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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

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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.

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

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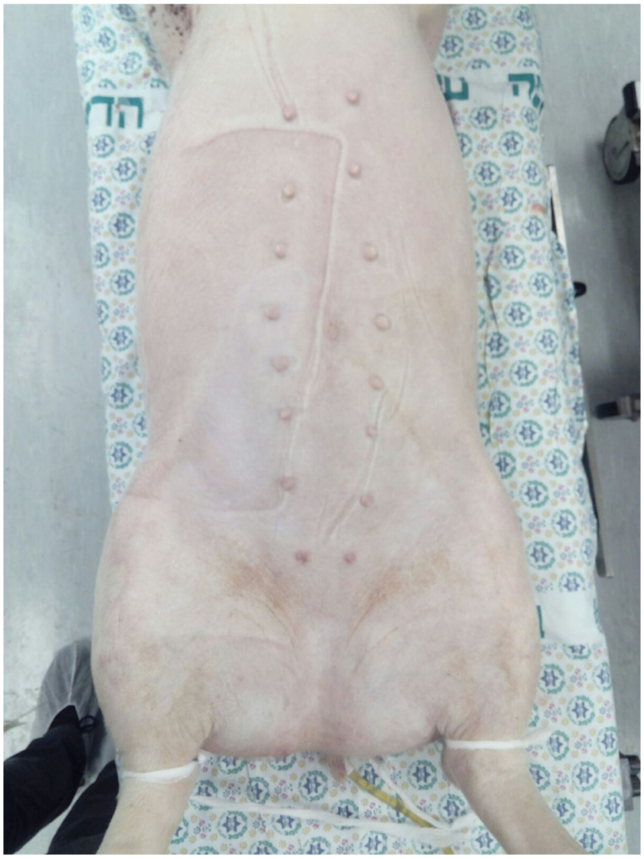

Fig. 1. Sus scrofa domesticus in supine position. Weight 49.9 kg.

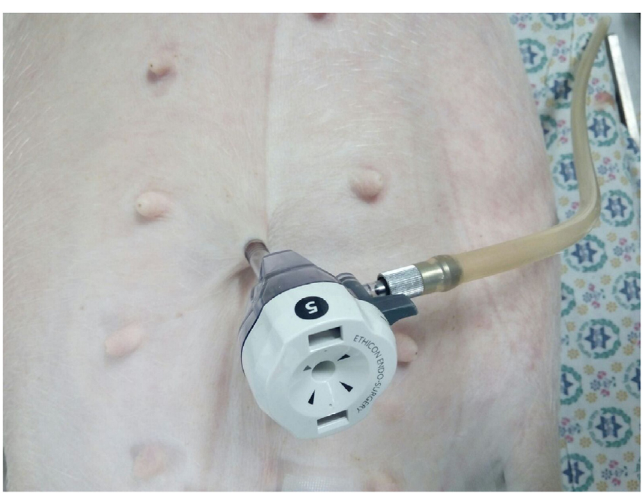

Fig. 2. Trocar placed over the *linea alba*, caudal from the umbilicus.

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,

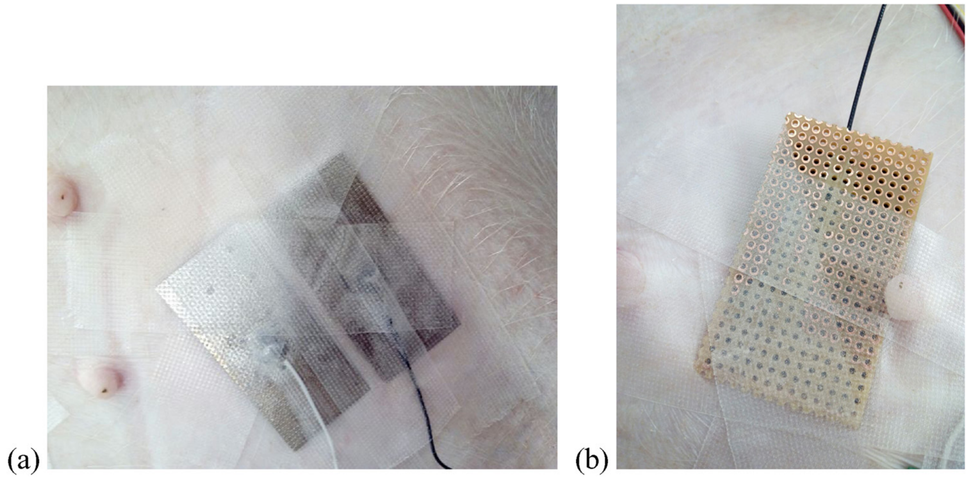

Fig. 3. (a) Bioimpedance electrodes. Stainless steel. 5 cm length, 2 cm width, separation 0.4 cm. (b) Patch antenna FXP100.07.0100A from Taoglas Ltd..

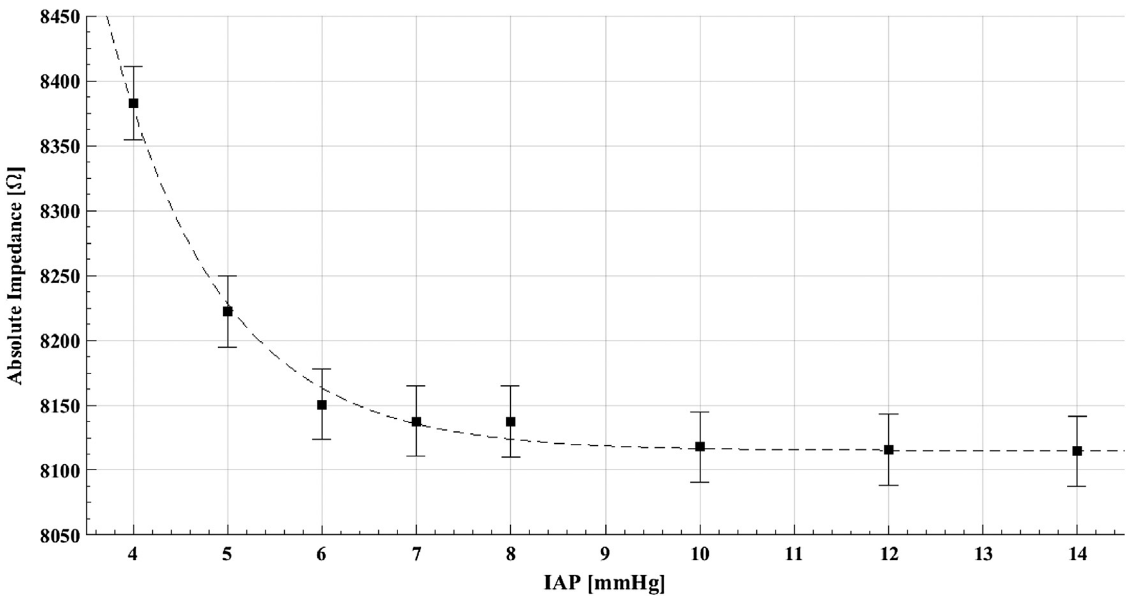

Fig. 4. Absolute impedance at 99.8 kHz vs IAP. The broken line shows the exponential trend.

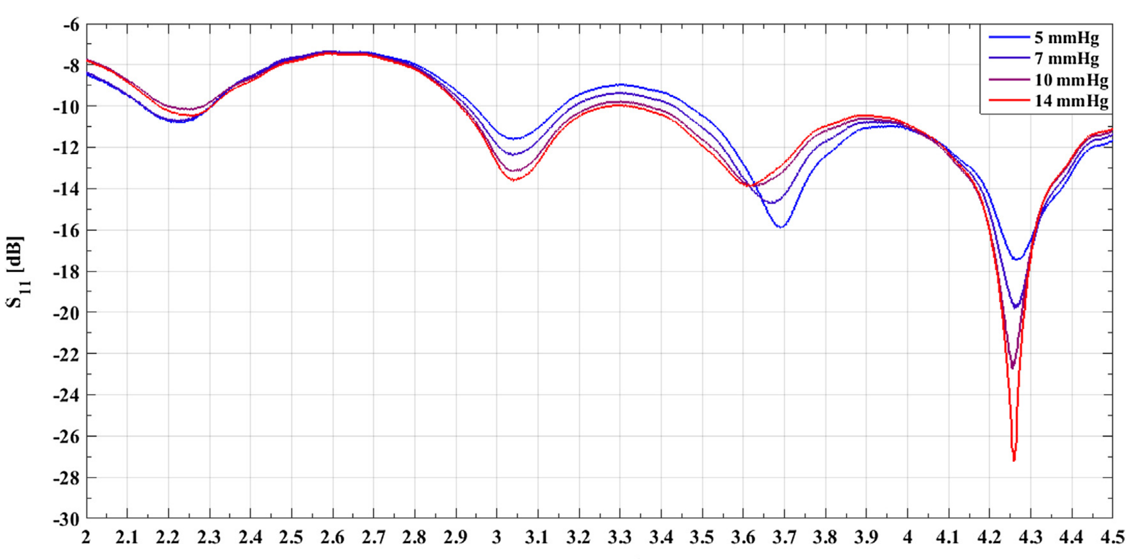

Fig. 5. Absolute S_{11} vs frequency for a sub-set of IAP. Maximum sensitivity is found at 4.25 GHz.

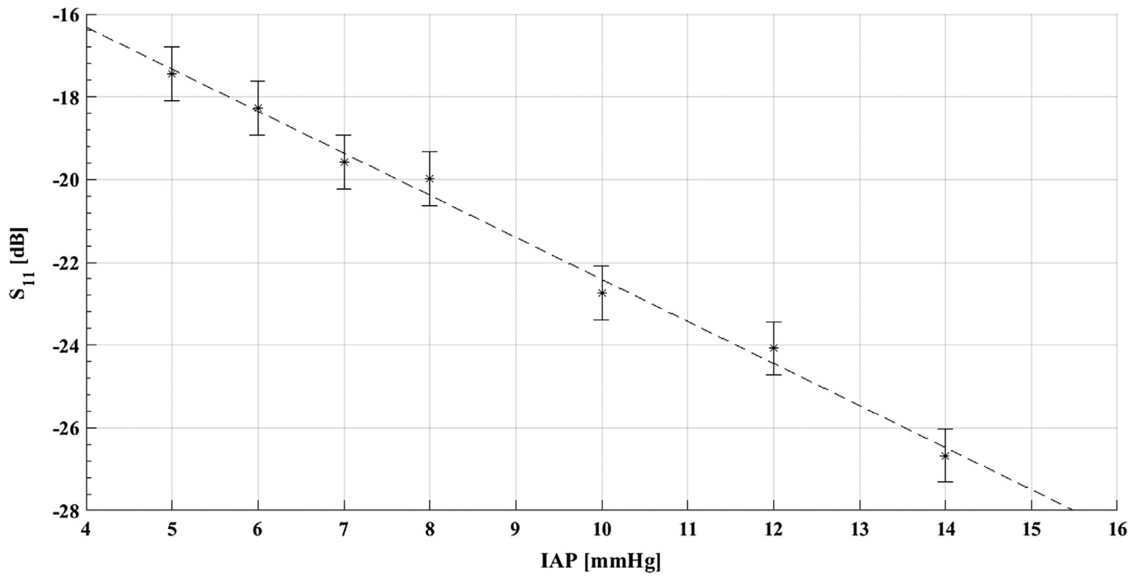

Fig. 6. Absolute value of S_{11} at 4.25 GHz vs IAP. The broken line shows the linear trend.

within a range from 1 kΩ up to 10 MΩ. The system's accuracy is 0.5%.

The measurements were done, using two dry rectangular stainless-steel electrodes (5 cm length, 2 cm width), separated 0.4 cm from each other, as shown in Fig. 3(a). The electrodes were placed 7 cm caudal from the umbilicus and 7 cm left from the *linea alba.*

2.4. Microwave system

In our previous work [15], we proposed that the maximum change in the wave impedance of the abdominal wall is expected in the frequency range between 3.5 GHz–4.2 GHz. Thus, for this study, we used the broadband flexible patch antenna FXP100.07.0100A from Taoglas Ltd., which has a working frequency band from 2.1 GHz up to 4.4 GHz. The antenna was placed 7 cm caudal from the umbilicus and 7 cm left from the *linea alba* (see Fig. 3(b)), and was connected to a Vector Network Analyzer from Agilent Technologies model E5071C. The reflection coefficient linking the antenna and the abdominal wall (see Section 2.2) is called S_{11}. The system's measurement accuracy is 0.65 dB, and was set to measure 1601 frequencies equally distributed from 2.0 GHz up to 4.5 GHz.

3. Results and discussion

3.1. Bioimpedance

The absolute values of the complex impedance measured at 99.8 kHz (the highest frequency measurable with the system available to us – lower frequencies presented lower sensitivity [15]), for different intra-abdominal pressures are presented in Fig. 4. Table 1 presents the complex impedance values of each measurement.

Together with the measurements and their accuracy range, an exponential fitting function is shown in Fig. 4. The exponential behavior of the changes in the bioimpedance is expected since the electrodes are coplanar and due to the elastic characteristics of the soft tissues in the abdominal wall [24,25,28,29].

Optimization of the electrodes configuration is yet to be researched in order to reach differentiability in measurements at higher IAP.

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

IAP [mmHg]	$\lvert Z_{AWTh}\rvert$ $[\Omega]$	$\sphericalangle Z_{AWTh}$ [deg]
4	8382.6	−80.3
5	8222.4	−79.7
6	8150.7	−78.9
7	8137.8	−79.3
8	8137.9	−79.7
10	8117.9	−79.8
12	8115.7	−80.5
14	8114.6	−81.1

Table 2
S_{11} scattering parameter absolute values.

IAP [mmHg]	$\lvert S_{11}\rvert$ [dB]
4	−15.9380
5	−17.4341
6	−18.2730
7	−19.5679
8	−19.9835
10	−22.7465
12	−24.0836
14	−26.6697

3.2. Microwave reflectometry

The absolute values of S_{11} measured by the VNA within the frequency range from 2.0 GHz up to 4.5 GHz, for different IAP are presented in Fig. 5 (for the sake of clearness in the graph, only a subset of IAP are shown). In accordance with the numerical analysis presented in [15], the maximum sensitivity can be found near the frequency 4.25 GHz. Table 2 and Fig. 6 present the absolute values of S_{11} for all measured IAP. In Fig. 6 the measurements' uncertainty and a proposed linear fitting are shown.

3.3. Biological variability and its influence in the acutal values of the measurement

Even though the dielectric properties of tissues are well determined and have relatively low variance [21,22], different subjects usually have different widths of layers, especially fat and skin (see Section 2.2) [24]. It follows that values of bioimpedance and S_{11}

will vary accordingly. However, relative changes of those measures when IAP increases would still present the same trend [15].

4. Conclusions

A pilot study on a porcine model of the feasibility of a continuous non-invasive assessment of the intra-abdominal pressure based on bioimpedance and microwave reflectometry was presented. The study's results are in accordance to theoretical considerations and show a solid correlation between IAP and bioimpedance measurements, for pressures up to about 7 mmHg, and also between IAP and S_{11} in the whole range of measured IAP.

Although further research is needed to optimize the sensitivity of the bioimpedance system at higher pressures, and more studies in-vivo are needed for a complete validation, we draw the conclusion that the use of both bioimpedance and microwave reflectometry can be developed into novel techniques for performing a continuous non-invasive assessment of Intra-Abdominal Pressure.

Ethical statement

The experiment and the preparation 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).

Conflict of interests

The authors declare no conflict of interests.

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