Alberto Battistel*, Peter P. Pott, Eric D. Roessner and Knut Moeller

Design of ultra-wideband antenna for the localization of pulmonary lesions during thoracoscopic surgery

Abstract: Biopsies or surgical excisions for diagnosis should be taken for pulmonary lesions which show evidence of growth or are larger than 8 mm. This is usually performed by video-assisted thoracoscopic surgery. To improve the intraoperative localization of these lesions, we propose to add an ultra-wideband antenna directly on a thoracoscopic tool and locate the lesion through microwave imaging. Here the design of an antenna for such a goal is undertaken. Numerical simulations are used to quantify the influence of a fictional lung lesion on the signal recorded by a bowtie antenna of different lengths (2 to 6 cm) and widths (0.5 to 1.5 cm). It is found that the most important design parameter is the total length of the antenna. The width of the antenna, instead, affects only marginally the signals, but it has a limited effect for deeper lesions.

Keywords: thoracoscopic surgery, electromagnetic simulations, bowtie antenna, lung lesion.

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1 Introduction

Small pulmonary lesions are frequently excised for diagnostic or therapeutic reasons by minimally invasive surgeries such as video-assisted thoracoscopic surgery (VATS). Due to the pro-

*Corresponding author: **Alberto Battistel:** Institute of Technical Medicine (ITeM), Furtwangen University (HFU), Jakob-Kienzle-Strasse 17, 78054 VS, Germany, and e-mail: alberto.battistel@hs-furtwangen.de

Peter Paul Pott: Institute of Medical Device Technology, University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany

Eric Dominic Roessner: Academic Thoracic Center Mainz, Division of Thoracic Surgery, University Medical Center of the Johannes Gutenberg University Mainz, Langenbeckstraße 1, 55101 Mainz, Germany

Knut Moeller: Institute of Technical Medicine (ITeM), Furtwangen University (HFU), Jakob-Kienzle-Strasse 17, 78054 VS, Germany

Figure 1: Cross-section of the thorax with a pulmonary lesion in the right lung (a). Effect of the lung collapse on the position of a pulmonary lesion (b).

grammed follow-ups of extrathoracic cancers and to the upcoming lung cancer screening programs the need for such kinds of operations is increasing [1].

Small nodules located deep into the lung tissue represent a challenge for VATS surgeons. In fact, the impossibility to locate these nodules either visually or through manual/digital palpation may lead to the intraoperative conversion of the minimally invasive surgery into a thoracotomy thus losing the rapid recovery, fewer complications, and shorter hospital stay associated with VATS.

None of the existing localization strategies such as pre-operative spiral computed tomography (CT) guided marking with metal guidewires [2], fiducial or dye as well as intraoperative cone-beam CT guidewire marking [3,4] have achieved a major practice because of their complexities and costs.

Figure 2: Top view of the 2 cm long and 1 cm wide simulated bowtie antenna.

Figure 1 illustrates the problem associated with the localization of a lung lesion during VATS. In part a), the exact position of the pulmonary lesion, as for example determined by CT, is known. However, during the surgery, the lung collapses thus changing the position of the lesion. (Figure 1 b).

In our previous works, we proposed the use of radiofrequency (RF) technologies to localize the lesion [5,6]. In fact, an antenna mounted on a thoracoscopic tool can illuminate the lung directly reducing the interferences coming from other organs and tissues. Since the antenna needs to fit the requirements of a thoracoscopic surgery its dimensions are critical. While one dimension can be up to several centimeters, the antenna should not be wider than circa 1 cm and because it needs to be moved into a limited space it should also have a compact shape with few asperities.

It was found that a frequency around 600 MHz guarantees the localization of a lesion up to 10 cm of depth inside the lung tissue [5]. The wavelength of the electromagnetic wave in the lung tissue associated with such a frequency is 6.81 cm. This means that the lesion localization up to several centimeters of depth happens in the antenna near-field and because of the strong attenuation in the lung tissue frequencies beyond 2 GHz are not feasible [5].

In this contribution, we focus on the design of a bidimensional biconical antenna also known as the *bowtie* antenna because of its shape which resembles that of the famous necktie (see Figure 2). The main advantages of this type of antenna are its broadband and its simple, compact, and self-sustained structure [7]. Also, it offers the possibility to be folded. Such a feature can be used, for example, to tune the directivity of the antenna or to retract the antenna inside the thoracoscopic tool.

We investigate through numerical simulations the effect of the length of the antennas, which relates to its main resonance frequency, and its width, which determines its broadband characteristics, but also its footprint on the sensitivity toward a target which mimics a lung lesion located at several depths inside a lung.

2 Methods

The simulations were performed with a Finite Difference Time Domain (FDTD) solver using gprMax version 3.1.5 [8] on a 3D space. The dimensions of the computation domain were 7 cm, 10.5 cm, and 9 cm for the x , y , and z -direction with a cell size of 0.5 mm. The top 2 cm of the domain were made of air ($\epsilon_r = 1$), while the bottom of lung tissue.

The dielectric permittivity and the conductivity for lung tissue were taken according to the *Deflated Lung* tissue from the work of Gabriel [9]. The dispersive properties of the lung material were incorporated into the simulations through a 3-terms Debye relaxation. For the relaxations, a relative permittivity of 24.6 was used with three permittivity deltas of 9490, 69.3, and 29.2, and three-time constants of $1.93 \cdot 10^{-7}$ s, $4.26 \cdot 10^{-9}$ s and $2.33 \cdot 10^{-11}$ s. The 3-terms Debye function gave a maximal error of 5.4 % for the wavelength.

The computation domain was truncated in all directions by a 10-cells-wide (0.5 cm) perfectly matched layer (PML) and the antenna was placed on the very top of the lung tissue.

The antenna was simulated as two triangular conductor patches energized by a transmission line element with a characteristic impedance of 50Ω placed between the patches as depicted in Figure 2 which shows an antenna with a length of 2 cm and a width of 1 cm. The lengths L of the bowtie antennas were 2 cm to 6 cm and the widths W were 0.5, 1, and 1.5 cm. The antenna was oriented along the z -direction and placed in direct contact with the lung tissue.

The transmission line, which mimics the physical connection between the transceiver and the antenna, was powered by an excitation shaped as the derivative of a Gaussian function with an amplitude of 1 V centered at 600 MHz, as this was found to be the best frequency in our previous works [5,6].

The voltage on the transmission line was used as a response signal as it would be seen by the transceiver.

The lung lesion was simulated as a spherical metallic target with a 0.5 cm radius. The position of the target was changed between 1 cm and 5 cm of depth into the lung tissue. A perfectly metallic object was taken as a lung lesion as there is no broadband information on the lung cancer dielectric properties. Such a target gives the maximal dielectric contrast compared to any other material, therefore, providing an upper limit on detectability.

3 Results and discussion

Figure 3 a) shows the waveforms for the 0.5 cm wide bowtie antenna of different lengths L without any target present in the

Figure 3: Waveform simulated without a target for the 0.5 cm wide antennas (a). Difference between the waveform with and without a target located at 1 cm of depth (b).

lung tissue. The shapes display two maxima and two minima. The main differences between the different antenna lengths are on the position and intensity of both minima and of the second maximum which appear beyond *ca.* 2 ns. The first maximum instead is mostly independent of the antenna length. In contrast, the intensity of the first minimum follows a trend connected with L , where shorter antennas have a smaller minimum. This behavior was in common to all the antennas studied in this work independently of their width.

The effect of the target on the waveforms is highlighted in Figure 3 b) where the difference between the simulations made with and without the target in the lung tissue is displayed. The presence of the target gives a signal intensity that is between 10 and 15 times lower than that of Figure 3 a). Also, in this case, all the antennas show the same features irrespectively of their width.

To further investigate the effect of the antenna length and width the Euclidean distance (2-norm) d :

$$d = \sqrt{\sum (\mathbf{w}_{with\ target} - \mathbf{w}_{without\ target})^2} \quad (1)$$

between the waveforms w simulated with and without the target was used. A high Euclidean distance means that the waveforms are significantly different while when the waveforms are very similar d goes to zero. This measure was taken as a

Figure 4: Euclidian distance as function of the target depth for the antenna of width 0.5 cm (a), 1 cm (b), and 1.5 cm (c).

quantitative value to express the sensitivity of the antenna design toward the target.

Figure 4 a), b), and c) display the Euclidean distance calculated against the depth of the target for the antenna width of 0.5, 1, and 1.5 cm, respectively.

The Euclidean distance is between *ca.* 0.5 V for shallow targets to *ca.* 30 mV for the target in the deepest position. This represents the main trend for all the antenna widths in Figure 4 meaning, as expected, that a deeper target has a smaller impact on the waveform recorded at the antenna.

For the shallowest targets, the best antennas, that is those showing the largest Euclidean distance, independently of their width, were those with the shortest length. In fact, in all cases, the antennas with $L = 2$ cm and $L = 3$ cm gave almost the same value of d . However, for deeper targets, the situation is different with either the antennas with a length of 3 or 4 cm giving

the best results. On the other side, the longest antennas, that is those with $L = 6$ cm, gave almost consistently the lowest values of d , apart from the deepest target where the shortest antennas gave the worst results.

This indicates that the best length for the antenna is between 3 and 4 cm which matches a wavelength of 6 to 8 cm in agreement with our preliminary results where the best performances were achieved operating at 600 MHz [5,6]. In fact, at this frequency, the electromagnetic wavelength inside the lung tissue is *ca.* 7 cm.

On the other hand, the width W of the antennas has a small effect on the simulations. This effect is negligible for shallow targets up to 2 cm of depth. However, its impact is stronger for the deepest targets and the difference between the antenna with a width of 0.5 cm (Figure 4 a) and that with a width of 1.5 cm (Figure 4 b) is of some 10 mV.

As a comparison, the addition of -80 and -60 dB white noise on the waveforms would produce an equivalent d of *ca.* 7 and 70 mV, respectively. In the latter case, the presence of a target would be detected up to 3 cm of depth for all the antennas' widths, but only the antenna with a width of 1 cm (Figure 4 b) and 1.5 cm (Figure 4c) and a length of 3 and 4 cm would be able to detect the target also at 4 cm of depth.

4 Conclusion

In this work, the design of an ultra-wideband antenna was investigated by numerical analysis. The purpose of this antenna is the localization of pulmonary lesions during a video-assisted thoracoscopic surgery.

The variation in signal intensity of a fictional lesion inside a slab of lung tissue was used to quantify which parameters affect the most antenna response.

It was found that for targets located at 1 cm of depth the best performances were given by a short antenna of length indifferently of either 2 or 3 cm. However, for deeper targets, the best antenna length was between 3 and 4 cm.

The effect of the antenna width was instead negligible for targets up to 2 cm of depth. Whereas, for deeper targets, the wider antennas gave marginally better results especially if noise is considered. However, weighting the improved performances against the increase in footprint, the best antenna width is around 1 cm.

Nevertheless, further improvements are still necessary. In fact, these are the best scenario results: a metallic target was used as a fictional pulmonary lesion and no environmental interferences were considered.

Different strategies can be employed to improve the signal quality by using spacing materials with tuned dielectric properties and by changing the shape of the waveform used.

Finally, we foresee testing with phantoms and biological tissues to consider the noise level and the real effective variability in dielectric properties even in the same organ.

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References

- [1] Meyer M, Vliegenthart R, Henzler T, Buerger D, Giordano FA, Kostrzewa M et al. Management of Progressive Pulmonary Nodules Found during and outside of CT Lung Cancer Screening Studies. *J. Thorac. Oncol. Off. Publ. Int. Assoc. Study Lung Cancer* 2017;12(12):1755–1765.
- [2] Kostrzewa M, Kara K, Rathmann N, Tsagogiorgas C, Henzler T, Schoenberg SO et al. Computed Tomography-Assisted Thoracoscopic Surgery: A Novel, Innovative Approach in Patients With Deep Intrapulmonary Lesions of Unknown Malignant Status. *Invest. Radiol.* 2017;52(6):374–380.
- [3] Uneri A, Nithianathan S, Schafer S, Otake Y, Stayman JW, Kleinszig G et al. Deformable registration of the inflated and deflated lung in cone-beam CT-guided thoracic surgery: initial investigation of a combined model- and image-driven approach. *Med. Phys.* 2013;40(1):017501.
- [4] Zhao Z-R, Lau RWH, Yu PSY, Ng CSH. Devising the guidelines: the techniques of pulmonary nodule localization in uniportal video-assisted thoracic surgery-hybrid operating room in the future. *J. Thorac. Dis.* 2019;11(Suppl 16):S2073–S2078.
- [5] Battistel A, Pott PP, Möller K. Numerical Analysis of the Localization of Pulmonary Nodules during Thoracoscopic Surgery by Ultra-Wideband Radio Technology. *Appl. Sci.* 2021;11(9):4282.
- [6] Battistel A, Möller K. Ultra-wideband Localization of Pulmonary Nodules During Thoracoscopic Surgery. In: Jarm T, Cvetkoska A, Mahnič-Kalamiza S, Miklavcic D, eds. *8th European Medical and Biological Engineering Conference*. IFMBE Proceedings. Cham: Springer International Publishing; 2021:1146–1155.
- [7] Loi KW, Uysal S, Leong MS. Design of a wideband microstrip bowtie patch antenna. *IEE Proc. - Microw. Antennas Propag.* 1998;145(2):137.
- [8] Warren C, Giannopoulos A, Giannakis I. gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar. *Comput. Phys. Commun.* 2016;209:163–170.
- [9] Gabriel C. *Compilation of the Dielectric Properties of Body Tissues at RF and Microwave Frequencies*. King's Coll London (United Kingdom) Dept of Physics; 1996. Available at: <https://apps.dtic.mil/docs/citations/ADA303903>. Accessed October 16, 2019.