A Feasibility Study of 2D Microwave Respiration Monitoring through Simulation Method

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Abstract. This paper studies the feasibility of two-dimensional microwave respiration monitoring. According to a real human computed tomography image, the chest cavity is established in the simulation, which is more realistic and persuasive. Based on the formula of 4-Cole-Cole expressions, some corresponding parts of the human body's relative permittivity and conductivity are calculated. Moreover, the dielectric properties within the lungs will change during respiration, and the changes will affect the transmission of microwaves in the human thorax. In this paper, the frequency of 433MHz and 915MHz is adopted to monitoring respiration. The simulation data is collected and analyzed to get intuitive maps. In summary, this study illustrates the feasibility of microwave respiration monitoring.

Keywords: respiration monitoring, microwave, feasibility study.

1. Introduction

Vital signs are of great significance in the early prevention and diagnosis of diseases. Respiration is an essential physiological activity to maintain the human metabolism among the vital signs. Some acute and chronic diseases, such as atypical pneumonia, cerebral ischemia, obstructive sleep apnea syndrome, etc., can cause abnormalities such as shortness of breath, pause, and irregular rhythms. If they are not intervened in time, it will bring the risk of complications from the slightest, and the other endangers the patient's life directly. From this point of view, the monitoring of respiratory system functions is essential for diagnostic and therapeutic medicine.

The noncontact detection characteristic of Doppler radar provides an unobtrusive means of respiration detection and monitoring. It avoids additional preparations, such as physical sensor attachment or unique clothing, which can be useful for specific healthcare applications. This method mainly detects the signal and frequency of breathing but cannot observe lungs' changes [1]. The breathing rate is a simple test of respiratory function, and it is mostly done by inspecting the color of skin and mucous membranes. However, it is both time-consuming and demanding on the part of health care personnel, and it is not suitable for situations where continuous monitoring is required [2]. Present biomedical imaging technology, including x-ray, computed tomography (CT), magnetic resonance
imaging (MRI) and etc., can provide high-resolution images. However, x-ray and CT have a large amount of ionizing radiation. Besides, the equipment for them is usually too bulky to be used for long time bedside monitoring. In addition, electrical impedance tomography (EIT) can sense the change of internal resistance through the current on the object's surface. In recent years, it has been used in the medical field, especially respiratory mechanics research. It can reflect the distribution of lung ventilation reliably. Nevertheless, EIT uses low-frequency current, which leads to limited spatial resolution [3, 4].

Furthermore, microwaves can also be used for respiratory monitoring through the lungs' relative permittivity and conductivity changes. Within the microwave spectrum, biological tissues are differentiated and can be imaged based on their dielectric properties [6]. The amount of air in the lungs will change during respiration so that the lungs' dielectric properties and conductivity will change accordingly. Therefore, microwaves can be used to monitor lung ventilation because their transmission is affected by the dielectric constant and conductivity [5]. Compared with CT, the microwave has no ionizing radiation, and the temporal resolution is high. Compared with EIT, microwave monitoring can provide higher spatial resolution because it uses higher microwave frequencies.

Lots of researchers have investigated the possibility of using the microwave as a biomedical imaging method. For example, the group of Semenov has demonstrated that microwave tomography (MWT) is applicable for breast cancer detection, diagnosis of lung cancer, brain imaging, and cardiac imaging [5]. The feasibility of microwave respiration monitoring was validated by H. Zhang et al. [6]. Volakis and his team integrate a wearable health monitoring sensor, which is presented for the diagnosis of pulmonary edema with microwave operating at 40MHz. They have made good progress in a wireless body area network (MS-BAN) for medical sensing, which is employed to provide remote data transfer [7].

In this paper, the feasibility of two-dimensional microwave respiration monitoring is demonstrated with COMSOL Multiphysics. A chest cavity model is set up in COMSOL, and an imitation of respiration is achieved by changing the relative permittivity and conductivity of the lungs. Microwaves of 433MHz and 915MHz are used separately. Ideal sources are placed around the thorax, and the simulated data is analyzed to study the monitoring of respiration. The remainder of this paper is organized as follows: Section II provides the principles and calculation of related parameters; Section III describes the establishment of the model; Section IV shows the numerical analysis of simulation results and illustrates the sensitivity of sensors in corresponding positions.

2. Numerical calculation of dielectric properties

Human tissues are dispersive medium. The changes in dielectric properties can reflect changes in tissues’ pathological states. Both relative permittivity and conductivity of human tissues have a special relationship with frequency. The spectrum extends from Hz to GHz and shows four dispersion regions, and Gabriel modeled the frequency dependence of the dielectric properties to the four dispersions spectrum [8].

Based on the formula of 4-Cole-Cole expressions published by Gabriel in [8], we can calculate the relative permittivity and conductivity of some corresponding parts of the human body, including lung, heart, muscle, fat, and skin. Besides, 433MHz and 915MHz are adopted as they belong to the industrial, scientific, and medical band (ISM). The specific data is reflected in Table 1, and the curve of relative permittivity can be seen in Figure 1.
Table 1. Relative permittivity and conductivity of tissues

|          | Frequency | Relative Permittivity ($\varepsilon_r$) | Conductivity ($\sigma$) (S/m) |
|----------|-----------|----------------------------------------|-------------------------------|
|          | 433MHz    | 915MHz                                 |                               |
| Heart    | 65.3287   | 59.7959                                | 0.9833                        | 1.2379                        |
| Muscle   | 56.8732   | 54.9970                                | 0.8049                        | 0.9481                        |
| Lung(deflated) | 54.1980   | 51.3728                                | 0.6945                        | 0.8637                        |
| Lung(inflated) | 23.5860   | 21.9722                                | 0.3799                        | 0.4593                        |
| Fat      | 11.5882   | 8.9994                                 | 0.0822                        | 0.1102                        |
| Skin     | 46.0789   | 41.3291                                | 0.7017                        | 0.8715                        |

Figure 1. The curve of relative permittivity and conductivity: (a) relative permittivity. (b) conductivity.

3. Chest cavity model establishment

In this simulation, a chest cavity model is built in COMSOL. The model is based on the real CT map of the human chest to make the results more realistic and persuasive. Fig. 1 shows the specific chest model. The thoracic cavity consists of five parts: heart, lung, muscle, fat, and skin. All of them are composed of irregular 2D graphics. The overall length of the model is about 22cm, and the width is about 15cm. Based on the assumption, the outermost layer is skin, and the inner layer is fat. The entire chest cavity contains the heart and lungs, and the rest of the inner space is muscle. For simplicity, the other biological tissues are omitted.

According to the data in Table 1, the corresponding relative permittivity and conductivity, mimicking the real dielectric properties of human tissues and organs, are set. 2-D delta sources represent 12 sensors, which are placed on the boundary between free space and human. The specific locations can be seen in Figure 2 (a), and all of the sources are perpendicular to the x-y plane. As it is infinitely long in the z-direction, the electric field is TM mode.

In order to truncate the calculation domain, radiation boundary is used. In some simulation experiments, a perfect electric conductor (PEC) or perfect magnetic conductor (PMC) can enclose the model. This enclosure could shield the transmitters and receivers from external interferences and avoid energy leakage from the transmitters to the outside. However, it is not convenient to use PEC or PMC in real life. So, radiation boundary, which is 12 cm away from the chest cavity, is used.

The accuracy is mostly related to the finite element meshes. The finite element mesh is used to subdivide the model into smaller domains called elements, over which a set of equations are solved. These equations approximately represent the governing equation of interest via a set of polynomial functions defined over each element. As the mesh is refined, the computed solution is more accurate,
but the calculation amount will increase dramatically. In this experiment, the number of mesh cells is 5044, and the specific finite element mesh refinement could be seen in Figure 2 (b).

![Chest cavity model: (a) two-dimensional model; (b) finite element mesh of the model.](image)

Figure 2. Chest cavity model: (a) two-dimensional model; (b) finite element mesh of the model.

4. IV. Simulation and data processing

Simulation-based on the model is made. Firstly, a microwave at 433MHz is used in the simulation. Twelve sensors serve as the transmitter in turn. When one port is emitting, the other 11 ports act as receivers. Figure 3 shows the electric field value of the entire domain when one port is emitting. In this case, received signals at receivers can be collected, and the transmission coefficients at different receivers can be calculated.

![Heat map of the electric field value: (a) frequency of 433MHz; (b) frequency of 915MHz.](image)

Figure 3. Heat map of the electric field value: (a) frequency of 433MHz; (b) frequency of 915MHz.

A 12*12 S-matrix is got after each sensor acted as the transmitter in turn. The receiving field varies with the change in the dielectric properties of the lung during the respiration process. This change will affect the propagation of microwaves, so the receivers will measure different electric fields. In this experiment, the electric field's dynamic range is 51.69dB, which is within the dynamic range of a vector network analyzer (VNA). Therefore, the electric field can be measured with enough accuracy. At the same frequency, sensors that are the most sensitive to dielectric changes can be distinguished through the absolute difference between signals obtained by the deflated and inflated lungs. The specific values are shown in Figure 4 (a) with the form of heat maps. For the microwave at 433MHz, the combination of sensor nine and sensor 12 is the most sensitive group, whose change can reach 8.58dB.

The model is also simulated with a microwave at 915MHz. The specific simulation method is the same as 433MHz. At this frequency, the electric field's dynamic range is 65.16dB, which also meets the requirement of VNA. In addition, the most sensitive sensors are sensor one and sensor eight under the
action of 915MHz microwave, the highest absolute difference can reach 15.99dB, the data can be seen in Figure 4 (b).

Some observations can be found when the results of 915MHz are compared with 433MHz. The dynamic range is more extensive for 915MHz, which means that higher frequency will suffer from more attenuations. However, the sensitivity of 915MHz seems to be larger, as a higher frequency can achieve a better spatial resolution. In the future study, systems that can work with multiple frequencies will have better microwave respiration monitoring performances.

Figure 4. Heat map of absolute difference of S-parameters: (a) frequency of 433MHz; (b) frequency of 915MHz.

5. Conclusion
Microwave respiration monitoring has great potential in medical research. In this paper, a chest cavity model is set and simulated based on the model are conducted. Data analysis shows the changing of received signals during the respiration process. In summary, the feasibility of microwave respiration monitoring is successfully demonstrated. Future work would be extended to involve real patient experiments and algorithms to explore a portable modality to monitor respiration using the microwave.

References
[1] Y. S. Lee, P. N. Pathirana, C. L. Steinfort and T. Caelli, "Monitoring and Analysis of Respiratory Patterns Using Microwave Doppler Radar," in IEEE Journal of Translational Engineering in Health and Medicine, vol. 2, pp. 1-12, 2014, Art no. 1800912.
[2] J. C. Lin and J. Salinger, "Microwave Measurement of Respiration," 1975 IEEE-MTT-S International Microwave Symposium, Palo Alto, CA, 1975, pp. 285 - 287.
[3] Victorino JA, Borges JB, Okamoto VN, et al. Imbalances in regional lung ventilation: a validation study on electrical impedance tomography. Am J Respir Crit Care Med, 2004, 169 (7): 791 - 800.
[4] Tomicic V, Cornejo R. Lung monitoring with electrical impedance tomography: technical considerations and clinical applications. J Thorac Dis, 2019, 11 (7): 3122 - 3135.
[5] H. Zhang, M. Li, F. Yang and S. Xu, "A feasibility study of microwave respiration monitoring," 2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP), Xi'an, 2017, pp. 1 - 3.
[6] Semenov Serguei. 2009 Microwave tomography: review of the progress towards clinical applications.Phil. Trans. R. Soc. A.367: 3021 – 3042.
[7] S. Salman, Z. Wang, E. Colebeck, A. Kiourti, E. Topsakal and J. L. Volakis, "Pulmonary Edema Monitoring Sensor With Integrated Body-Area Network for Remote Medical Sensing," in IEEE Transactions on Antennas and Propagation, vol. 62, no. 5, pp. 2787-2794, May 2014.

[8] C. Gabriel, “Compilation of the dielectric properties of body tissues at RF and microwave frequencies,” Brooks Air Force Base, San Antonio, TX, Tech. Rep. AL/OE-RE-1996-0037, 1996.