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Non-Invasive Stethoscope for Continuous Assessment of Lung Water: Towards AI-based Data Augmentation and Prediction

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Abstract*—Pulmonary edema (excessive fluid in the lungs) is a common pathway for acute and chronic conditions such as heart failure, acute respiratory distress syndromes, and kidney failure. Early detection of pulmonary edema is key to prevent the patients from deteriorating into these critical conditions. Previously, we have developed a prototype non-invasive wireless cardio-pulmonary stethoscope (CPS) and demonstrated its capability of estimating the *change of lung water content* and associated vital signs (e.g., heart rates, respiratory rates) for a cohort of 26 patients in a clinical trial. We aim to enable the wireless CPS to estimate *absolute* lung water content and expand its usage to a *diverse population* of patients. A promising approach to achieve these goals is to build a personalized machine learning model to estimate the absolute lung water content based on the sensor measurements (i.e., S-parameters) from the CPS. However, the hurdle is the lack of a comprehensive database of the S-parameters of the lungs with excessive fluid in a variety of patients. In this paper, we outline a roadmap of using AI-based data augmentation to build such a database. As a critical initial step, we propose an automatic workflow to convert computerized tomography (CT) scan images to 3D lung objects in high-frequency simulation software (HFSS), in order to obtain S-parameters of the lungs at different water levels. The proposed workflow allows us to utilize a large NIH database and establish personalized lung water assessment models for a diverse population of patients. Simulation results validate our concept.

I. Introduction

Pulmonary edema occurs when fluid within the blood vessels extravasates into the alveoli (e.g., air sacs) of the lung, and is a final common pathway for a number of acute and chronic conditions, including heart failure, acute respiratory distress syndrome, and kidney failure. Therefore, it is widely believed that *early detection* of pulmonary edema is key to provide timely fluid assessment and improve treatment for patients with chronic diseases such as heart failure.

However, existing modalities of monitoring pulmonary edema are either costly (e.g., chest X-ray and CT scan) and/or invasive (e.g., cardiac catheterization), making them unsuitable for continuous monitoring and early detection of pulmonary edema. Therefore, we have developed a wireless cardio-pulmonary stethoscope (CPS) to proactively detect pulmonary edema and to continuously monitor other vital signs (e.g., heart rates, respiratory rates) [1][2]. The proposed CPS consists of small sensors that can be conveniently attached to the patient's chest and a smart device that receives the measurements from the sensor and displays the estimates of the lung water content along with other vital signs (see Fig. 1 for illustration).

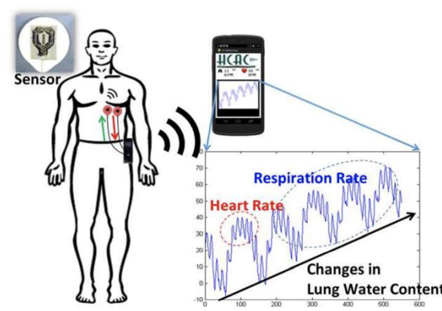

Figure 1. Overview of the wireless CPS.

The continuous non-invasive monitoring capability of the proposed CPS is achieved by using highly penetrating radiofrequency (RF) and electromagnetic waves. At microwave frequencies, the S-parameters of lung tissues are closely related to the amount of water content in the lungs, as discovered and validated by our prior works through animal experiments and human subjects [1][2]. Our prior efforts of clinical trials have demonstrated that the CPS can accurately detect the change in lung water content [1][2].

In this work, we propose a roadmap for artificial intelligent (AI) based lung water prediction to significantly expand our prior work in two aspects. First, we aim to estimate the *absolute* lung water, instead of the change of lung water Second, we aim to build accurate *personalized* AI models for *diverse patient populations*. While our prior work had promising clinical results, the patient population in our clinical trial (26 patients with hospitalized heart failure or hemodialysis) was not diverse enough for us to develop a personalized model to estimate lung water for a large patient population with different genders, ages, heights, weights, and so on. The lack of data hinders our ability to develop accurate personalized models to assess lung water content, because individuals are different both in the baseline S-parameters of lung tissues without edema and in the changes of S-parameters under different severities of edema.

Despite the challenges, the necessity of non-invasive continuous monitoring of lung water calls for innovative solutions to overcome the limitations caused by the lack of data. Based on a large NIH data set of CT scan images, we develop an automatic workflow to obtain *high-fidelity* data from 3D high-frequency simulation software (HFSS), and propose *AI-based data augmentation* to populate our data set. This will generate a large-scale data set that includes patients with varying ages, genders, and sizes, and the S-parameters of their lung tissues under various amounts of lung water. Such a data set is key for the future development of a high-accuracy machine learning model for personalized estimation of lung water.

II. OVERVIEW OF THE PROPOSED WORK

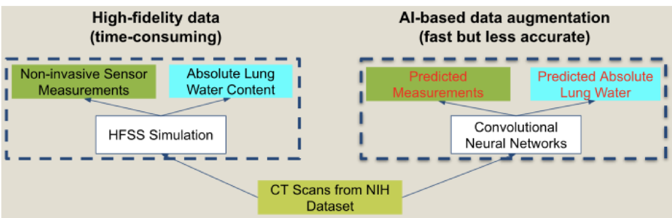

Figure 2. Overview of the hybrid approach to create a comprehensive data set.

Fig. 2 illustrates the proposed hybrid approach to create a comprehensive database. The database should include a diverse population of patients of different ages, genders, body compositions, and so on. Each data sample should contain the context information of the patients (e.g., age, gender, chest circumference, etc.), the S-parameters of the sensor measurement (preferably at different lung water levels) and the corresponding lung water levels. Such a database will allow us to develop a personalized AI-based lung water assessment model.

We propose to build such a database upon a large-scale NIH dataset with a diverse patient population. The dataset contains chest CT scan images of patients, based on which we can create 3D lung models and use HFSS to measure S-parameters at different lung water levels. This process will generate high-fidelity data on the relationship between the S-parameters of lung tissues and the amounts of lung water. Since HFSS calculation is time-consuming, we propose to use the high-fidelity data obtained from HFSS as seed data, and perform AI-based data augmentation to generate more data. While the AI-generated data is not as accurate as the ones obtained from HFSS, we can generate such data at low cost, which allows us to obtain the sufficient amount of data for training state-of-the-art machine learning models. In summary, our proposed hybrid approach allows us to build a high-quality database in a timely fashion.

III. AUTOMATIC HIGH-FIDELITY DATA GENERATION USING HFSS

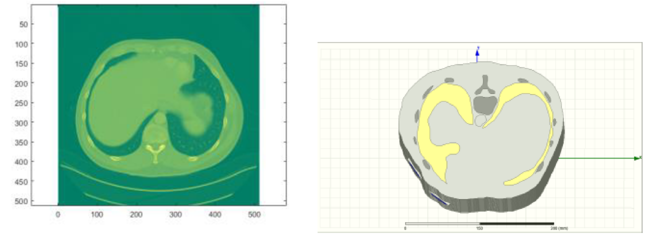

Figure 3. Overview of the automatic workflow that converts CT scan images to 3D objects in HFSS. The left figure shows the CT scan image read by MATLAB. After detecting the edges of the lungs, a 3D object of the lung, with a sensor attached, is built in HFSS.

Here we describe our automatic workflow for generating high-fidelity data (illustrated in Fig. 3). First, we read the CT scan images in MATLAB, detect the edges of lung and bone structures, and extract these shapes for HFSS simulation. Next, we estimate the absolute lung water content through the Hounsfield Unit (HU) values of the lung in the scan. Then we create a 3D model of the lungs and place a modeled CPS at the proper location. Finally, we can vary the lung water content and obtain the S-parameters at different lung water levels using HFSS.

Fig. 4 shows examples of the S-parameter versus lung water content curves obtained for two different patients. We can see that the magnitude and the phase vary linearly as the lung water content increases. Importantly, the slopes of the curves are different for different patients, which stresses the importance of developing personalized assessment models based on our database.

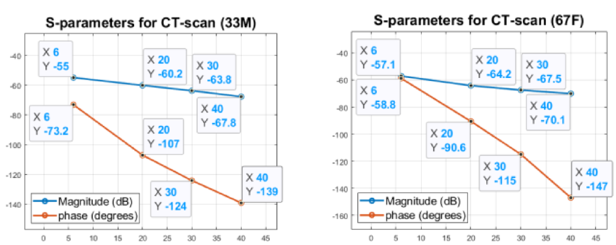

Figure 4. Sample results of HFSS simulation for a 33-year-old male and a 67-year-old female. We obtain curves of magnitudes and phases of S-parameters at different lung water levels.

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