Dual Patch Antenna Sensor for Pneumothorax Diagnosis: Sensitivity and Performance Study

Maria I. Christopoulou – *IEEE Member*, and Stavros D. Koulouridis – *IEEE Member*

***Abstract*—Pneumothorax may cause serious health problems and often death if medical and surgical treatment is delayed. The absence of reliable, safe, portable and easy-to-use equipment in the ambulance is the primary clinical motivation of this work. We investigate pneumothorax diagnostic performance and sensitivity of a dual patch antenna system (sensor). The operation frequency range is set to 1–4 GHz. Parametric study is conducted using simplified rectangular tissue numerical models. Variation of S_{12} parameter, related to frequency, is compared in order to distinguish healthy and pneumothorax cases, reaching a difference of 20.1 dB, at 1.87 GHz. MRI-based anatomic models are also modified in order to simulate pneumothorax incident, in realistic clinical case. The best performance configuration scenario is applied onto the modified anatomic models, revealing satisfactory sensor performance (7.1 dB, at 2.3 GHz). Sensor diagnostic ability reaches 1 cm of air thickness. The paper concludes with proposed design specifications for thorax experimental phantom.**

I. INTRODUCTION

Pneumothorax refers to an abnormal collection of air in the pleural cavity between the lung and the chest wall. It is a life threatening condition since it can result in collapse of the lung. Pneumothorax may occur in healthy persons (primary spontaneous) or following a known lung disease (secondary). The incidence of primary spontaneous pneumothorax is 0.24‰ a year in men and 0.1‰ a year in women in England [1]. In order to calculate the size of pneumothorax, the technique recommended by the British Thoracic Society is to measure the distance between the pleural surface and the lung edge (at the level of the hilum). If this is 2 cm or more, it represents a pneumothorax of at least 50% of the hemithorax [2]. Pneumothorax may cause serious health problems and often death if medical and surgical treatment is delayed. It is conventionally primarily diagnosed with radiography methods (x-rays and CT) or ultrasound imaging. Although these methods are generally reliable, they are not always available on-site in order to help diagnosis of the patient, during an emergency. Concerning pneumothorax, the mortality rates could have been lower if the diagnosis methods included smart portable devices. During recent years, wireless technologies for body-worn applications are developed and applied in the field of healthcare monitoring, facilitating the disease prediction and diagnosis (e.g. [3]).

In this paper, a compact dual patch antenna system (sensor) for pneumothorax diagnosis is proposed. In order to fully assess the sensor performance, parametrical air detection scenarios are investigated, revealing the best configuration for the application during a realistic clinical scenario, simulated by modified MRI-based whole-body numerical models.

II. MATERIALS AND METHOD

A. Theoretical Background

Assuming a homogeneous electromagnetic plane wave propagating in free space, which is incident vertically onto a structure of N successive layers of biological tissue, described as:

$$\underline{E}^{inc} = \hat{x}E_0 e^{-jk_0 z} \tag{1}$$

where $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ is the free space wave number, ω is the angular frequency, ε_0 and μ_0 are the free space permittivity and magnetic permeability, respectively. The amplitude of the electromagnetic wave reflected by or transmitted through the body depends strongly on the dielectric properties of the tissues, and can be altered significantly by the existence of air cavities inside the body, placed close to the skin surface. It is known that the complex relative permittivity of a biological tissue is expressed by the Cole-Cole equation [4].

$$\dot{\varepsilon}_r(\omega) = \varepsilon_r(\omega) + \frac{\sigma(\omega)}{j\omega\varepsilon_0} \tag{2}$$

where ε_r is the relative permittivity and σ is the conductivity. Let assume a system of low-power radiating antennas (sensor), used as diagnostic device, which is placed onto the thorax surface. The reflected wave monitored by the sensor can be altered significantly, due to presence of air close to lung. The penetration depth δ and sensor sensitivity depend on frequency and intermediate tissue layer thickness. The dominant biological tissues which are present into the layered section of thorax, from the surface of the skin to the pleural cavity, are: skin, fat, muscle and bone, in case of the intercostal space. The existence of air would result to alternation of the reflected wave that the sensor detects. Considering the above, the corresponding values for the penetration depth for the dominant tissues, as well as that the averaged chest wall thickness (CWT) does not exceed 35

The research project is implemented within the framework of the Action «Supporting Postdoctoral Researchers» of the Operational Program "Education and Lifelong Learning" (Action's Beneficiary: General Secretariat for Research and Technology), and is co-financed by the European Social Fund (ESF) and the Greek State.

M. I. Christopoulou and S. D. Koulouridis are with the University of Patras, Department of Electrical and Computer Engineering, Rio, 26504, Greece (phone: +30 2610 996168; fax: +30 2610 997342; e-mail: mchrist@ece.upatras.gr, koulouridis@ece.upatras.gr).

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

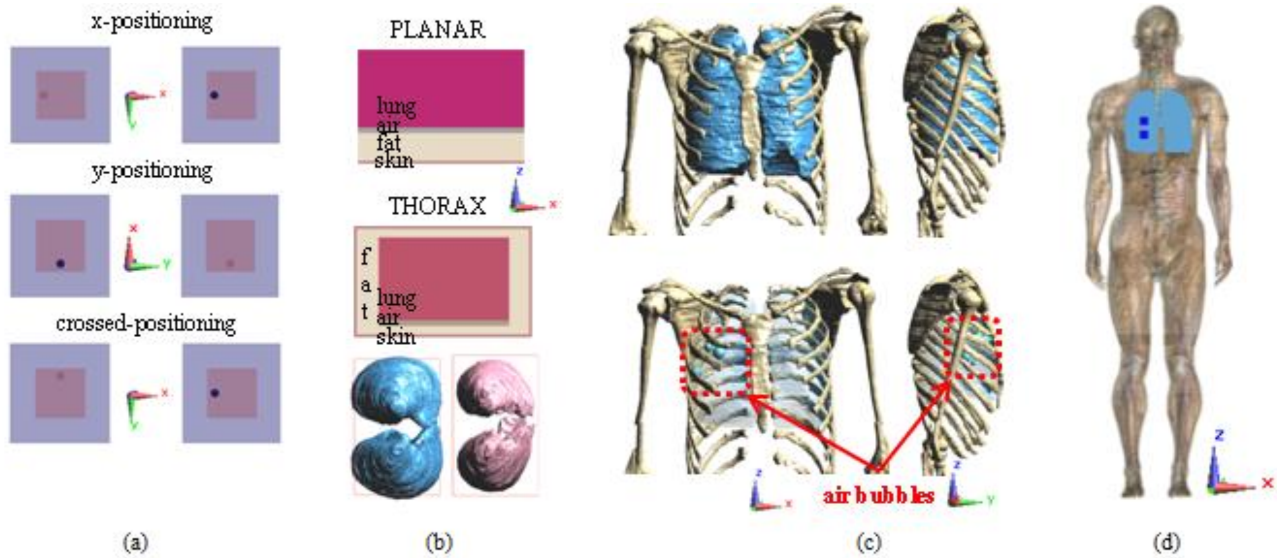

Figure 1. Numerical models: (a) relative configuration of the dual patch antenna system (sensor), (b) rectangular tissue models (PLANAR and THORAX) and xy illustration of lung size in Duke (blue) and Ella (pink) models, compared to the THORAX lung contour (red box), (c) pneumothorax modeling by scaling down (85%) the lung (top) and inserting air bubbles in two regions of interest [9] (bottom), (d) typical clinical scenario: dual patch antenna system (sensor) onto Duke model. The lungs are voxelized for best illustration.

mm [5], the frequency range of the sensor under design is 1 – 4 GHz, as described in detail in [6].

A. Patch Antenna Numerical Model

A microwave sensor composed of two patch antennas is designed for the detection of air layer into the body. Each patch is 1.44 × 1.44 cm^2. A rectangular (2.9 × 2.9 cm^2) dielectric layer made of Rogers RO3210 ($\varepsilon_r = 10.2$ and $\tan\delta = 0.003$, thickness = 0.32 cm on z-axis) interposes. Patches are fed 0.5 cm off-center on x-axis by coaxial cable through their substrate. The geometrical details of the model are summarized in [7]. Fig. 1(a) illustrates all relative configurations for two patch antenna models: corresponding to x-, y-, and crossed positioning of the coaxial feeding probe. Only one feed is active in each pair, denoted with dark blue colour. Their intermediate separation distance is kept 2 cm. Therefore, the maximum surface of the antennas configuration is 7.8 × 2.9 cm^2 which can be considered affordable for pneumothorax diagnosis.

B. Tissue Numerical Models

In this paper, three kinds of tissue numerical models are utilized. In all models, the healthy case corresponds to absence of air. The models are summarized as following:

PLANAR: A coarse planar multilayered tissue numerical model (top Fig. 1(b)). It consists of dry skin, fat, air and inflated lung, in order to model a semi-infinite section of the thorax in the intercostal space. The thickness (z axis) for each tissue is set: 5 mm (dry skin), 50 mm (fat), 0-50 mm, with 10 mm step (air) and 100 mm (inflated lung). XY dimensions of the planar model are set 300 × 300 mm^2 (i.e. $\lambda_0 \times \lambda_0$, λ_0 denotes the free space wavelength at f = 1 GHz).

THORAX: A closed rectangular multilayered thorax numerical model. It consists of dry skin, fat, air and inflated lung, in order to model a typical closed section of the thorax in the intercostal space. The dimensions of the model are based on the average values of two anatomical MRI-based Virtual Family whole-body models, Duke and Ella [8] (Fig. 1(b)). Duke and Ella correspond to 34-year-old male and 26-year-old female, respectively. Therefore, THORAX model has width (x axis): 324.90 mm, depth (z axis): 200.20 mm while height (y axis) is selected equal to λ_0 free space wavelength at f = 1 GHz (i.e. 300 mm). The surrounding skin layer thickness is set stable to 5 mm at both x and z axes and 0 mm at y axis, representing the thorax cut. The lungs are modeled as box, based again on the averaged dimension values of Duke and Ella lungs (bottom Fig. 1(b)). Therefore, the lungs have width (x axis): 238.10 mm, depth (z axis): 159.62 mm and height (y axis): 220.42 mm. The lungs are centered into the THORAX, resulting to fat layer thickness of 38.40 (x axis), 15.29 mm (z axis) and 39.79 mm (y axis). Depending on the air layer thickness, which varies between 0 and 50 mm, with 10 mm step (degree of pneumothorax), the lungs thickness is reduced accordingly.

DUKE and ELLA: A section of the thorax (including lungs) of two anatomical Virtual Family whole-body numerical models, Duke and Ella [8]. The thorax sections DUKE and ELLA have been modified in order to model a typical pneumothorax case. Two approaches have been applied: a) lungs scaled down to 85% only in width (air gap in x axis: 1.5-2.0 cm) and depth (air gap in y axis: 1.5-2.0 cm) (top Fig. 1(c)), and b) insertion of air bubbles in the anterior second intercostal space (ICS) at the midclavicular line (MCL) and in the lateral forth intercostal space of the affected hemithorax (bottom Fig. 1(c)), which are considered the most common regions [9] where the air is trapped during

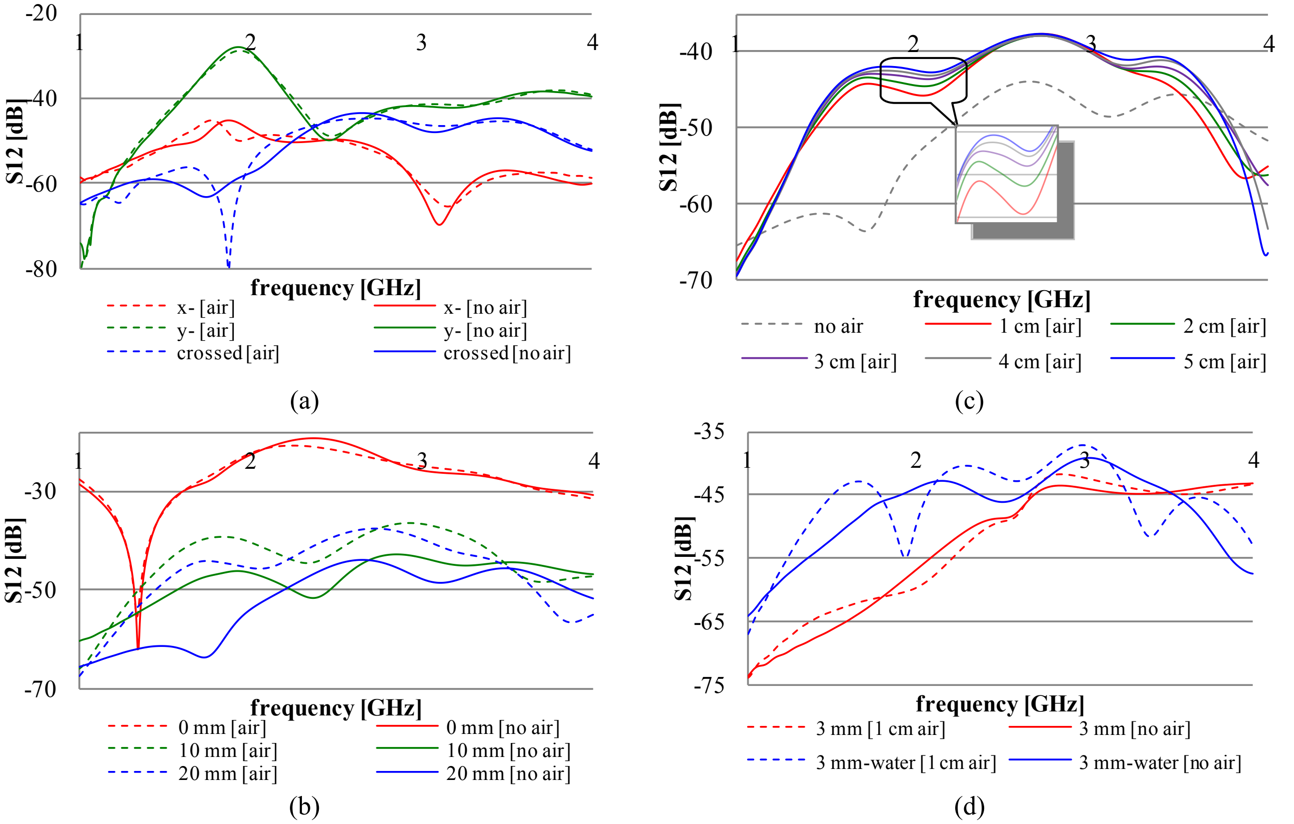

Figure 2. Parametric S_{12} variation with frequency, by usign rectangular models: (a) antennas relative configuration onto PLANAR for air thickness = 1 cm, (b) antennas separation distance of crossed configuration onto THORAX for air thickness = 1 cm, (c) air thickness of crossed configuration onto THORAX, (d) application of water coat into the skin-sensor distance 3 mm, for crossed configuration onto THORAX, for air thickness = 1 cm.

pneumothorax, given the lying position of the patient. The air gap extent is selected according to [2].

C. *Simulation Details for Air Detection Scenarios*

The antenna sensor is placed onto the skin surface of the tissue models and the S_{12} coefficient is calculated, assessing its potential differentiation, due to the presence of air close to the lung. The parameters that are applied in order to assess sensor sensitivity and performance are: i) antennas relative configuration, ii) air layer thickness, and iii) skin-sensor separation distance. The electromagnetic exposure problem is solved by applying Finite Difference Time Domain (FDTD) method, using software platform SEMCAD-X 14.8.4 [10]. Broadband simulations are carried out for frequency range of 1 – 4 GHz. Multipole Debye materials are selected to characterize electrically the biological tissues.

III. Results

Selected air detection scenarios calculate the variation of S_{12} antenna parameter in relation to frequency, in order to distinguish healthy cases from the presence of air layer into the tissue model.

A. *Parametric Investigation in Rectangular Models*

Firstly, sensor sensitivity and performance are preliminarily assessed, by applying the sensor onto the simplified rectangular models: PLANAR and THORAX. In order to investigate relative antennas configuration, the scenarios which correspond to x-, y- and crossed positioning of the antennas centred onto PLANAR model are applied. The air layer has thickness of 1 cm (pneumothorax) or 0 cm (healthy case), alternating respectively the thickness of inflated lung. S_{12} variation is illustrated in Fig. 2(a). It is obvious that the crossed configuration results to the largest differentiation, reaching 20.1 dB in S_{12}, at 1.87 GHz. This dB level of difference is considered safe for measurements in order to provide true-positive in pneumothorax detection. Additionally, in order to investigate the minimization of the sensor active surface, the intermediate separation distance between the two antennas is varied between 0-20 mm, with step of 5 mm. This alternation is done for the crossed configuration onto the THORAX model, which considered more realistic, for the detection of air thickness = 1 cm. Fig. 2(b) illustrates indicative results for 0, 10 and 20 mm separation distance. It is observed that the largest differentiation is calculated for 20 mm separation distance, reaching 19.3 dB, at 1.7 GHz.

Next, in order to assess sensor diagnostic sensitivity, the air layer thickness is varied. The best performance configuration (i.e. crossed) is applied onto realistic THORAX model. The air layer thickness ranges from 0 to 5 cm, with 1 cm step, covering a large range of pneumothorax extent [2]. Fig. 2(c) illustrates comparatively the S_{12} variation, revealing that the significant differentiation (19.3 dB, at 1.7 GHz) between healthy (0 cm) and pneumothorax (1 cm) case is not further increased significantly, as the trapped air increases. This outcome is verified by using PLANAR model, as well, concluding to unaffected sensor sensitivity by pneumothorax size.

Last but not least, a crucial parameter for the sensor performance is investigated. In real application, it is inevitable that air gaps will be present in between skin surface and sensor radiating patches, due to the application mismatch and skin curvature. Therefore, the skin-sensor distance is varied from 0 to 5 mm, with 1 mm step, during detection of 1 cm of air, applying the crossed configuration onto THORAX model. Results reveal that the intermediate air layer plays significant role in the sensor diagnostic ability, since above 2 mm of air gap, healthy and pathological case cannot be distinguished. The effective operation of the sensor is enhanced by using a layer of distilled water (e.g. water coat) as coupling medium. Fig. 2(d) compares the S_{12} differentiation with and without water, for the critical skin-sensor distance of 3 mm. Results reveal that the application of water coat improves the sensor differentiation ability from 2.2 to 10.3 dB, at 1.9 GHz.

B. Realistic Application: Typical Clinical Scenario

The antenna configuration with the best performance (i.e. crossed with intermediate separation distance of 20 mm) is applied onto modified DUKE and ELLA models. In order to reassure the effective operation of the sensor, distilled water is used as coupling medium. In realistic application, patient skin surface can be pressed by the sensor which, in this study, is modelled by reducing only skin thickness up to 10% in selected regions of high curvature. The dual patch antenna system is applied onto the right frontal hemithorax, centred on the lung of DUKE, for healthy and pathological case (85% scaled lungs, simulating a typical pneumothorax) (Fig. 1(d)). Fig. 3(a) illustrates S_{12} variation where the maximum differentiation (7.1 dB) is calculated at 2.3 GHz. At this frequency, the electric field distribution is assessed on xy plane, at the height of active feed, for both cases. Fig. 3(b) depicts the relative volume of the lungs, while in pneumothorax case, the non uniformity of E-field distribution is clear, due to the existence of trapped air into the chest cavity. Last but not least, in order to conform to IEEE C95.1–2005 [11] (peak spatial $SAR_{10g} < 2$ W/kg) basic restrictions for general public exposure, the actual input power of the active antenna should not exceed 42 mW.

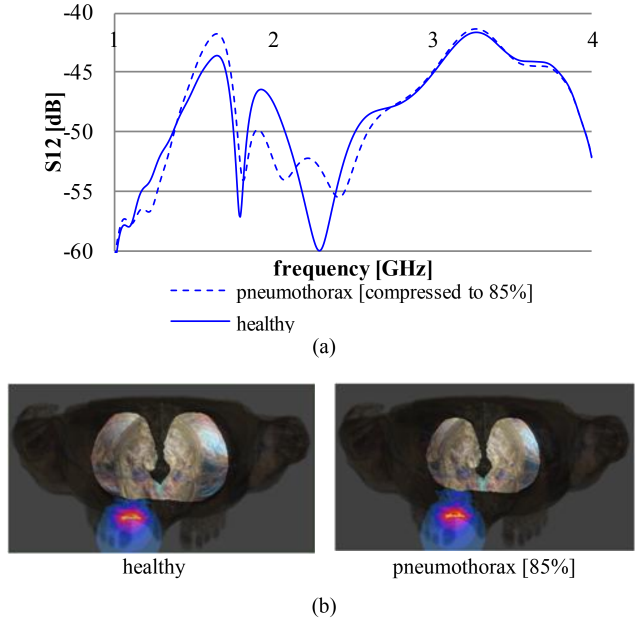

Figure 3. (a) S_{12} variation with frequency for a typical clinical scenario (healthy and 85% scaled lung), (b) E-field distribution on xy plane, at height of active feed, at 2.3 GHz. The values are normalized to 1 W input power, resulting to maximum value of 4.69E+03 V/m.

IV. Conclusion

This paper proposed a dual patch antenna (sensor) for pneumothorax diagnosis. First, sensor performance is parametrically investigated, using simplified tissue models. The crossed antenna configuration is improved and applied onto modified, according to literature, anatomical numerical models, assessing a typical clinical pneumothorax case. Two modifications are proposed in order to simulate realistic pneumothorax case: lungs scaling and air bubbles insertion into selected structural regions. As matching material, water coat has been selected, reassuring the sensor performance. Sensor sensitivity reaches 1 cm of air. Next steps are planned towards measurements verification, by applying the sensor onto a modified thorax experimental phantom. The phantom is currently under design, including broadband lung-tissue simulated structures and varied air gaps in selected regions of interest. According to the research project workflow, the study is planned to conclude with in-vivo tests on supervised pigs, with selected degrees of pneumothorax.

References

[1] Wakai AP; Spontaneous pneumothorax. Clin Evid (Online), pii: 1505, Jan 17, 2011.

[2] Pleural Disease Guidelines; British Thoracic Society, Sept. 2010.

[3] N. Celik, R. Gagarin, G. Ch. Huang, M. F. Iskander, and B. Berg, “Microwave Stethoscope: Development and Benchmarking of a Vital Signs Sensor Using Computer Controlled Phantoms and Human Studies,” *IEEE Trans. Biomedical Engineering*, [Epub ahead of print], 2013.

[4] S Gabriel, R.W Lau, and C. Gabriel, “The dielectric properties of biological tissues: III Parametric models for the dielectric spectrum of tissues,” *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2231-2293, 1996.

[5] M. Frank, V. Schorge, K. Hegenscheid, A. Angermaier, A. Ekkernkamp, N. Hosten, R. Puls, and S. Langner, “Sturdivan’s formula revisited: MRI assessment of anterior chest wall thickness for injury risk prediction of blunt ballistic impact trauma,” *Forensic. Sci. Int.*, vol. 212, pp. 110–114, June 2011.

[6] M. Christopoulou and S. Koulouridis, “Design requirements of microwave sensor for pneumothorax diagnosis”, in *Proc. IEEE International Symposium on AP - URSI*, Florida, USA, July, 7-13, 2013.

[7] M. Christopoulou and S. Koulouridis, “Patch antenna configuration for pneumothorax diagnosis”, in *Proc. Joint Meeting of BEMS and EBEA-BioEM 2013*, Thessaloniki, Greece, Jun 10 - 14, 2013.

[8] A. Christ, et al., “The Virtual Family – Development of surface-based anatomical models of two adults and two children for dosimetric simulations,” *Phys. Med. Biol.*, pp. N23–N38, vol. 55(2), 2010.

[9] Advanced Trauma life Support Program for Doctors. Ed 6, Chicago. IL American College of Surgeons, 1997.

[10] SEMCAD-X, Schmid & Partner Enineering AG: http://www.speag.com/products/semcad/overview/

[11] “IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300GHz,” *IEEE Standard C95.1–2005*, 2005.