Miniaturized vivaldi antenna system for pneumothorax diagnosis: proposed air detection scenarios

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Short Summary

A novel sensor model based on a miniaturized Vivaldi antenna is investigated, in order to non-invasively diagnose air volumes into the pleural cavity of lung area (i.e. pneumothorax). Proposed detection scenarios are calculated using simplified a) planar multilayered, b) closed rectangular layered thorax and c) MRI-based anatomical whole body phantoms. The frequency range of operation is set to 1 - 4 GHz. The best detection scenario for 1 cm air thickness consists of two antennas with given relative positioning onto the closed thorax model and results to 38.2 dB difference in $S_{12}$, at 3 GHz.

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. Given that the transmission and reflection of Electromagnetic Fields (EMF) through the body strongly depend on the tissues dielectric properties, EMF can be utilized for diagnosis, for relatively small depths, such as the chest cavity. During emergencies, a safe, compact, portable and easy-to-use microwave sensor (antenna system) can be also applied.

In literature, there are plenty antenna types proposed for emergency diagnosis (e.g. UltraWideBand [1]). Our previous work [2] focused on rectangular patch antennas configuration, in order to non-invasively diagnose pneumothorax. The need to minimize the contact surface between the skin and the sensor, enabling its use onto the intercostal space, led to the exploitation of a miniaturized Tapered-Slot Antenna (TSA) antenna, using exponential tapering (i.e. Vivaldi). Combining thorax tissues thickness and EMF penetration depth, the operation frequency range under study is limited to 1 – 4 GHz [3]. It should be noted that the scope of the sensor modelling is to mainly reveal its differential capability, in order to efficiently distinguish healthy and pathological cases (i.e. pneumothorax).

DESCRIPTION OF ANTENNA, PHANTOM MODELS AND AIR DETECTION SCENARIOS

The antenna sensor that is modeled is a miniaturized Tapered-Slot Antenna (TSA) antenna, using exponential tapering (i.e. Vivaldi). The miniaturization procedure followed the methodology described in [1][1], according to which the width (w) and length (l) of the traditional antipodal Vivaldi antenna are substantially reduced, maintaining the ultrawideband performance. Fig. 1(a1) illustrates the configuration of the proposed antenna. The width (w), length (l), aperture ($w_a$), microstrip thickness ($w_t$) and microstrip feeder positioning (f) are set according to Fig. 1(a2). Depth of the corrugations ranges from 1 mm (#1: inner) to 3 mm (#8: outer), while their width is uniform and is equal to 0.5 mm. Rogers RT6010 (thickness = 0.64 mm, dielectric constant = 10.2) is selected as substrate material.

In the frame of this work, three (3) tissue phantoms are modeled:

- **PLANAR**: A coarse planar multilayered tissue numerical model. 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), 10 mm (air) and 100 mm (inflated lung). XY dimensions of the planar model are set 300 x 300 mm$^2$ (i.e. $\lambda_0 \times \lambda_0$, $\lambda_0$ 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 (2) anatomical MRI-based Virtual Family whole-body models, Duke and Ella [4][4] (Fig. 1(b1, b2)). 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 $\lambda_0$ 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 (Fig. 1(b2)). 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).

- **DUKE and ELLA:** A section of the thorax (including lungs) of two anatomical Virtual Family whole body numerical models [4], Duke and Ella. 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 (x axis) and depth (y axis) (Fig. 1(c1)), 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 (Fig. 1(c2)). In case of pneumothorax, the air that is trapped into the pleural cavity tends to gather in the upper parts of the thorax, due to the lying position of the patient. These two regions are considered the most common ones [5].

Three air detection scenarios are considered for PLANAR model: a) one Vivaldi antenna, having its width side parallel to x axis (P1x) (Fig. 1(d1)), b) two Vivaldi antennas, separated on x-axis by 20 mm, having their width side parallel to x axis (P2x), c) two Vivaldi antennas, separated on x-axis by 20 mm, having their width side parallel to y axis (P2y) and centered onto PLANAR center. Three additional scenarios are considered for THORAX model, named correspondingly: A) (T1x): one antenna with its width side parallel to x axis, B) (T2x): two antennas, separated on x-axis by 20 mm, with their width side parallel to x axis and C) (T2y): two antennas, separated on x-axis by 20 mm, with their width side parallel to y axis. Crossed antennas scenarios (i.e. one antenna with its width side parallel to x axis and the second one to y axis) have been avoided, since this would obstruct the sensor use into the narrow intercostal space. All antenna configurations onto THORAX and PLANAR models are in touch with the skin layer. The antenna configuration with the best performance is selected to be applied onto DUKE and ELLA models. In this case, it is noteworthy that due to DUKE and ELLA non-flat skin surface, which results to inevitable air gaps between the antenna surface and the skin, distilled water is used as coupling medium. The electromagnetic exposure problem is solved by applying Finite Difference Time Domain (FDTD) method, with the use of the software platform SEMCAD-X 14.8.4 [6]. Broadband simulations are carried out for a frequency range of 1 - 4 GHz. Multipole Debye materials are selected to characterize electrically the biological tissues.

**Figure 1.** Numerical models and air detection scenarios: (a1-2) Geometrical details of the Vivaldi antenna. (b1) xz and (b2) xy illustration of lung size in Duke (blue) and Ella (pink) models, compared to the THORAX lung contour (red box). Pneumothorax modeling by (c1) scaling down (85%) the lung, (c2) inserting air bubbles in the two regions of interest [5]. Air detection scenarios in xz plane: (d1) P1x and (d2) T2x.

**SIMULATION RESULTS AND DISCUSSION**

All above mentioned air detection scenarios are differentially compared to the corresponding healthy cases with no air layer into the tissue model. The air layer has thickness of 1 cm (pneumothorax) or 0 cm (healthy case), alternating respectively the thickness of inflated lung. The variation of transmission coefficient $S_{11}$, $i = 1, 2$ is differentially evaluated for pneumothorax and health case (Fig. 1(a-c)). Additionally, this variation is presented comparing corresponding
scenarios using PLANAR (P1x, P2x, P2y) and THORAX (T1x, T2x, T2y) models. Concerning the models, the differentiation between pathological and healthy case is generally quite clear mainly for the THORAX model, which is a more realistic representation of the thorax cut. More specifically, the maximum difference in $S_{11}$ throughout the frequency range reaches i) 6.5 dB at 1.62 GHz (P1x) and 0.6 dB at 1.5 GHz (T1x), ii) 1.3 dB at 1.1 GHz (P2x) and 11.5 dB at 1.1 GHz (T2x), iii) 2.2 dB at 3.1 GHz (P2y) and 38.2 dB at 3 GHz (T2y). The frequency where the maximum difference is calculated for the two antennas corresponds to 1 GHz for x-positioning and is shifted to 3 GHz for y-positioning, influenced by the relative polarization of the antennas.

Based on the best air detection scenario (i.e. T2y), electric field distribution is extracted (Fig. 2(d)) in dB on xz plane at 3 GHz, for both healthy and pathological cases. Only one Vivaldi antenna is active. All E-field values are normalized to 1 W input power, therefore 1.29E+03 V/m corresponds to 0 dB. Both subfigures are zoomed, focusing on the air layer of 1 cm thickness. This layer is simulated as lung in the top subfigure and air in the bottom one. Fig. 2(d) reveals the E-field reflection due to the existence of 1 cm air layer before lung tissue, which results to the differentiation of $S_{12}$ value at the same frequency.

Results concerning the anatomic models are to be presented in the conference. The preliminary outcomes, assessed by the rectangular phantoms, are expected to be verified. The sensitivity of the sensor will be evaluated in relation to the extension of the compressed lung and its relative positioning onto the air bubbles trapped in the pleural cavity. The results will be additionally enhanced, by altering the air layer thickness and the separation distance between the skin and the antenna.

**Figure 2.** $S_{11}$ and $S_{12}$ as a function of the selected frequency range 1 – 4 GHz for the configurations (a) P1x, T1x, (b) P2x, T2x, (c) P2y, T2y. (d) E-field distribution [dB] on a zoomed region of xz plane for T2y scenario, at 3 GHz. One antenna is active. The values are normalized to 1 W input power. 0 dB corresponds to 1.29E+03 V/m.

**CONCLUSIONS**
In order to non-invasively detect the air collection into the pleural cavity of lung area (i.e. pneumothorax), diagnostic scenarios using miniaturized Vivaldi antenna are proposed, within this paper. Proposed detection scenarios are calculated using simplified a) planar multilayered, b) closed rectangular layered thorax and c) MRI-based anatomical whole body phantoms. The frequency range of operation is set to 1 - 4 GHz. The scenarios focus on the minimization of a) the air thickness detected by the Vivaldi sensor, investigating the detector sensitivity and b) the contact surface between the skin and the sensor, enabling its use onto the intercostal space. The best detection scenario for 1 cm air thickness reached 38.2 dB difference in $S_{12}$, between healthy and pathological case, calculated at 3 GHz. This scenario consists of two Vivaldi antennas facing each other, separated by 20 mm and placed in contact to the closed thorax phantom. Verification with modified anatomical models will follow.

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