Review of Systems for the Detection and Monitoring of Accumulated Fluids in the Human Torso

(Invited)

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***Abstract*— A fluid buildup in the torso, such as inside the lungs (pulmonary edema) or around the lungs (pleural effusion), is among the common symptoms of various diseases such as cancers, and heart and liver failures. The chest X-ray and computer tomography (CT)-scan are the most widely used non-invasive devices for the detection of the accumulated fluid. Due to the high cost and ionizing radiation of the aforementioned diagnostic tools, there has been huge research efforts to design alternative tools that are non-invasive, efficient, low-cost and safe for long term monitoring. This paper presents a brief review of the recently proposed systems for the detection of torso fluid accumulation using different modalities. This review indicates that microwave-based imaging systems are the most promising technique as a diagnostic tool of this serious medical condition.**

Keywords*— *Microwave imaging, pulmonary edema, pleural effusion, heart failure, medical diagnostic systems.

I. Introduction

According to World Health Organization (WHO), heart diseases and strokes are the predominant causes of death in the world [1]. One of the common symptoms of these diseases is the accumulation of fluid in the torso (inside or around the lungs). Therefore, early stage detection and monitoring of the lungs is the key to early medical intervention to prevent health deterioration or even death. This aim is of great importance for the welfare of the society, and is essential to relieve the associated burden from the healthcare system. Considering the lack of sensitivity in X-ray devices, ionizing nature of CT-scan and high costs and lack of accessibility of magnetic resonance imaging (MRI) devices, there is a necessity to develop new systems that are affordable, accurate and suitable for safe long term monitoring.

There has been intensive research to realize such a system in the past four decades [2] - [26]. The realized systems can be classified under two main categories; 1) detection only systems [2] - [11] and 2) detection and localization ones [12] - [26]. The first category aims at monitoring the level of accumulated fluids in the torso by observing certain aspects of reflected or transmitted signals, and linking the presence of the fluid to any sensible changes in those quantities. The second category, on the other hand, aims at detecting the presence of the fluid and defining its approximate or accurate position by creating two or three dimensional images. Those images map the torso, especially lungs, tissues' properties by calculating the intensity of the electromagnetic field or impedance distribution of tissues depending on the utilized imaging algorithm. This paper reviews the operating basis of the proposed systems with different modalities and their achieved results.

II. Detection Systems

This section reviews the systems that only aim detecting the presence or absence of fluid (mainly water) inside the torso. The main purpose of those modalities is to provide a preliminary piece of information to help define the required medication to be given by paramedics at the accident scenes encountering lung injuries or beach rescue teams dealing with drown people.

A. Standing Wave's Node Monitoring

The feasibility of using microwave signals as a reference for the detection of fluid accumulation inside the lungs was first investigated by Susskind in 1973 [2]. This study revealed that the position of the node of standing wave changes when it encounters water content, and hence it can be used as a measure for monitoring fluid content inside the lungs. In this study, a simple structure that includes a pair of sponges was used to model the lungs. Two transmitting/receiving horn antennas were used at both sides of the sponges, which are sandwiched between two metal sheets and represent the torso shell. The study does not define the best operating frequency, yet, it denotes that the signals above 10 GHz cannot be used due their short wavelengths that limit signal penetration deep inside the torso. The reported results revealed that by gradually inserting water inside the sponges, the node in the standing wave on the source changes and its shift is consistent with the dampness of the sponge.

B. Amplitude and/or Phase Analysis

It is well-known that microwave signals tend to be absorbed more in tissues with higher water content than the normal ones [3]. This fact led to the investigation of the effects of presence of water inside the lungs on the levels of amplitude and phase of the reflected or transmitted signals [3] - [8]. To that end, an applicator was directly placed on the chest of a subject under study to record the changes in the amplitude and phase of signals [3]. The applicator was designed to operate at 915 MHz with a power of 50 – 500 μW to enhance the required signal penetration. The results showed a 1 dB change in the amplitude and 5° variation in the phase of the reflected signal during normal breathing. Further experiments revealed that locating the applicator at the rear side of the torso provides larger variations both in phase and amplitude of the reflected signal. To test the possibility of detecting fluid using potential changes, massive amounts of water was inserted into the lungs of a dog, and it was found that a significant shift, up to 15 times, occurs in the level of the baseline of the amplitude. The same changes in the baseline of the phase were not observed.

Considering the fact that the transmission coefficient between two sources is determined by the dielectric properties of the medium between them, further studies reported changes in the level of the transmitted signal by increasing the fluid amount inside the lungs [4]. Additional studies concluded that the transmission tests are 50 times more sensitive to changes than the reflection ones [5]. To address the uncertainty between selecting the amplitude, phase or mix of them as the determining criteria for monitoring the fluid level changes, a numerical study in which the lung was divided into three regions was conducted [6]. Different positions for the transmitter and receiver were investigated and the obtained results were compared. It was shown that amplitude variations are more consistent compared to the phase ones. However, as the variations in the amplitude are significantly smaller than the phase one, phase variations were determined as a more robust measure of monitoring changes. This measure is extended to the most recent experiments using reflection coefficients [7] - [8].

C. Acoustics

By considering the well-known fact that sound travels faster in water compared to air, the possibility of using acoustic system for lung water monitoring was investigated in [9]. To evaluate the usefulness of the abovementioned notion about the speed of water, a White Gaussian Noise (WGN) covering 0 – 4 KHz is used as a source signal that is transmitted into the lungs through a funnel from the mouth. Four electric statoscopes were used in the experiment to assess the received signal using adaptive filter processing. By applying the technique on a torso phantom that is made of foam, and considering the gravity dependency of the water, it was found that the stethoscope which is located below the water receives the transmitted signal with the least delay compared to the other ones, and hence detects the presence of fluid.

D. Radiometry

Using the electromagnetic radiation emission from the body is another approach that is used for detection and monitoring the lung water content [10]. This value is measured in brightness temperature that relates the emissivity and electrodynamic temperature of the body. By calculating the emissivity of the lungs using the complex dielectric properties of the lungs tissues, blood, air and water, a certain value is obtained. This value changes with different levels of water inside the lungs, and hence alters the emitted electromagnetic radiation from the body. These changes can be monitored using radiometers that are able to record these emissions. The measurements were conducted at the frequency range of 0.4 – 1 GHz. It was shown that despite the limitations of the radiometers operating at low frequencies, 0.260-K change in the brightness temperature occurs with one percent change in the level of the accumulated water.

E. Permittivity Estimation

Detecting water accumulation was shown to be possible by estimating the average dielectric properties of the lungs [11]. In this method, several sensors are involved in the measurements. One of the many sensors that are spread across the chest wall is fed by a 40 MHz radio frequency (RF) signal, whereas the others measure the amplitudes of the reflected signals from the body. These values are then processes using a weighted sum of the collected signals from the sensors to estimate the average dielectric value. Considering the fact that when water accumulates inside or around the lungs, it changes the dielectric properties of the lungs' tissues significantly, this method detects the presence of water by monitoring any variations to the obtained value for a healthy lung.

III. IMAGING SYSTEM

This category of systems provide a more advanced type of diagnosis and focus on both detecting and locating the accumulated fluid. Positioning fluid is of great importance in cases where invasive sampling is essential to determine the exact type of the disease causing the edema, and therefore define the exact medication. To that end, locating the fluid on either sides of the torso accelerates the process while reducing patient's pain and biopsy costs.

A. *Electrical Impedance Tomography*

One of the relatively new methods in imaging the human body is Electrical Impedance Tomography (EIT). This technique relies on the tissues' bio-impedance properties, which carry important information about the changes that occur inside the body [12]. In this method, several electrodes are placed around the imaging area (lungs in this case) and the current is non-invasively injected to the body and the occurred voltage is recorded at receiving electrodes. These systems typically use a range of low and high frequencies of 1 MHz or 20 GHz, respectively. This method models the fluids, such as blood and water, as resistors while modelling the membranes of the cells as capacitors. Considering the fact that different tissues and cells have different sizes, angles and thicknesses, a wide range of impedances are obtained. Tomographic imaging algorithms are then used to image the impedance of each tissue within the imaged area. As lungs have extremely different impedances during inhale and exhale due to the air volume, the presence of the water alters the obtained impedance; that variation can be shown as an image [13] - [16].

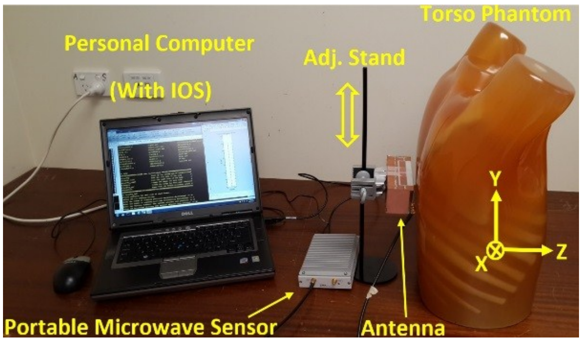
B. *Radar Based Microwave Imaging*

Radar based microwave imaging has been applied largely for detection and imaging of breast cancer, brain stroke in recent years [17]. There are two main types of these systems; monostatic and multistatic. In the monostatic approach, a single antenna or microwave sensor is used for transmitting and receiving signals, while in the multistatic several antennas transmit and receive simultaneously. Multistatic configuration requires large numbers of antennas and switching systems; however, they provide more information that increases the accuracy of the detection. These systems are based on the fact that unhealthy cells have generally different dielectric properties, and hence the reflected microwave signal from those tissues are different compared to the healthy ones. These reflections are then processed using different imaging techniques including inverse and direct ones to obtain the intensity of the field inside the imaged area.

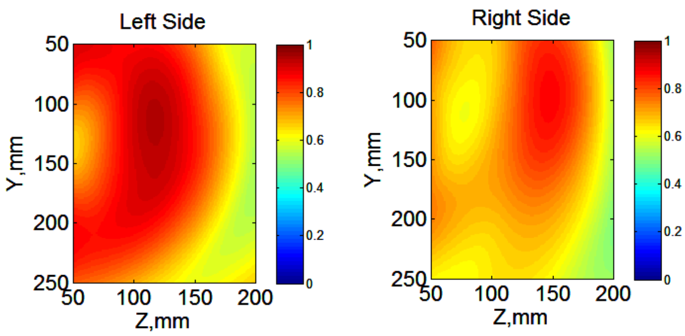
The potential of using this technique for lungs' fluid monitoring is studied in [18]-[26]. It has been shown that a wide frequency band within 0.7 – 1 GHz, provides the required penetration while maintaining a high image resolution [18]. As shown in Fig. 1, the obtained results revealed that the lungs in the presence of fluid (mainly water) show significantly higher reflections [18] - [20]. One of the main drawbacks of imaging lungs is the presence of heart inside the lungs, which can create false detections due to its large size and high dielectric constant value of blood inside the heart. To overcome this problem, systems that use differential imaging techniques are developed [21]-[25]. These methods image different regions of the lungs of a healthy subject, and subtract the obtained images from each other to obtain a threshold. The obtained values are then used as the boundary for healthy and unhealthy subjects (Fig. 2). The obtained values tested on realistic torso size phantom with cardiovascular organs and animal lungs have shown to be effective in detecting small volumes of water [23]-[26]. Trials on unhealthy subjects are needed to confirm the obtained results and provide information on the sensitivity and specificity of the system.

IV. CONCLUSION

An overview of systems proposed for fluid detection inside the human torso has been presented. Operational mechanism of these systems and their detection methodologies are briefly discussed. It was shown that the present systems can be categorized under two types. The first one only aims at detecting the presence of fluid by analyzing standing wave ratio shift or estimating effective permittivity. It can be concluded that these systems are not applicable in realistic clinical test due to their over simplified modelling and vulnerability to the test environment. The second category, which both detects and locates its position, presents a more robust solution and has been mainly tested on realistic models and even human subjects. Considering all the factors, microwave imaging shows the highest potential for realization as a fast, accurate and low cost system for the detection and monitoring torso fluid accumulation.

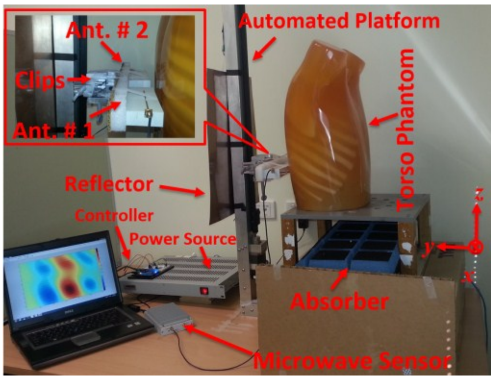


(a)

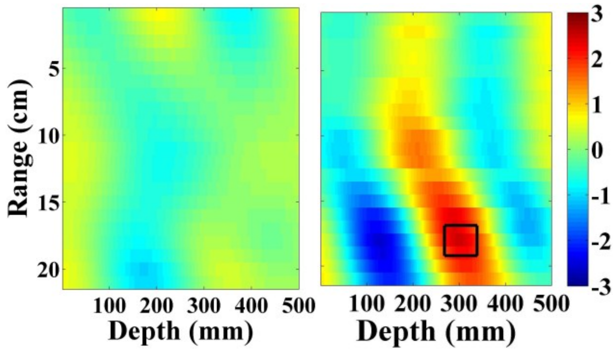


(b)

Fig. 1. (a) Fluid build-up detection system using one antenna with (b) obtained images (water at the left side) [19].



(a)



(b)

Fig. 2. (a) Fluid build-up detection system using two simultaneous antennas with (b) obtained images (water at the right side) [21].

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