Lung Capacity Estimation Through Acoustic Signal of Breath

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Abstract - **Breathing disorders are generally associated with the lung cancer disease. Through daily treatment, lung cancer patients often use a traditional spirometer to measure their lung capacity. However, the use of a spirometer device for accurate measurement requires some sort of training and adjustment, which may be inconvenient for certain groups of patients, especially the elderly. In addition, the spirometer readings can become unreliable if the measurements are not taken as instructed. On the other hand, a microphone, say the microphone on a hand-held device such as a smart-phone, can easily capture the acoustic signal of breath without certain instructions. This signal can then be processed to estimate the lung capacity. In this paper, we propose a methodology through the simply recorded acoustic signal of breath, splitting the breathing cycle to inhale, pause, exhale and pause phases to measure the depth of the breath along with the time duration and signal energy of the breathing phases. We show how these computed parameters are used to estimate the lung size with a high degree of accuracy. This work is part of a virtual reality platform embedded within a smart-phone to assist lung cancer patients regulate their breath. Furthermore, the lung capacity estimation methodology proposed in this paper can also be used to aid patients with other breathing disorders.**

Keywords - Acoustic signal of breath, lung capacity, microphone.

I. INTRODUCTION

A. Motivation

Lung cancer is the number one leading cancer-caused death in the United States. In addition, according to [1], one fourth of all types of diagnosed cancers involve the lung organs. Therefore, research on lung cancer prevention and treatment has received much attention in medical fields as well as various systems/engineering research aspects.

Lung cancer patients generally have breathing problems as the lungs are responsible for respiration. Lungs distribute oxygen to the entire body through blood flow via blood cells [2]. Hence, any form of exercise that regulates the respiratory system, enhances the lung functionality in providing oxygen to the rest of the body, and as a result, can diminish lung cancer symptoms.

Post-operative breathing exercises can reduce pulmonary complications by encouraging deep breathing to also improve the lung function [3]. One of the major challenges for lung cancer patients and those with breathing disorders is preventing serious attacks in which the patient's lung capacity is significantly reduced. This can even lead to severe shortness of breath and may require emergency treatment [4].

The lung capacity degradation for most patients with breathing disorders generally occurs over an initial period of two to four days [5]. This can be identified if the patient performs daily measurements of the lung capacity. Spirometers are the most widely used devices for such daily measurements, which also provide medical records for the patient [5]. However, the spirometer device often requires manual settings and/or certain instructions and may not be easy to use by certain age groups, e.g. the elderly. In addition, there have very few indications of using hand-held devices that can measure the patients' lung capacity easily at home, as these areas are active fields of research.

Through virtual reality (VR) revolution and the impact of VR in the medical field, which could also be used as a simulation technology for healing purposes [6-7], there has been an indication to use VR to assist the lung cancer patients [8]. In addition, smart phone devices are nowadays becoming increasingly popular in several aspects of daily life, and the usability; especially the effectiveness and acceptance of smart-phone applications by patients has become an appealing matter [9].

Figure 1. Smart-phone application of the proposed technique.

As virtual reality using smart phones has also evolved rapidly in the scale and scope of developing virtual reality applications for medical purposes [10], applying virtual reality to assist lung cancer patients via smart phones is a big challenge. In this paper, we present an automated approach to quantify the lung capacity through the acoustic signal of breath. We propose a methodology using the microphone to capture the acoustic signal of respiration and process the signal using voice segmentation and signal energy computation to estimate lung capacity for the lung cancer patients. The idea here is to build a virtual therapy platform on a smart-phone device to assist lung cancer patients as shown in Figure 1. This will be done by permitting patients to see a virtually real image of their lungs while they are breathing, so that when their inhale/exhale is less than normal, they will be motivated to take their next coming breath more efficiently. This, in turn, will lead to increasing the oxygen percentage in their blood. The work presented in this paper is a part of the intended virtual therapy platform. The implementation and integration of the overall VR framework, however, is beyond the scope of this paper, and is left as our future plan.

B. Background

Lung capacity refers to the amount of air inhaling to or exhaling from the lung and is measured by L (liters) as a volume measurement unit [11]. However, the total volume of air voluntarily moved in one's breath from full inspiration to maximum expiration represents the vital capacity (VC) or more precisely, forced vital capacity (FVC) [12]. FVC usually ranges between 4-5L in healthy young men and between 3-4L in young women [13]. Forced Vital Capacity (FVC) is defined as the maximum volume expired after maximum inspiration or the total volume of air exhaled during the expiratory phase, as shown in the following equation:

$$\mathrm{FVC_m} = 0.1524 \times h - 0.0214 \times a - 4.6500 \quad (1)$$

$$\mathrm{FVC_f} = 0.1247 \times h - 0.0216 \times a - 3.5900 \quad (2)$$

where:
a: Age (in years)
h: Height (in inches)
m: male
f: female

Considering the time duration of when the air blow is performed as a factor of lung capacity measurement, the Forced Expiratory Volume after one second (FEV1) is another terminology that can often be used. This refers to the total volume of air forcedly exhaled for one second into the spirometer device, and is computed as follows [13]:

$$\mathrm{FEV1_m} = 0.1052 \times h - 0.0244 \times a - 2.1900 \quad (3)$$

$$\mathrm{FEV1_f} = 0.0869 \times h - 0.0255 \times a - 1.5780 \quad (4)$$

C. Contribution

In this paper, we use microphone features to depict the lung capacity via the time period of the signal and the energy of the signal during the breathing cycles. Our technique is based on segmenting the breathing cycle via speech and silence detection and computing the start and end of each speech cycle in order to determine the time duration and the signal energy for each breathing cycle. The automated lung capacity computation technique presented in this paper is part of our intended virtually reality platform to be implemented on a smart-phone to assist lung cancer patients.

D. Paper Organization

The rest of this paper is organized as follows. Section II glances at earlier work related to measuring the lung capacity. In Section III, our proposed work including the segmentation technique, the important metrics and factors, and the methodology used in this study are described. Next, Section IV shows the results obtained. Finally, Section V presents conclusions and recommendations for future work.

II. RELATED WORK

The spirometer is the main device used for measuring lung capacity [5]. There are two of kinds of spirometer devices; traditional spirometer and the electronic one. The traditional spirometer is available in the market with affordable prices and is not difficult to use [14]. Most of the traditional spirometer users are patients who had gone through lung surgery to recover in short time and need to maintain clear lungs by measuring the lung size daily [5]. The electronic spirometer is available in hospitals, clinics and research centers. Electronic spirometers are expensive and generally not easy to operate, but the accuracy is higher, as more parameters are involved in the device implementation [15]. Both traditional and electronic spirometers require manual settings and/or certain instructions and may not be easy to use by certain age groups, e.g. the elderly.

In [16] an accurate mobile spirometry for self-management of asthma was introduced. The design of this spirometer device was customized for special use, and could be connected to a smart-phone win android application for monitoring the patient spirometry readings. The inter-device deviation in flow readings was less than 8%, and could detect more than 95% of erroneous cough maneuvers. Though the results and performance were promising, a separate hardware including a pressure sensor was designed to interact with the smart-phone API. Hence, the patient is required to also purchase the peripherals which costs more in addition to the fact that the patient would need to deal with more devices and settings for self monitoring.

In [17], a gas flow sensor based on the sound generated by turbulence has been developed as a way to detect the breathing cycle phases using the microphone to capture the flow rate. This work mostly describes the hardware and signal processing circuitry invloved in the sensor design. The main drawback of this design is ambient noise and vibration, which would require certain filter designs to eliminate the noise. As will be seen, our work is intended to be designed with minimal or even no additional hardware cost to the smart-phone.

In [5], a game was introduced to motivate patients to perform post-operative breathing exercises. The work mostly described the early progress of an interaction device, game design, initial play testing and the usability of the game.

III. PROPOSED METHODOLOGY

In [18-19], it is shown that the breathing phases are divided into four different phases: inspiratory phase, inspiratory pause, expiratory phase and expiratory pause. The breathing phases are defined as starting with the onset of inspiration from the moment the air inflow starts. When the airflow stops, the inspiratory phase ends and the inspiratory pause begins and lasts until the air begins to flow out from the lungs, in which the expiratory phase starts. The expiratory phase is followed by the expiratory pause, which lasts until the end of the breathing cycle, as shown in Figure 2.

In this paper, we identify the breathing phases and extract certain metrics of each phase to estimate the lung capacity.

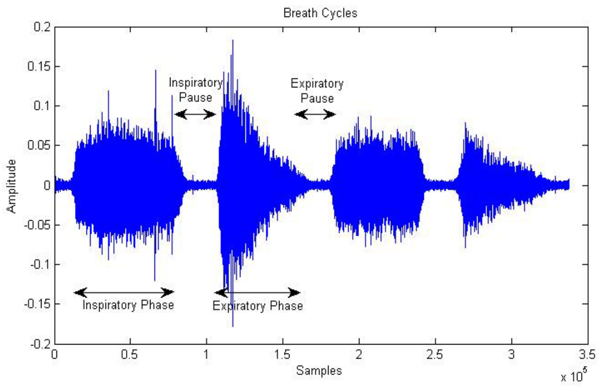

Figure 2. Breath cycles showing different phases.

A. Segmentation

In our study, Voice Activity Detection (VAD) technique is used for segmentation purposes. VAD is one of the most effective functions that can differentiate between silence and speech phases [20]. The basic assumption for the VAD algorithm is that the spectrum of the speech signal changes quickly, but the background noise is relatively stationary and changes slowly [21]. In addition, the active speech level is usually higher than the background noise level.

In this work, the basic VAD algorithm is fine-tuned for the acoustic signal of breath to differentiate the silence and breathing phases (See Figure 3). It is implemented by first filtering the signal to remove the undesired low-frequency components, and second, calculating the power with different window sizes of the Fast Fourier Transform (FFT) of the input signal [21].

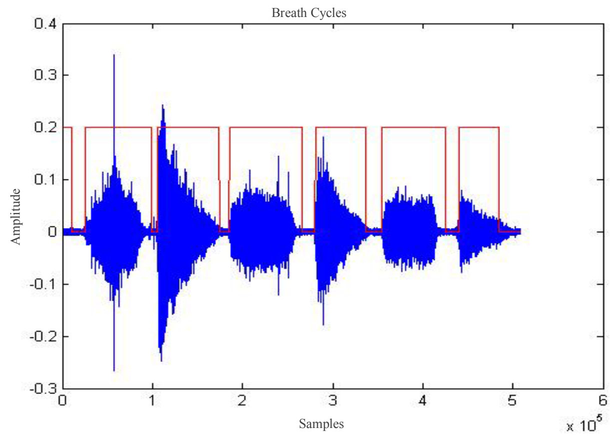

Figure 3. Segmenting acoustic signal of breath using VAD.

In our work, we are ignoring the pause phases and considering them as silence phases. However, the voice (speech) phases are considered to be one inhale (inspiratory) phase and one exhale (expiratory) phase per breath cycle. The total time duration of the overall recorded breathing cycles for an individual is shown in the following equation:

$$\mathrm{T}_{\mathrm{Breath}_{\mathrm{cycles}}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{t}_{1\,\mathrm{voice}_\mathrm{i}} + \mathrm{t}_{1\mathrm{silence}_\mathrm{i}} + \mathrm{t}_{2\,\mathrm{voice}_\mathrm{i}} + \mathrm{t}_{2\mathrm{silence}_\mathrm{i}} \quad (5)$$

In the above equation, the parameters are:

$t_{1\ \mathrm{voice}}$: Inspiratory phase
$t_{1\ \mathrm{silence}}$: Inspiratory pause
$t_{2\ \mathrm{voice}}$: Expiratory phase
$t_{2\ \mathrm{silence}}$: Expiratory pause
n: number of breathing cycles

In this work, we apply the VAD technique to the acoustic signal of respiration to extract the voice (speech) segments of the breathing cycles and compute the time duration the patient inhales or exhales air:

$$T_{\mathrm{Speech-Phases-of-Breath}} = \sum_{i=1}^{n} t_{1\,\mathrm{voice}_i} + t_{2\,\mathrm{voice}_i} \quad (6)$$

The energy of the voiced (speech) segments of the signal are also calculated in our work:

$$E_{\mathrm{Speech-Phases-of-Breath}} = \sum_{i=1}^{n} e_{1\,\mathrm{voice}_i} + e_{2\,\mathrm{voice}_i} \quad (7)$$

Where *E* or *e* refers to the energy within the corresponding speech segments:

$$E = \sum |x(t)|^2 \quad (8)$$

In the above equation, *x*(*t*) refers to the signal amplitude of time (sample) *t*.

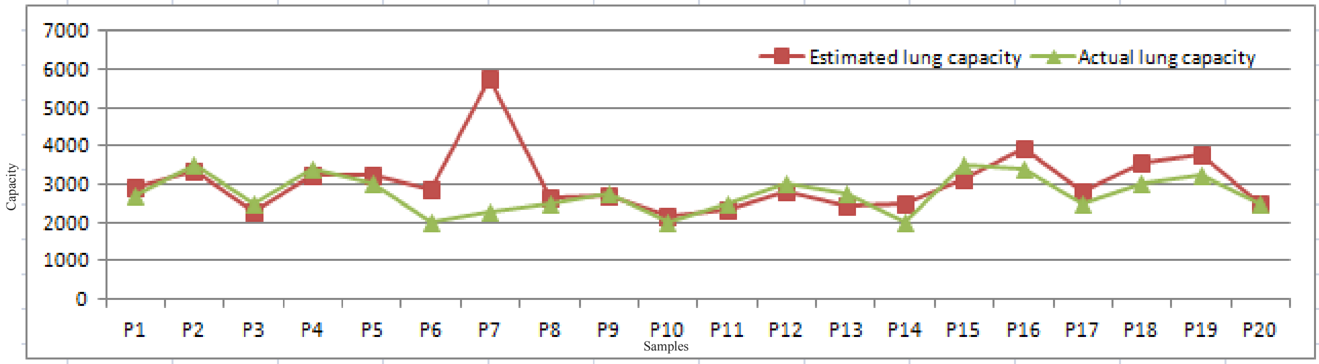

Figure 4. Estimated and actual lung capacity values for 20 subjects.

B. Important Metrics and Factors

The following metrics are used in computing the lung capacity in our work:

1. Gender and adult state: The subject's gender can affect the computation result.
2. Age: Subject's age in years
3. Height : Subject's height in inches
4. Duration: The duration of the subject blowing air in the microphone as shown in Figure 3.
5. Signal energy: is the amplitude of the acoustic signal through time.

C. Procedure

The following steps show the lung capacity measurement procedure in our work.

- First, the recorded signal for each speaker is split into inhales and exhales (speech segments). The splitting process was implemented using the VAD technique.
- Second, the start and end point of each speech segment (inhale and exhale duration) is marked.
- Third, the time duration between each start and end of speech segments (inhale and exhale) are computed (Equation 6).
- Fourth, the energy of the signal between each speech segment (considering all samples within the speech segments) is calculated (Equation 7).
- Finally, the lung capacity is computed using the following Equations (9 and 10) by substituting the five important factors (gender, age, height, breath time, and energy). This equation was derived using empirical data and estimates provided from Equations 1-4.

Estimated lung capacity:

$$\mathrm{FVC}_m = \frac{15e}{100}(0.1524h - 0.0214a - 4.65)t \quad (9)$$

$$\mathrm{FVC}_f = \frac{15e}{100}(0.1247h - 0.0216a - 3.59)t \quad (10)$$

Where t is the average time duration of exhale and inhale and e the signal energy.

In the above equations, the signal energy has been included in the lung capacity calculations in addition to the breathing time, which was reflected in Equations 3 and 4. Through analyzing the statistical model of lung capacity estimation, it is clear that signal energy plays an important role in lung capacity calculation, since it refers to the power of the breath signal. Essentially, this means that the actual power and depth of breath within a certain time of air blow forms the basis of lung capacity estimation. This is almost analogous to the blow of air measurements for spirometer readings.

IV. RESULTS

We have applied our technique on 20 different speakers/subjects. Each subject's acoustic signal of respiration was captured using a microphone in ten breathing cycles. The recordings of all speech samples took place at the same location for all subjects to provide uniformity. In our experiments, the "SONY VAIO VPCEB42FM microphone (Realtek High Definition Audio) [22] professional microphone is used. The microphone was placed approximately 10cm away from the speaker (Figure 5). All samples were recorded with a sampling frequency of 44.1 KHz. Portions from all volunteers were then copied into MATLAB for processing. The sound utterances were segmented using the voice activity detection technique.

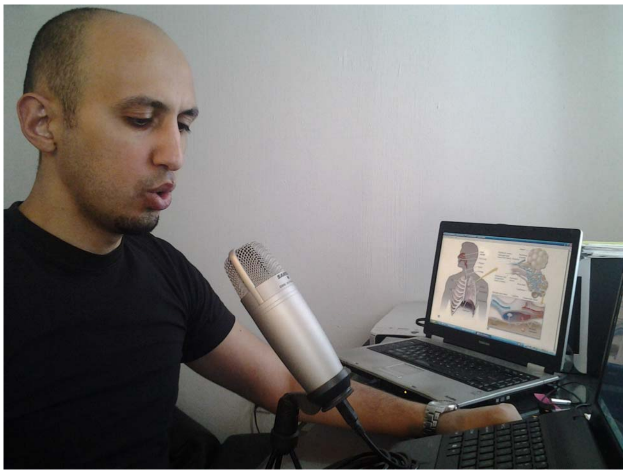

Figure 5. Recording a breathing signal for a subject.

Figure 6. Measuring lung capacity using traditional spirometer.

Our formulations (Equations 9-10) were used to estimate the lung capacity (FVC) for 20 subjects. We also extracted the actual lung capacity using the traditional spirometer (Figure 6) and plotted these values as shown in the two graphs of Figure 4. The *x* axis represents the number of subjects, and the *y* axis represents the lung size in liter/minutes. As seen from the graphs our estimated results are very close to the actual numbers.

Table I also shows the comparison in terms of actual numbers between the spirometer readings vs. our estimation on the lung size. The table also includes the accuracy in terms of the error. The overall accuracy of our lung estimation methodology on the tested subjects turns out to be 86.42%.

TABLE I. Comparison of spirometer readings and the average time duration of breathing cycle.

Subject or Patient No.	Signal Energy	Period (second)	Spirometer reading	Error
p1	257	2940	2700	0.088
p2	2667	3350	3500	0.042
p3	2880	2260	2500	0.096
p4	2279	3220	3400	0.052
p5	5555	3260	3000	0.086
p6	1451	2847	2000	0.423
p7	2655	5760	2250	1.560
p8	4587	2642	2500	0.056
p9	495	2690	2750	0.021
p10	3478	2156	2000	0.078
p11	3917	2323	2500	0.070
p12	4552	2790	3000	0.070
p13	2946	2456	2750	0.106
p14	6212	2478	2000	0.239
p15	3864	3125	3500	0.107
p16	2669	3951	3400	0.162
p17	2754	2789	2500	0.115
p18	4001	3551	3000	0.183
p19	2995	3753	3250	0.154
p20	3427	2487	2500	0.046
Overall error				0.13581

V. CONCLUSIONS AND FUTURE DIRECTIONS

Splitting the breathing acoustic signal captured using a microphone by applying VAD and then computing the average time duration and energy of the breathing cycle was proposed in this work to estimate the lung capacity. As a proof of concept, the overall accuracy of the estimated lung capacity results using a microphone confirms the efficiency of the proposed technique. The results motivate us to deploy a microphone already embedded within a hand-held device for lung capacity estimation. This work was part of a larger research project for assisting lung cancer patients through virtual therapy. In continuation of this research, we intend to fully implement the virtual reality platform to assist lung cancer patients regulate their breath by integrating the proposed methodology to estimate the lung capacity with a high quality animated application on a smart-phone. This would aid lung cancer patients regulate their breath by having a daily basis estimate of their lung size using a hand-held device at home.

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