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 \( \varepsilon^*_T \) 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 \( \varepsilon^*_T \) is described by equation (1) [22]:

\[
\varepsilon^*_T(\omega) = (d_1 + d_2) \cdot \frac{\varepsilon^*_1(\omega)\varepsilon^*_2(\omega)}{\varepsilon^*_1(\omega) + d_1\varepsilon^*_2(\omega)}
\]

where \( d_1, \varepsilon^*_1, d_2, \) and \( \varepsilon^*_2 \) 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 \( d_1, \varepsilon^*_1, d_2, \) and \( \varepsilon^*_2 \) [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 sus 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.
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 I²C. 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 I²C 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.
Ethical statement
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).

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References
[1] De Waele JJ, De Laet I, Kirkpatrick AW and Hoste E. Intra-abdominal Hypertension and Abdominal Compartment Syndrome. Am J Kidney Dis. 2011 57 159-69.
[2] Malbrain ML et al. Results from the International Conference of Experts on Intra-abdominal Hypertension and Abdominal Compartment Syndrome. I. Definitions. Intensive Care Med. 2006 32 1722-32.
[3] Sugrue M, Bauman A, Jones F, Bishop G, Flabouris A, Parr M, Stewart A, Hillman K and Deane SA. Clinical examination is an inaccurate predictor of intraabdominal pressure. World J Surg. 2002 26 1428-31.
[4] Malbrain ML et al. The role of abdominal compliance, the neglected parameter in critically ill patients a consensus review of 16. Part 1: definitions and pathophysiology. Anaesthesiol Intensive Ther. 2014 46 392-405.
[5] Malbrain ML et al. The role of abdominal compliance, the neglected parameter in critically ill patients a consensus review of 16. Part 2: measurement techniques and management recommendations. Anaesthesiol Intensive Ther. 2014 46 406-32.
[6] David M, Pracca F and Simini F. Non-invasive negative pressure system to treat abdominal hypertension. In: Jobbágy Á (ed.): 5th European IFMBE Conference. 37. Budapest: Springer Science & Business Media 2011 211−4.
[7] David M, Geido D, Pracca F, Sánchez G, Simini F and Zoppolo C. Negative pressure device for intraabdominal pressure reduction. J Phys Conf Ser 2007 90.
[8] Pracca F, Biestro A, Gorrassi J, David M, Simini F and Cancela M. ABDOPRE: an external device for the reduction of Intra-Abdominal Pressure. Preliminary clinical experience. Rev Bras Ter Intensiva 2011 23 238–41.
[9] Pracca F, Biestro A, Moraes L, Pupo CB, Calvo SM, Gorrasi J and Cancela M. Direct measurement of intra-abdominal pressure with a solid microtransducer. J Clin Monit Comput. 2007 21 167-70.
[10] Iberti TJ, Lieber CE and Benjamin E. Determination of Intra-Abdominal Pressure using a transurethral bladder catheter: clinical validation of the technique. Anesthesiology 1989 70 47-50.
[11] Cheatham ML and Safcsak K. Intraabdominal pressure: a revised method for measurement. J Am Coll Surg. 1998 186 594-5.
[12] Kirkpatrick AW et al. Intra-abdominal hypertension and the abdominal compartment syndrome: updated consensus definitions and clinical practice guidelines from the World Society of the Abdominal Compartment Syndrome. Intensive Care Med 2013 39 1190–206.
[13] David M, Berkovich U and Pracca F. A Numerical Analysis Towards the Continuous Non-invasive Assessment of Intra-Abdominal Pressure in Critical Patients Based on Bioimpedance and Microwave Reflectometry. 13th IEEE Biomedical Circuits and Systems Conference, 2017 21-24.
[14] David M, Raviv A, Peretz A, Berkovich U and Pracca F Towards a continuous non-invasive assessment of intra-abdominal pressure based on bioimpedance and microwave reflectometry: A pilot run on a porcine model. *Biomed Signal Process Control* 2018 44 96-100.

[15] Grevious MA, Cohen M, Shah SR and Rodriguez P Structural and functional anatomy of the abdominal wall. *Clin Plast Surg*. 2006 33 169-79.

[16] Caix P Anatomy of the abdominal wall. [Article in French] *Ann Chir Plast Esthet*. 1999 44 289-311.

[17] Ger R The clinical anatomy of the anterolateral abdominal wall musculature. *Clin Anat*. 2009 22 392-7.

[18] Quinn TH, Annibali R, Dalley AF 2nd and Fitzgibbons RJ Jr Dissection of the anterior abdominal wall and the deep inguinal region from a laparoscopic perspective. *Clin Anat*. 1995 8 245-51.

[19] Simini F and Bertemes-Filho P *Bioimpedance in Biomedical Applications and Research*. 1st ed. Springer International Publishing. 2018.

[20] Gabriel S, Lau RW and Gabriel C The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Phys Med Biol*. 1996 41 2251-69.

[21] Gabriel C and Gabriel S Compilation of the Dielectric Properties of Body Tissues at RF and Microwave Frequencies. Internet document; URL: http://www.dtic.mil/doi/tr/fulltext/a2/a305826.pdf (authorized mirror at http://niremf.ifac.cnr.it/docs/DIELECTRIC/home.html). Last accessed: Apr 2019.

[22] LH Deng, SH Karagiannoglou, WI Sakkas and JC Barbenel Effect of geometrical factors of coplanar electrodes on biomedical measurements as exemplified by the electrical impedance measurement of saline and blood. *Proceeding of the second joint EMBS/IEEE* conference, 2002 1667-8.

[23] CH Clausen, GE Skands, CV Bertelsen and WE Svendsen Coplanar Electrode Layout Optimized for Increased Sensitivity for Electrical Impedance Spectroscopy. *Micromachines* 2015 6 110-20.

[24] G Yang, H Long, H Tian, S Luo and H Huang Bioimpedance Measurement: Modeling of Coplanar Electrodes and Impedance Characterization. 2008 *2nd International Conference on Bioinformatics and Biomedical Engineering*, Shanghai, 2008 1248-51.