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Short communication

Towards a continuous non-invasive assessment of intra-abdominal pressure based on bioimpedance and microwave reflectometry: A pilot run on a porcine model

Marcelo David[a,b,*], Aviad Raviv[a], Aviad Peretz[a], Uriel Berkovich[a], Francisco Pracca[c]

[a] Department of Electrical Engineering, Jerusalem College of Technology – Lev Academic Center, Jerusalem, Israel
[b] Núcleo de Ingeniería Biomédica, Universidad de la República, Montevideo, Uruguay
[c] Department of Intensive Medicine, Hospital de Clínicas, Universidad de la República, Montevideo, Uruguay

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ABSTRACT

In this work we describe two novel indirect intra-abdominal pressure (IAP) assessment techniques, based on electrical bioimpedance and microwave reflectometry measurements. A pilot run was performed on a female *Sus scrofa domesticus* (domestic pig). IAP was induced by inflation of the abdominal cavity using a trocar placed near the umbilicus over the *linea alba* at a depth of 1 cm. The abdominal cavity was inflated to different IAP values. The whole run was done within one hour since the subject was sacrificed. An exponential trend linking between the bioimpedance values at 99.8 kHz and the IAP was found, with drastically reduced sensitivity for IAP above 7 mmHg. Also, a linear relationship between IAP and the microwave reflectometry measurements at 4.25 GHz was established. Although further research is needed to optimize the sensitivity of the bioimpedance system, we draw the conclusion that the use of electromagnetic spectrometry methods might be developed into novel techniques for performing a continuous non-invasive assessment of changes in IAP.

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1. Introduction

More than half of the patients in intensive-care units suffer from intra-abdominal hypertension (IAH) during the hospitalization [1]. IAH is directly associated with increased morbidity and mortality [1–4]. Different degrees of Intra-Abdominal Pressure (IAP) have been proposed [2–4]: IAP of 10 mmHg already affects blood flow leading to low organ perfusion. In some cases, abdominal decompression, either surgical or non-surgical [5–8], is indicated. Therefore, continuous monitoring of IAP in every critical patient has become a standard [3,4].

Invasive indirect measurements of IAP in ICUs are mostly performed by means of transduction using balloon catheters [4–6,9]. The most widely used is the Kron's intravesical catheter (1983) published by Iberti [10] and modified by Cheatham in 1998 [11]. In 2013, the World Society of the Abdominal Compartment Syndrome published a list of risk factors for which IAP monitoring is indicated, and recommended the use of Kron's intravesical catheter for trans-bladder measurement of IAP, as the standard [12].

As for non-invasive monitoring of IAP, Intra-Abdominal Volume (IAV) and Abdominal Wall Compliance (CAB) have been proposed as a correlative parameter: Relative changes in the abdominal perimeter, correlate well with changes in IAP in patients with healthy BMI [13]. In 2008, van Ramshorst et al. [9] showed that the abdominal wall tension also correlates with IAP. Later in 2011, van Ramshorst et al. [14] published a prototype which allowed intermittent non-invasive assessment of the abdominal wall tension.

In light of [9,13,14], we have proposed [15], that changes in the IAP ultimately alters the abdominal wall thickness (AWTh) and, therefore, can be continuously and non-invasively monitored by measuring either the overall surface electrical bioimpedance or the microwave reflection coefficient at the abdominal surface. In this work, we present preliminary results of a pilot run on a porcine model.

2. Materials and methods

2.1. Sus scrofa domesticus

The experiment was performed on a cadaver of a female *Sus scrofa domesticus* (domestic pig) weighing 49.9 kg. Before the experiment the porcine received 3.5 l of NaCl solution 0.18 M, and was put in supine position as shown in Fig. 1. Caudal and next to the

* Corresponding author at: Jerusalem College of Technology – Lev Academic Center, HaVaad HaLeumi 21, 9372115, Jerusalem, Israel.
E-mail address: marcelod@jct.ac.il (M. David).

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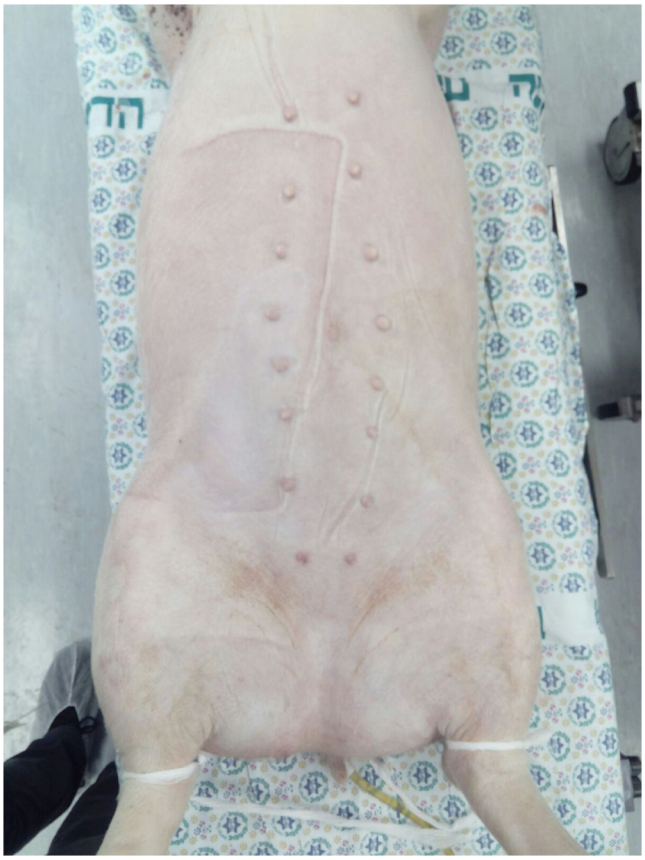

Fig. 1. Sus scrofa domesticus in supine position. Weight 49.9 kg.

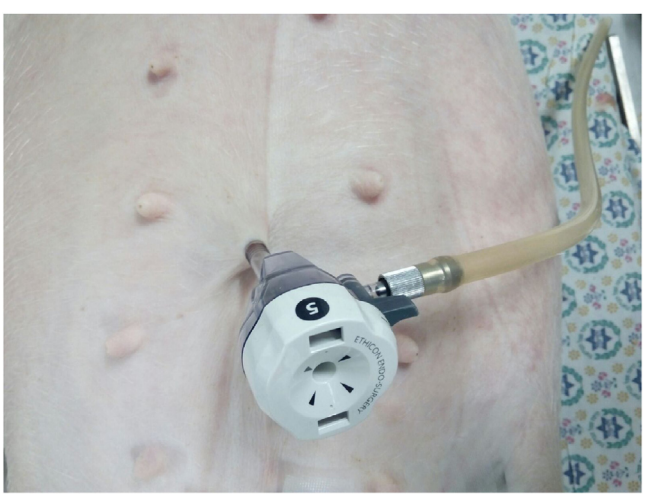

Fig. 2. Trocar placed over the *linea alba*, caudal from the umbilicus.

umbilicus, over the *linea alba*, a trocar was placed, 1 cm deep, reaching the intraperitoneal abdominal cavity. Through the trocar the abdominal cavity was inflated to different pressures with a precision of 0.1 mmHg. Fig. 2 shows the location of the trocar. The abdomen of the subject was inflated to eight different pressures: 4, 5, 6, 7, 8, 10, 12 and 14 mmHg. The whole run was done within one hour since the porcine was sacrificed, maintaining the IAP value for 1.5 min before performing the measurements of bioimpedance and microwave reflectometry (see Ethical Statement).

2.2. Electromagnetic model of the abdominal wall

1 The abdominal wall can be modeled as five main tissue layers [15–19]:
2 Skin and subcutaneous tissue
  a Camper's fascia (fat)
  b Scarpa's fascia (fibrous)
3 Fascia
4 Muscle
5 Fascia transversalis
6 Peritoneum

A simple electromagnetic model of the abdominal wall is proposed: six parallel dielectric slabs, each one characterized by its relative complex dielectric coefficient [20–22]:

$$\varepsilon_r^*(\omega) = \varepsilon_r(\omega) + \frac{\sigma(\omega)}{j\omega\varepsilon_0} \tag{1}$$

where ε_r and σ are the relative permittivity and conductivity of the tissue at frequency ω as published in [21,22], j is the imaginary unit and ε_0 is the permittivity of the vacuum.

At frequencies up to a few MHz, a layered structure of two or more materials having different dielectric properties is the simplest case of interfacial polarization when subject to an external electric field, so-called Maxwell-Wagner polarization [20,23]. In the case of two parallel layers of biological tissue with frequency dependent dielectric properties, the overall dielectric spectrum of the structure (ε_T^*) is described by Eq. (2) [23]:

$$\varepsilon_T^*(\omega) = (d_1 + d_2) \cdot \frac{\varepsilon_1^*(\omega)\,\varepsilon_2^*(\omega)}{d_2\varepsilon_1^*(\omega) + d_1\varepsilon_2^*(\omega)} \tag{2}$$

where d_1, ε_1^*, d_2, and ε_2^* are the width and dielectric coefficient of each layer, respectively. Therefore, the overall surface bioimpedance measured over the abdominal wall will be a function of the relation between the abovementioned layers' widths and complex permittivities [20,23]. Due to the elastic nature of biological tissues, it follows that the overall surface bioimpedance will be a function of the IAP [24,25].

At frequencies of a few GHz (S and C bands), the layered structure can be understood as a structure of lossy dielectric slabs. For each interface, the reflection response can be calculated by the recursion shown in Eqs. (3) and (4) [26,27]:

$$\Gamma_i = \frac{\rho_i + \Gamma_{i+1} e^{-2jk_i l_i}}{1 + \rho_i \Gamma_{i+1} e^{-2jk_i l_i}} \tag{3}$$

$$\rho_i = \frac{\eta_i - \eta_{i-1}}{\eta_i + \eta_{i-1}} \tag{4}$$

where k_i and l_i are the angular wavenumber and width of the ith slab, respectively. The characteristic impedance of the slab (η_i) is determined by the complex dielectric coefficient of the tissue. ρ_i is the elementary reflection coefficient in the interface to the ith slab.

2.3. Bioimpedance system

Based on results published by Gabriel S. et al. and Gabriel C. et al. [21,22], we estimated that a maximum sensitivity to changes in the bioimpedance of the abdominal wall due to changes in its width, can be found at a frequency range from about 80 kHz up to 200 kHz [15]. Actual values of the impedance will depend on the electrodes geometry and separation.

For this study, we used a 12-Bit impedance meter from Analog Devices: AD5933 in its evaluation board EVALAD5933EBZ. This impedance meter is described to be able to measure impedance from 10 Hz up to 100 kHz, with a frequency resolution of 27 bits,

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