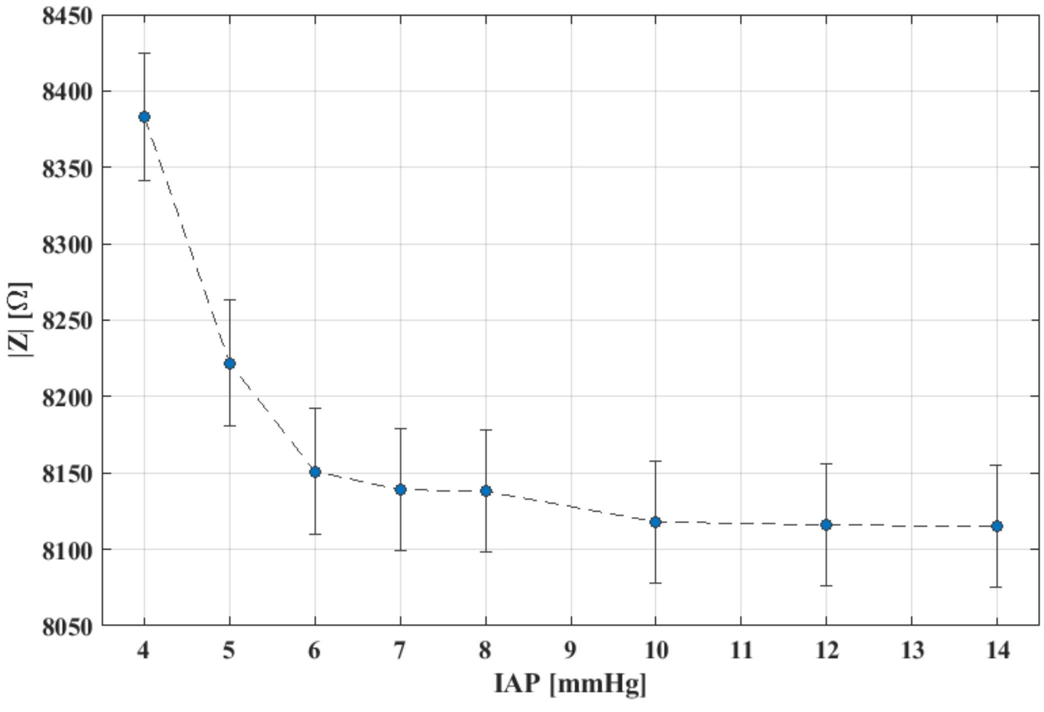

Figure 1. Absolute impedance values vs intra-abdominal pressure at 99.8 kHz

3. A medical grade bioimpedance measurement system

In order to run the first set of clinical trials, we designed an easy-to-use medical grade, low-cost portable and compact bio-impedance spectroscopy system (from 5 kHz to 100 kHz), based on AD5933. The

device complies with IEC 60601-1 standard on isolation breakdown and leakage currents and with IEEE-C95 for exposure to electromagnetic fields in controlled environments. To the best of our knowledge, no such open source and low-cost hardware has been previously developed or published.
Our design required a Linux based microcontroller able to communicate by means of I^2C. The software developed for the device was coded in C++, and has the following workflow:

1. The user is asked to connect the calibration impedance.
2. Calibration parameters are calculated.
3. The user is asked to place the electrodes on the abdomen (over the *linea alba* [14]), and to connect them to the device.
4. The system performs 20 consecutive measurements, and calculates the average and standard deviation for each frequency (500 evenly distributed from 5 kHz up to 100 kHz).
5. The results are stored in CSV files and presented graphically on screen.

From laboratory tests we have seen that the system has a relative accuracy of about 1% (when calibration was done in accordance to AD5933 datasheet).

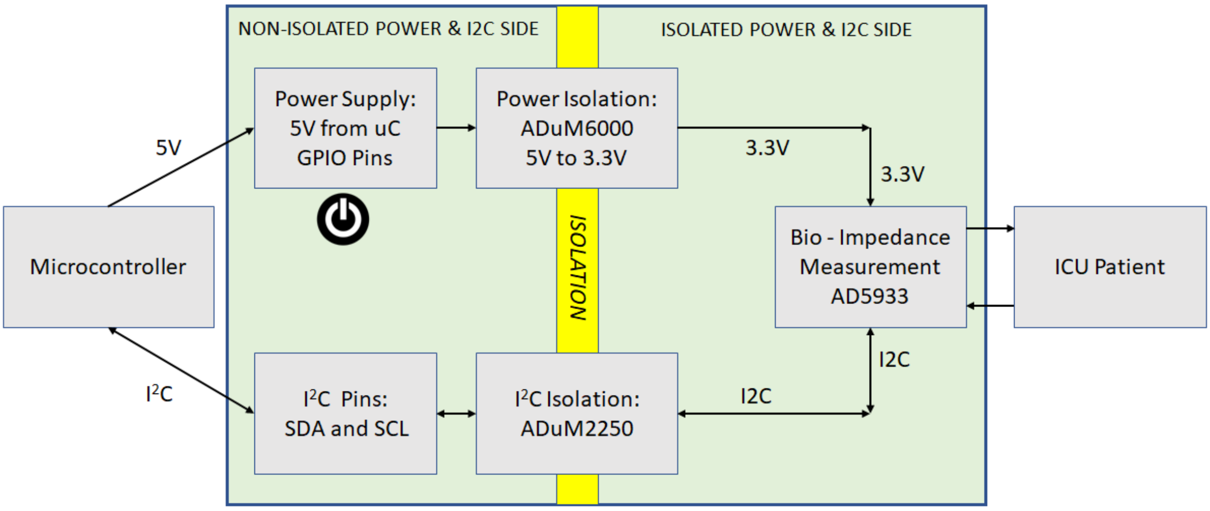

Figure 2. Schematic representation of the system

Figure 2 presents the schematic representation of the whole system. The board has two sides: the non-isolated side is connected to the microcontroller which is powered by the hospital grid, and the isolated side where the AD5933 (to which the applied parts are connected) resides. The ADuM6000 voltage isolator and ADuM2250 I^2C isolator are used for isolation and withstand the barrier between them, and are certified (according to Analog Devices) to comply with IEC-60601-1.

4. Discussion and conclusions

Our hypothesis that coplanar electrodes can measure the changes in the overall impedance of the abdominal wall was proven correct by the trials on *sus scrofa domesticus*. Results show a solid correlation between IAP and the bioimpedance measurements, for pressures from 4 to 7 mmHg [14]. The reduction of sensitivity for higher pressures (from 8 to 14 mmHg) requires further research on the optimization of electrode placement over the abdomen. However, the current state-of-the-art developed by our group, might introduce a novel IAP monitoring technique for patients in intensive care.
We conclude that the system we developed may be the precursor of simple clinical IAP monitoring devices, the use of which may prevent about 50% of the ICU patients from having to use Kron's intravesical catheter, thus avoiding their intrinsic drawbacks.

IOP Conf. Series: Journal of Physics: Conf. Series **1272** (2019) 012013 doi:10.1088/1742-6596/1272/1/012013

Ethical statements

The experiments and the preparations were done according to the ethical considerations of The Center of Innovative Surgery of Hadassah Medical Center in Jerusalem, Israel, and local regulations (the strictest among them).

Acknowledgements

The authors warmly thank David Kushnir, Chief Operation Officer at The Center of Innovative Surgery of Hadassah Medical Center in Jerusalem, Israel.

Support for this research was granted by the Lev Academic Center: Internal Grant 5777/8.

Analog Devices generously provided us with free samples of its ICs that we used in this project.

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