Design requirements of microwave sensor for pneumothorax diagnosis

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Abstract—We investigate the design of a low-power, non-invasive device for detection of air cavities in the space between chest and lung (i.e., pneumothorax). To this end, we study the operational frequency band and sensitivity capabilities of such device. Simplified scenarios of parameterized layered biological models in the exposure of electromagnetic plane wave and coupled radiating antennas are assessed via an analytical solution and Finite Difference Time Domain (FDTD) method. The frequency band under study is 1-10 GHz. Differential comparative calculations of reflection coefficient and reflected electric field indicate the frequency band and resolution of the sensor. Results reveal that the existence of air alters considerably the reflection coefficient in the frequency band of 1-3 GHz. The resolution of the sensor is predicted to reach 5 mm of air layer thickness.

I. INTRODUCTION

Pneumothorax refers to a collection of air in the pleural cavity between the lung and the chest wall. It is a life-threatening medical condition and it is usually diagnosed by X-rays, Computed Tomography (CT) or ultrasound imaging. The body regions under examination are: a) the anterior second intercostal space at the midclavicular line, b) the lateral forth intercostal space of the affected hemithorax [1]. For these two regions, the averaged values of chest wall (CW) and adipose tissue (AT) thickness reach 35.9 mm and 16.4 mm, correspondingly [2]. The dominant biological tissues in the thorax section are: skin, fat, muscle and bone, not in case of the intercostal space. Inter-subject variability reasons, such as gender; weight; height; obese factor; fitness factor can influence the thickness of mainly fat and muscle layers.

The idea of a sensitive, low-power microwave sensor, placed in the proximity of patient’s thorax has triggered the authors (e.g. Error! Reference source not found.). The sensor can monitor differentially the reflected waves, which alter in phase and amplitude, due to the presence of air cavities close to the skin surface. The paper focuses on the preparatory phase of the research workflow [4] in order to assess the interaction between a planar layered tissue model of thoracic area and one or multiple microwave sources. The variations in reflection coefficient and reflected electric field will define the operational frequency band of the sensor. The paper is organized as follows. Section II describes materials and methods. Indicative results are presented in Section III. The paper concludes in Section IV, providing future research planning.

II. MATERIALS AND METHODS

Assuming an electromagnetic source at microwave frequencies that radiates the thorax; the amplitude, phase and return time at source point of the reflected electromagnetic wave should depend strongly on the dielectric properties of the tissues. The complex relative permittivity of a biological tissue is frequency dependent and is described by a Cole-Cole equation [5]. The penetration depth $\delta$ and the wavelength $\lambda$ of the electromagnetic wave that propagates into the biological tissue are calculated for skin and fat, i.e. tissues that respectively correspond to high and low water-content. These values may provide a first indication of the appropriate frequency band for the under-design sensor. Referring to $f = 1$ and $10$ GHz, $\delta$ varies from 20.7 to 1.8 mm for skin and 71.1 to 5.7 mm for fat, while $\lambda$ from 50.1 to 5.7 mm for skin and 134.2 to 15.3 mm for fat. Based on the averaged CW thickness, which does not exceed 35 mm [2], and the required sensor’s resolution of 5-10 mm, it is concluded that the frequency band of 1-10 GHz is suitable for the operation of the diagnostic device.

The exposure scenarios are assessed by a) an analytical recursive formula [6] that gives the reflection coefficient for a plane wave with normal incidence at a semi-infinite 2D multilayer model and b) applying Finite Difference Time Domain-FDTD [7] method, with the use of electromagnetic simulation platform SEMCAD X [8] at a 3D multilayer model irradiated by a normal incident plane wave, propagating to the direction of $z$. Initially, a simplified planar model of up to N=6 successive layers is assessed. It consists of skin, fat, muscle, bone, air and lung. Reflection coefficient, reflected electric/magnetic field and power density are recorded in frequency and time domain. Results are referenced against healthy cases, i.e. without air cavities.

III. RESULTS

First, the recursive formula is applied for variable air layer thickness $h_{air} = 0, 1, 5, 10, 15$ mm in planar models of skin(5 mm)-fat(10 mm)-air-lung. Results show that the presence of $h_{air} \geq 5$ mm significantly modifies the reflection coefficient for two frequency regions of 2.5-3.2 GHz and 4.6-5.6 GHz. At $f_0 = 2.6$ GHz, $h_{air} = 15$ mm case varies 12 dB from the reference (see...
Fig. 1). No significant variations are found for cases of \( h_{\text{air}} = 1 \) mm. Further, no significant variations are observed for frequencies above 6 GHz. This is probably due to the strong attenuation of the travelling wave through the tissues before reaching the air layer. If a bone layer (10 mm) is also considered (e.g. the sensor is placed over the rib), then because of the presence of air, considerable differences (4-8 dB) for the reflection coefficient, are observed, for the frequency region of 1.4-2 GHz and for \( h_{\text{air}} \geq 5 \) mm [9].

Next, FDTD method is applied for a 3D planar model of 150×150 mm² aperture irradiated by an incident plane wave. Analytical results indicate that optimum frequency region is restricted to 1-5 GHz. Numerical simulations for variable air layer thickness \( h_{\text{air}} =0, 1, 5, 10, 15 \) mm in models of skin(5 mm)-fat(10 mm)-bone(10 mm)-air-lung(300 mm), show that reflected power density is significantly affected due to the presence of \( h_{\text{air}} \geq 5 \) mm (see Fig. 2).

Figure 3. Alternation in reflected electric field, due to the variation of \( h_{\text{air}} = 0, 15 \) mm, in the 3D planar model of 150×150 mm², for time domain.

Similarly, for skin(5 mm)-fat(10 mm)-air-lung model, results in time domain (see Fig. 3) show that the presence of \( h_{\text{air}} = 15 \) mm has strong effect on reflected electric field.

IV. CONCLUSIONS AND FUTURE WORK

This work investigates the operational frequency region and resolution of a microwave-based sensor for pneumothorax. Preliminary results for a normal incident plane wave and simplified planar thoracic model indicate that the most appropriate frequency region is restricted to 1-3 GHz. In this region, air layer 5 mm thick or greater is detected. Observed differences of reflection coefficient (>5 dB) in conjunction with time domain information should allow not only for detecting pneumothorax but also estimating its severity. Antenna system for the device is currently being designed and should be small, broadband and allow for the detection of pneumothorax in various human body profiles.

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REFERENCES