



Non-invasive indirect monitoring of intra-abdominal pressure using microwave reflectometry: system design and proof-of-concept clinical trial

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Abstract

Monitoring intra-abdominal pressure (IAP) has become a standard in intensive care units. Correlation between the abdominal wall's thickness (AWTh) and IAP has been reported previously. The abdominal wall can be modeled as a compound of parallel dielectric slabs; changes in their width have a direct effect on the reflection coefficient of the abdominal wall at microwave frequencies. This work describes the design of a reflectometry system and its proof-of-concept trial on five patients during laparoscopic surgery. The system complies with IEEE Std. C95.1-2005 concerning exposure of humans to microwave electromagnetic fields in controlled environments. The results putatively show an inverse correlation between IAP and the reflection coefficient, and a strong dependence on the body mass index. A better understanding of the dynamics in the changes of the AWTh (during intra-abdominal hypertension) will allow further development of a microwave-based technique for the continuous non-invasive indirect monitoring of IAP in critical patients.

Keywords Intra-abdominal pressure · Microwave reflectometry · Non-invasive

1 Introduction

Intra-abdominal pressure (IAP) is the steady-state pressure concealed within the abdominal cavity [1]. The monitoring of IAP has become a standard in intensive care units (ICUs) as intra-abdominal hypertension (IAH) is directly associated with increased morbidity and mortality [2]. This relies on the fact that IAH (i.e. IAP over 12 mmHg) entails a negative impact in abdominal organ perfusion which could lead to organ dysfunction [2]. The most feared consequence of IAH, known as abdominal compartment syndrome (ACS), is defined as a sustained IAP > 20 mmHg, associated with severe organ dysfunction [2–5]. By monitoring IAP, our ultimate goal is to guarantee an adequate organ blood flow

and, consequently, to reduce the risk of organ dysfunction, employing corresponding treatments [6]. Since IAH affects about 54–59% of critical patients [1, 7], monitoring IAP is usually indicated in ICUs [2, 8].

Diverse techniques are used in intensive care for monitoring IAP [9, 10]. Continuous monitoring of IAP has been researched by several groups in the past years [2, 3, 11–13], but no feasible or easy-to-use non-invasive method has reached clinical use yet [3]. In 2017, David et al. [14] proposed a generic numerical electromagnetic model of the abdominal wall as for correlating abdominal wall's thickness (AWTh) to microwave reflectometry. In 2018, David et al. verified the theory by preliminary results on porcine models [15].

This work presents the design and a proof-of-concept clinical trial of AbdoRF: an easy-to-use, portable, microwave reflectometry system (in the frequency range between 3.90 and 4.45 GHz), which complies with IEEE C95 standards regarding exposure of humans to non-ionizing electromagnetic radiation in controlled environments.

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2 Materials and methods

2.1 Patients

The target population were patients hospitalized in the Hospital de Clínicas—Universidad de la República, admitted by the Emergency Department for laparoscopy surgery due to acute abdominal pathologies.

Inclusion criteria:

- Adults (at least 18 years old) from the target population.
- Ability to accept or decline signing the informed consent.

Exclusion criteria:

- Pregnant.
- Vesical or pelvis trauma.
- Obstructive uropathy.
- Urosepsis.

2.2 System design and description

The abdominal wall mainly consists of five soft tissue layers as described in [16–19]:

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

A detailed description of the electromagnetic (dielectric) model of the abdominal wall is presented in [14, 15]. For simplicity, the abdominal wall can be considered a compressible non-homogeneous anisotropic dielectric slab [20–22], which will be compressed as IAP increases and will, therefore, change its thickness. Previously published numerical analysis [14] suggests that such changes in the AWTh, correlate well with the reflection coefficient of the abdominal wall (called S_{11} —input port reflection coefficient). S_{11} is a ratio between the reflected power ($P_{reflected}$) and transmitted power ($P_{transmitted}$) at the antenna, usually measured in dB (Eq. (1)) [14].

$$S_{11} = 10 \cdot \log\left(\frac{P_{reflected}}{P_{transmitted}}\right) \text{ [dB]} \quad (1)$$

AbdoRF is a portable, relatively low-cost microwave reflectometry system, designed to evaluate the reflection coefficient of a patch antenna non-invasively attached to the abdominal wall.

The hardware consists of the following parts as shown in Fig. 1 (design files of the system are available upon reasonable request to the corresponding author):

1. A generic microcontroller that commands and links between the hardware devices.
2. A Voltage Controlled Oscillator (VCO) for radiofrequency wave generation in the range between 3.90 and 4.45 GHz.
3. A wideband flexible patch antenna.
4. A bidirectional RMS detector measures the power of the transmitted and reflected wave through the antenna.
5. A digital-to-analog converter and amplifiers to control the VCO input.
6. Analog-to-digital converters for sampling instantaneous RMS power values measured by (4), used for calculating S_{11} .

2.3 IEEE Std. C95.1-2005: human exposure to EM fields in controlled environments

IEEE C95.1 is an approved standard for safety levels concerning human exposure to electric, magnetic and electromagnetic fields. It states that, for electromagnetic fields within the frequency range between 2 and 5 GHz, the maximum RMS power density allowed for exposure in controlled environments (such as clinical use) is:

$$\Phi_{max} = 10 \frac{\text{W}}{\text{m}^2} \quad (2)$$

In the clinical trial, the antenna FXP100.07.0100A (Taoglas Ltd.) was used. Given that (according to the antenna's datasheet) the radiation area of the antenna is $A = 744 \text{ mm}^2$ (see Fig. 2), the maximum power driven to the antenna (in the ideal case of complete transmission from the antenna to the abdominal wall) is:

$$P_{max} = \Phi_{max} \cdot A = 10 \frac{\text{W}}{\text{m}^2} \cdot 744 \text{ mm}^2 = 7.44 \text{ mW} \approx 8.7 \text{ dBm} \quad (3)$$

The VCO used in our system, HMC391 (Analog Devices), supplies a power of only 5 dBm; thus, the system complies with the IEEE C95.1 standard.

2.4 Clinical trial setup

This proof-of-concept clinical trial is a prospective observational study in which we randomly enrolled five patients

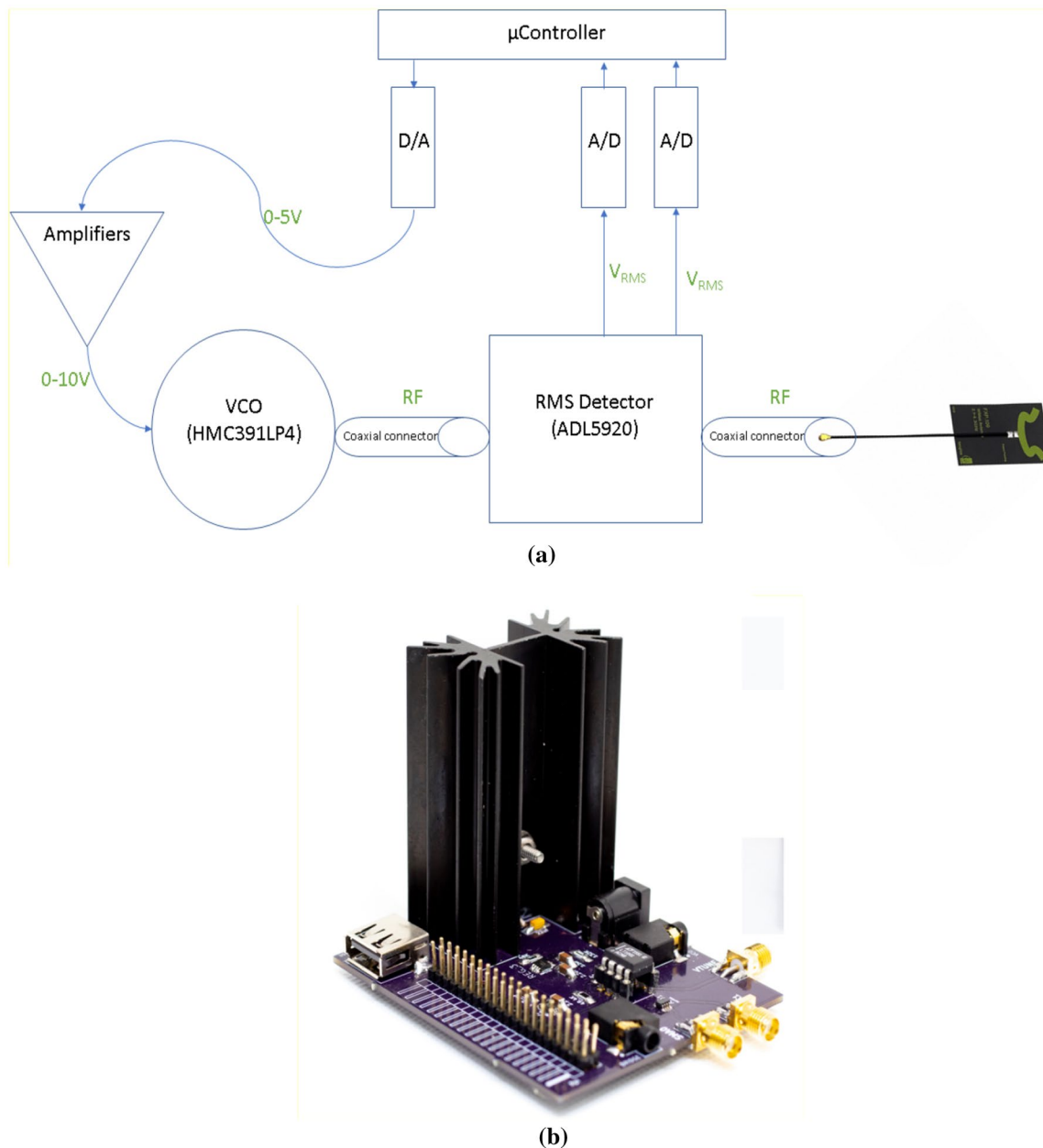


Fig. 1 AbdoRF **a** system schematic diagram **b** picture of the device

undergoing laparoscopic surgery (see Sects. 2.1 and 2.2). Before anesthetic induction, premedication by 1 $\mu\text{g}/\text{kg}$ of fentanyl was supplied. Balanced general anesthesia was performed at inhalation on mechanical ventilator support with orotracheal intubation. Anesthetic induction was intravenous with 2–4 mg/kg of Propofol, and muscle relaxation with 0.6 mg/kg of Atracurium. After orotracheal intubation, anesthetic maintenance was performed with 0.5 MAC inhalation isoflurane and remifentanyl in the range of 0.25–0.50 $\mu\text{g}/\text{kg}/\text{min}$. Muscle relaxation was maintained based on Atracurium 0.3 mg/kg when required. During mechanical ventilation, the

volume-controlled mode was used, with a tidal volume of 6–8 ml/kg , PEEP in the range of 5–10 cmH_2O , adjusting the respiratory rate according to exhaled- CO_2 values.

Patients were in supine position; a trocar was inserted across the abdominal wall, reaching the intraperitoneal abdominal cavity for the laparoscopic pneumoperitoneum. Through the trocar, the abdominal cavity was inflated using CO_2 (influx of 0–30 l/min) to different pressures as needed for the surgical procedure. As recommended by WSACS (The Abdominal Compartment Society), the induced IAP was kept constant for about 60 s before performing the



Fig. 2 Antenna FXP100.07.0100A (Taoglas Ltd.). Radiation area 24 mm×31 mm

measurements [2, 9, 10], the measurements were performed at the end of expiration. Each reflectometry measurement was performed five times for each IAP. Due to logistical constraints during the surgery, the antenna was placed over the left-inferior quarter of the abdominal wall (except Patient E—see Sect. 3.1), next to the *linea alba* as shown in Fig. 3. Note that the front-side of the antenna (radiation area) is facing the abdomen, thus its back-side is seen in the picture.

3 Results

3.1 Patients

Five patients were studied in this clinical trial, as presented in Table 1. Patients A–D underwent cholecystectomy, while Patient E underwent an appendectomy. In the case of Patient

Table 1 List of patients in the clinical trial and their relevant variables

Patient	BMI	Height [m]	Age	Gender	Diagnosis
A	25.71	1.65	60	F	Cholecystectomy
B	17.58	1.60	60	F	Cholecystectomy
C	38.05	1.58	38	F	Cholecystectomy
D	33.87	1.63	34	F	Cholecystectomy
E	23.94	1.71	21	M	Appendectomy

E, the antenna was placed on the left-superior quarter of the abdominal wall (under the diaphragm).

Since the five patients are approximately the same height, body mass index (BMI—Eq. (4)) can be directly related to the accumulation of fat tissue in the abdominal wall [4]. This, in turn, has an impact on the compressibility of the abdominal wall [4] and its overall wave impedance (and thus the reflection coefficient S_{11}) [14, 15].

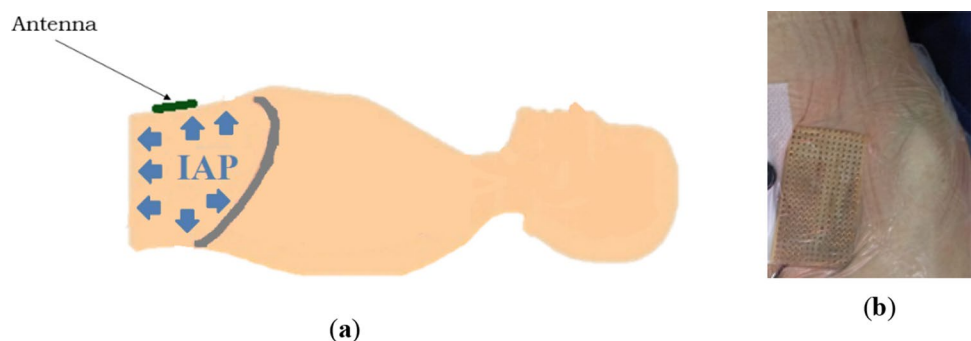
$$BMI = \frac{weight [kg]}{(height [m])^2}. \quad (4)$$

3.2 Reflectometry results

Each reflectometry measurement was performed five times for each IAP induced by air insufflation during the laparoscopic procedure. The measurements were averaged and the standard deviation was calculated. Reproducibility of these results depends on a well-coupling of the antenna and the abdominal wall; special care is to be taken to ensure that the whole antenna is touching the abdomen without any separation.

Figure 4 presents absolute values of reflection coefficient S_{11} vs frequency at different IAP for patient A (similar behavior is observed for all patients—raw data are available upon request to the corresponding author). In all patients, maximum sensitivity to changes in IAP was found at a critical frequency of about 4.41 GHz (see Table 2).

Fig. 3 Antenna over the abdominal wall while the patient is in supine position: **a** schematic sagittal cut; **b** Patient A—the antenna is placed over the left-inferior quarter of the abdominal wall



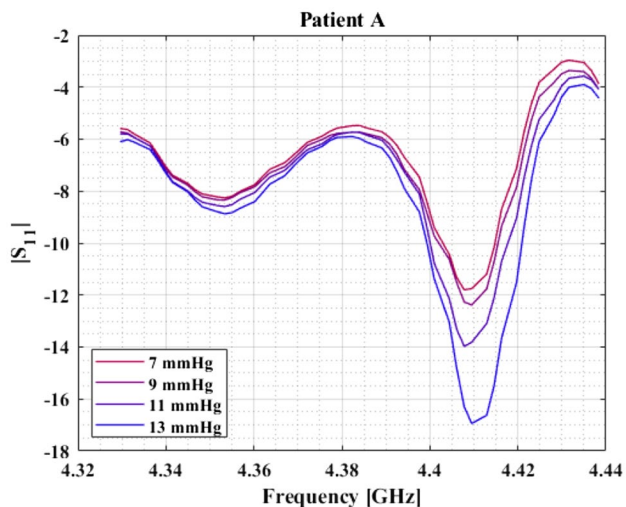


Fig. 4 Absolute values of reflection coefficient in dB vs. frequency at different IAP for patient A. Similar behavior is observed in every patient

Table 2 Critical frequency (maximum sensitivity)

Patient	Critical frequency
A	4.408 GHz
B	4.413 GHz
C	4.410 GHz
D	4.415 GHz
E	4.415 GHz

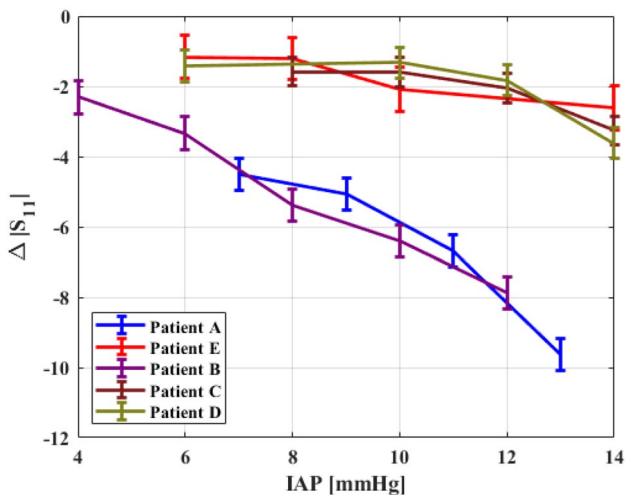


Fig. 5 Relative changes in reflection coefficient (in dB) at the critical frequency vs. IAP for each patient

A linear regression linking S_{11} and IAP was proposed for each patient. Figure 5 presents the relative changes in the reflection coefficient S_{11} at the critical frequency (with

corresponding uncertainty (standard deviation)), vs. IAP for each patient—the differences in slope are justified by the differences in the abdominal wall compliance [14].

Given that the abdominal wall’s compliance is linked to the BMI, and it influences the slope of S_{11} vs. IAP, we propose that there might exist a correlation between BMI and reflectometry results. Figure 6 presents values of the slope of ΔS_{11} vs. IAP, as a function of the patients’ BMI. Patient E was not included in this graph since the antenna was placed in another section of the abdominal wall (see Sect. 3.1) [4].

4 Discussion

Reflectometry results over five laparoscopic surgery patients clearly show an inverse correlation between IAP and the reflection coefficient; these results are supported by theoretical considerations [14]. Even though the dielectric properties of tissues are well determined and have relatively low variance [23, 24], different subjects usually have different widths of each abdominal layer, especially fat and skin [14, 15]. It follows that the values of S_{11} are expected to vary with the BMI, as seen in this trial (Fig. 6). Thicker layers of fat screen the compression of the inner layers, thus, affecting the sensitivity of the whole measurement.

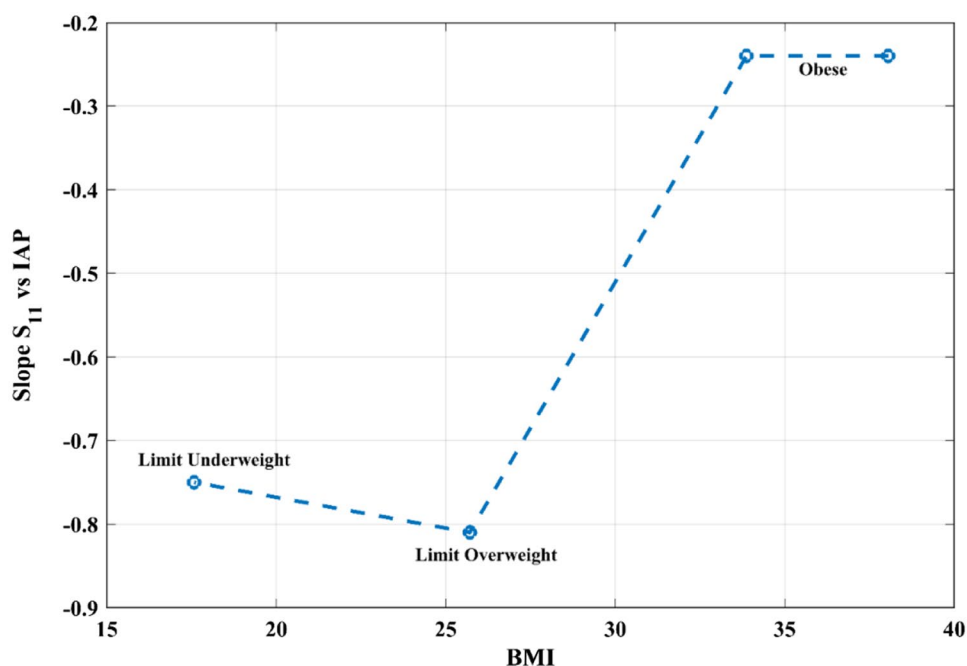
Patient E was operated for appendectomy and the procedure required placing the antenna on the superior-left quarter of the abdominal wall (next to the diaphragm and over the limit of the abdominal cavity), which has comparably smaller compliance. Therefore, we can argue that relative changes in the AWTh (given by increments in IAP) are smaller in the left-superior quarter [4], rendering a low sensitivity of the AWTh to changes of IAP. In consequence, the sensitivity of S_{11} is also relatively lower, as seen in Fig. 5.

Regarding abdominal compressibility, it can be argued that no evident dependence on the patient’s gender has been reported in the literature.

A better understanding of the dynamics in the changes of the AWTh (during IAH) will render a more solid correlation model between BMI, the compression of the abdominal wall, and reflectometry. Among the sources of error in the measurement, we can find ventilation and motion. Any mechanical change in the abdominal wall, where the antenna is placed, will render strong artifacts in the measurements.

It must be noted that the current development of the system is able to assess changes in IAP; however, measurement of absolute values of IAP using microwave reflectometry remains a challenge.

Fig. 6 Slope of reflection coefficient vs. IAP as a function of BMI and body mass classification



5 Conclusions

A microwave reflectometry system named AbdoRF was developed and clinically tried for proof-of-concept on five patients during laparoscopic surgery, which aims to estimate changes in IAP. Dependence of the reflection coefficient on the BMI is hypothesized.

Further research is still needed to optimize the sensitivity of the system; this includes optimal placement of the antenna, and redesign of the antenna itself to get larger variations of S_{11} for changes in IAP.

This work presents results for IAP up to 14 mmHg, due to the standards for laparoscopic surgery. Future studies will address the study of cases for which IAP is larger as in the cases of ACS.

The applicability of this system and technique relies on a better understanding of the dynamics of the abdominal wall compressibility under the mechanical stress of IAP. Further research towards a numerical model of the AWTh dependence on IAP is needed to address the challenge of measuring absolute values of IAP by means of microwave reflectometry. Based on such a numerical model, the use of microwave reflectometry could be developed into a novel easy-to-use technique for performing a continuous non-invasive assessment of IAP.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The proof-of-concept clinical trial was conducted on laparoscopy patients. The trial was approved by the Ethical Committee of the Hospital de Clínicas—Universidad de la República in Uruguay, in accordance with local and international regulations (permit 0512/18).

Informed consent All patients and families were informed, voluntarily accepted, and signed the required informed consent.

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