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A mobile Based Platform for Monitoring Respiratory Diseases

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A MOBILE BASED PLATFORM FOR MONITORING

RESPIRATORY DISEASES

by

Fatma Khalil Zubaydi

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Approval Signatures

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Acknowledgment

Dedication

To my beloved partner, great mother and father, merciful sister and brothers

for their endless love and support

Abstract

Chronic respiratory diseases are diseases of the airways and other structures of the lung, usually resulting in difficulty in breathing and other symptoms. Chronic obstructive pulmonary disease (COPD) and Asthma are considered to be the most common of respiratory diseases. By taking into consideration the possibility of disease worsening over time and the negative impact on patient's daily activities, the continuous monitoring and managing of these diseases has become a necessity. Currently, *spirometry* remains the recommended test for monitoring and diagnosing both, COPD and Asthma. A patient suffering from COPD or Asthma should be able to monitor his disease in order to avoid a worsening condition over time or exacerbation of the disease in severe cases. Proper monitoring requires regular visits to medical centers for spirometry checks, or else the purchase and use of a portable spirometer; both options are costly in terms of money and time. In this work and due to the pervasiveness and advancement of smartphones, we attempt to make use of their built-in sensors and ever increasing computational capabilities to provide patients with a mobile-based spirometer capable of diagnosing and managing COPD and Asthma in a reliable and cost effective manner. We developed a model that allows the computation of two critical lung parameters: FVC and FEV1 by establishing a relationship between the frequency response of human exhalation recorded by mobile microphone, and the actual flow rate. These two parameters and the FEV1/FVC ratio are critical in assessing the progress and status of the diseases. We designed a Pretest Activity that together with these computed lung parameters is used in the diagnosis phase. Sample data used to test the system is collected from patients at both Oriana, and Al Zahra hospitals in Sharjah, United Arab Emirates (UAE), under the supervision of consultant pulmonologists. Results and the medical diagnosis of the implemented system proved to be in very close proximity with those produced by *clinical spirometers*. Our work is an attempt among many to confirm the notion that mobile Health (m-Health) can and will play an important role within the healthcare industry in the near future.

Search Terms: mHealth, eHealth, signal processing, COPD, Asthma, android.

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Chapter 1: Introduction

Respiratory diseases refer to many disorders affecting lungs that range from infections such as influenza to life-threatening ones like lung cancer. Some of these can lead to respiratory failure [1]. During a day, a human breathes thousands of times. During this operation lungs take in oxygen from the air and deliver it to the bloodstream and expel carbon dioxide. A problem in any part of the previous operation could lead to respiratory disease so that a person will face difficulty in breathing. Different factors could lead to respiratory diseases such as smoking, genetics and infections, which are considered the leading causes of lung diseases [2]. Among the most common lung diseases, COPD and Asthma are in the front with COPD as the third leading cause of death in the world [3], and more than 25 million people are known to have asthma in United States; approximately seven million of them are children [4].

Chronic obstructive pulmonary disease (COPD) is a progressive disease that makes breathing hard due to chronically poor airflow. Different factors lead to COPD with smoking in the lead. Therefore, most of the people with COPD are either current smokers or past smokers. Also, long-term exposure to some lung irritants such as chemical fumes, dust and air pollution may contribute to COPD. A COPD patient can suffer from one or more of the common symptoms like dyspnea, chronic cough, sputum production, wheezing and chest tightness. Similarly, Asthma is a chronic lung disease that narrows and inflames the airways which causes different symptoms like dyspnea, episodic cough, chest tightness, shortness of breath and recurring periods of wheezing. For Asthma patient, coughing often occurs at night or early in the morning. Asthma most often starts during childhood. As researchers claim, the exact cause of asthma is not known yet but several factors may contribute such as [5]:

- An inherited tendency to develop allergies, called atopy.
- Parents who have asthma.
- Certain respiratory infections during childhood.
- Contact with some airborne allergens or exposure to some viral infections in infancy or in early childhood when the immune system is developing.
- Some people develop asthma because of contact with certain chemical irritants or industrial dusts in the workplace. This type of asthma is called occupational asthma.

- Most, but not all, people who have asthma have allergies.

In order to diagnose COPD or Asthma, patients typically first experience some of the symptoms and then conduct some tests to confirm the diagnosis of the disease. One of the most common pulmonary function tests is spirometry, which is used to measure lung functions especially the amount and speed of inhaled and exhaled air. In case of respiratory disease COPD and Asthma, which are chronic and progressive diseases, patient should notice the progress and changes in the symptoms, also patient should undergo regular checkups by performing the spirometry test in order to catch the disease earlier and avoid exacerbations. Unfortunately these tests are time and money costly. An alternative solution could be achieved by adopting a mobile Health (mHealth) approach to diagnose and manage respiratory diseases.

mHealth is one aspect of eHealth that is pushing the limits of traditional healthcare. It is expected that mHealth will be part of many healthcare related activities due to the following advantages:

1. It can eliminate the need of regular tests and hence reduce the cost of medical care and consequently provide healthcare for people with low income.
2. It can reach patients in even the most remote locations.
3. It can increase the reach and efficiency of healthcare:
   o It empowers the patients, smartphones can help patients monitor their disease at home. Furthermore, it can be used as a tool for patients to manage appointments, renew prescriptions or view medical records.
   o Doctors are increasingly using smartphones, allowing them to access medical materials. They can also reach patients in rural areas through remote diagnostics and information alerts.
   o Remotely monitoring hospital patients or the elderly can free up much needed capacity in hospitals and nursing homes.

The work in this thesis focuses on designing and implementing an Android application that is able to diagnose and manage the two pulmonary diseases, COPD and Asthma. The proposed system makes use of the built-in microphone in smartphone in order to mimic the spirometer and perform the spirometry test. The objective is to make use of the pervasiveness of smartphones and introduce clinic-based tests at home cheaply. The important part of the proposed thesis is to develop an algorithm that can analyze user's exhalations to reliably infer lung measurements and assess if a patient

suffers from a pulmonary disease. This algorithm is built on the previous published work in this area, experimental work, input from health and physician experts, and observations from real life experiments and tests. We performed the test on 25 subjects, 10 of whom already had been diagnosed with COPD and Asthma, 5 smokers, and 10 subjects who are healthy with no symptoms. The results showed that 100% of test samples were correctly diagnosed, and the mean percent error between FVC, FEV1, and FEV1/FVC ratio data resulted by our MobSpiro application and the clinical spirometer is 4.6%, 3.1%, and 3.5% respectively.

The rest of the thesis is organized as follow: Chapter 2 presents background of Asthma and COPD diseases. Literature review of related research is discussed in Chapter 3. Chapter 4 presents the methodology of extracting patient's lung measurements, diagnosing and managing the disease. The proposed system architecture will be outlined in chapter 5.Chapter 6 presents and discussed the experimental work and its results. Implementation of the application is explained in Chapter 7. Chapter 8 is a presentation and discussion of the results. Finally, the conclusion is presented in Chapter 9.

Chapter 2: Background

COPD and Asthma are obstructive lung diseases. The spirometery test is still used at clinics in diagnosing, classifying, and monitoring the disease. In addition to the spirometery, the pulse oximeter is used to manage the disease in order to avoid exacerbation of the disease.

2.1 Obstructive and Restrictive Lung Diseases

Lung diseases fall under two categories obstructive and restrictive lung diseases. Obstructive lung disease conditions make it hard to exhale all the air in the lungs due to the damage in the lungs or narrowing of the airways inside the lungs. People suffering from restrictive lung diseases have difficulty in fully expanding their lungs with air due to stiffness in the lungs themselves, stiffness of the chest wall, weak muscles or damaged nerves [6]. Both Obstructive and restrictive lung diseases share the same main symptom which is shortness of breath with exertion.

2.2 COPD and Asthma

COPD and Asthma are two common obstructive lung diseases. COPD patient may have one or more of the following disorders: emphysema, peripheral airways disease and chronic bronchitis. Emphysema destroys air sacs deep in the lungs, while chronic bronchitis causes inflammation, congestion, and scarring in the airways [7]. According to [8], COPD is defined as a disorder characterized by abnormal tests of expiratory flow that don't change markedly over periods of several months' observation. Also, Asthma patient may have significant reversibility after treatment, but patient with COPD may develop airway obstruction with little to no reversibility.

2.3 Spirometry

Spirometry is considered the golden standard for diagnosing, staging and managing of COPD and Asthma diseases. Spirometry test is performed using a device called spirometer. During the test, the patient will blow as hard as he can into a tube connected to a device. The device will measure how much air a patient breathes out and how fast he can blow air out as seen in Figure 1.

Most spirometers display two spirograms: a volume-time curve and a flow-volume loop as shown in Figure 2, and provide one or more of the following common measured parameters:

1. Forced vital capacity (FVC): The volume of air that can be expired after a maximum inspiration.
2. Forced expiratory volume in one second (FEV1): Volume of air expelled in the first second of a forced expiration.
3. Forced expiratory flow 25–75% (FEF 25–75): Average expiratory flow rate in the middle part of a forced expiration.
4. FEV1/FVC: This is the ratio of the vital capacity which is expired in the first second of maximal expiration
5. PEF (peak expiratory flow) is the maximal expiratory flow rate achieved.

Figure 1: Spirometry test [56].

Available spirometers have different types with different prices. High end spirometers cost upwards of $5000 and comparable in size to a small refrigerator. Portable (ATS-endorsed) spirometers cost approximately $1000-$4000 and are comparable in size to laptops.

Figure 2: Standard spirometry curves [55].

2.4 Pulse Oximetry

Pulse oximetry is another tool used to assist patients suffering from respiratory disease with the management of their disease. Pulse oximetry measures oxygen saturation of hemoglobin in arterial blood (SpO2), therefore it can provide an early warning of dangerous hypoxemia [9]. It complements, rather than competes with spirometry in the assessment of respiratory diseases and possibly of exacerbations.

2.5 COPD Diagnosis and Classification

According to the global initiative for obstructive lung disease (GOLD) [10], COPD diagnosis should be considered for an individual over age 40 that experiences one or more of the following indicators:

- Dyspnea that is progressive (worsen over time).
- Chronic cough which may be intermittent and may be unproductive.
- Chronic sputum production.
- History of exposure to risk factors such as Tobacco smoke, smoke from home cooking and heating fuels and occupational dusts and chemicals.
- Family history of COPD.

In case the patient is likely to have COPD based on the previous indicators, spirometry will be conducted to confirm that. If the post bronchodilator ratio FVC/FEV1 is less than 0.7, this confirms that patient has COPD. COPD assessment is required to determine its severity according to FEV1% predicted as shown in Table 1.

FEV1% predicted is defined as FEV1% of the patient divided by the average FEV1% in the population for any person of similar age, sex and body composition. Furthermore, by using the pulse oximetry with COPD patients, anSpO2 of 92% or less should prompt referral for further investigation and perhaps the need for long-term oxygen therapy [9].

Table 1: COPD classification.

Stage	FEV1/FVC	FEV1
Mild COPD	<0.7	FEV1>=80% of predicted value
Moderate COPD	<0.7	FEV1 50% to <80% of predicted
Severe COPD	<0.7	FEV1 30% to <50% of predicted
Very severe COPD	<0.7	FEV1 <30% of predicted plus chronic respiratory failure

2.6   Asthma Diagnosis and Classification

Asthma diagnosis will be based on medical and family history, physical examination and lung function test. For the medical and family history, patient will be asked if he has family history of asthma or allergies, what asthma symptoms he suffers from, and when and how these symptoms occur. During the physical exam, the doctor will listen to patient's breathing to know if he has asthma signs like wheezing and will check for runny nose and allergic skin conditions such as eczema. For the lung function test, which is used to diagnose and manage Asthma, one of the most common tests is of course spirometry.

For Asthma, the patient should perform basic spirometry to perform FEV1 and FVC measurements. In case the ratio FEV1/FVC is less than 0.7, patient should continue and perform bronchodilator challenge test by inhaling an asthma drug to open air passages (bronchodilator such as albuterol). After that, patients repeat the spirometry

test and the FEV1 and FVC measurements are recorded again. Finally, if there is more than 12% increase in FEV1 or 200 ml increase in FVC, the patient mostly has Asthma. Asthma severity will be assessed depending on symptoms and FEV1% predicted as in Table 2.

By using the pulse oximetry with Asthma patient, an SpO2 of 92% or less may indicate a need for oxygen supplementation [9].

Table 2: Asthma classification [11].

	Signs and symptoms			
Asthma classification	Difficulty breathing, wheezing, chest tightness, and coughing	Interface with daily activities	Nighttime symptoms	FEV1% predicted
Mild Intermittent	Fewer than 2 days a week.	Do not interfere with normal activities	Fewer than 2 days a month.	>=80%
Mild persistent	More than 2 days a week but do not occur every day.	Attacks interfere with daily activities.	3 to 4 times a month.	>= 80%
Moderate persistent	Daily. Inhaled short-acting asthma medication is used every day.	Interfere with daily activities.	More than 1 time a week, but do not happen every day.	60%< and <80
Severe persistent	Throughout each day.	Severely limit daily physical activities.	Often, sometimes every night.	<=60%

2.7   Differentiate Between Asthma and COPD

COPD and Asthma are often confused. Both COPD and Asthma are chronic inflammatory diseases that cause airflow limitation. On other hand, several factors and clinical maneuvers could be used to differentiate between Asthma and COPD. One of the factors that differentiate between Asthma and COPD is the age of initial disease presentation. Asthma is usually diagnosed in childhoods, but COPD in adulthood over the age of 40. Moreover, Smoking is the main cause of COPD, but not Asthma. Also, spirometry values and symptoms vary over time with Asthma, but COPD associated

with a steady, slow decline. Cough in Asthma is worse at night and after exercise. COPD is considered irreversible, which means it doesn't respond markedly to treatment to open airways up. On other hand, the constriction of airways through inflammation in Asthma tends to come and go, and it responds to treatment. Therefore, Pulmonologists usually use a test called the bronchodilator reversibility test to differentiate Asthma and COPD.

Bronchodilator reversibility test utilizes the spirometry to check the level of airways obstruction reversibility. First, the patient is asked to perform the spirometry test and the spirometry results will be considered the baseline for the Bronchodilator reversibility test. Then, the patient will be given a dose of bronchodilator medication which is whether inhaler or nebulizer. After 15 minutes of waiting, the patient will repeat spirometry test. If there is a significant bronchodilator response, the patient is more likely have Asthma.

Chapter 3:   Literature Review

Smartphones have been applied in the context of healthcare for a few years now. As of March 2013, according to a report from Research2guidance [12] there were more than 97,000 mHealth applications listed in 62 full catalogue app stores; mHealth applications may target patients or healthcare professionals. Smartphones have advantages over the existing healthcare methods such as portability, ease of use, and availability. Moreover, smartphones are more helpful in case clinicians are at a distance from their patients, or in rural areas where computers are not available. In the context of chronic diseases like COPD and Asthma, patients need regular medical checkups in order to monitor their health status and manage the progress of their disease. E-health and m-health fields have addressed the issue of progressive diseases by providing efficient and cheaper ways of managing the disease. E-health and m-health have been applied in the context of respiratory diseases in several projects as summarized in the following sections.

3.1   Smartphones Applications in mHealth

Researchers have used mobile devices for enforcing knowledge retention by questioning the user or giving him health tips. Such systems aim to help the patients manage disease by educating them about the causes and triggers, symptoms, possible progress and required life style to live with the disease. Finkelstein and Wood [13] presented an eLearning platform to inform an asthma patient about this chronic condition and enforce knowledge retention by questioning the user. The presented system could be utilized as a universal mobile eLearning platform for interactive patient education.

Ding et al. [14] developed the M-COPD system to assist clinicians to remotely monitor and manage COPD conditions and events. In the system, patients use mobile phones to update self-assessment and observation data relating to COPD symptoms and vital signs, such as sputum, wheezing, cough, heart rate, body temperature, etc., this data is stored in a remote server. Clinicians can access patient's data remotely and review the patients' information on a daily basis to assess the disease progress. Based on the clinical assessments, exacerbations of COPD can be detected at early stages.

3.2   Usage of Smartphone in Analyzing Recorded Patient's Exhalations

Abushakra and Faezipour [15] tried to mimic spirometer by using external microphone connected to a computer or mobile. They proposed a methodology of splitting the breathing acoustic signal captured using a microphone by applying voice activity detection (VAD) techniques and then computing the average time duration and energy of the breathing cycle. They derived equations to estimate the lung capacity (FVC) for both genders. The overall accuracy of their lung estimation methodology on the tested subjects was approximately 86.42%. However, they didn't use the built-in microphone in smartphones, but their results motivated other researchers to use the built-in microphone for lung capacity estimation.

3.3   Usage of Smartphone with Health Sensors to Monitor Respiratory Diseases

Heijden et al. did built a system that includes health sensors and/or external portable spirometer communicating with smartphone to diagnose and manage a chronic disease [16]. They developed a disease management system for patients with chronic obstructive pulmonary disease (COPD). The goal of the system is to predict and detect exacerbations in order to help patients self-manage their disease to prevent hospitalization. The system consists of a mobile device that is able to collect case specific, subjective and objective, physiological data, micro-spirometer and pulse-oximeter to alert the patient by a patient-specific interpretation of the data by means of probabilistic reasoning and by using Bayesian networks. Collected data is also sent to a central server for inspection by health-care professionals.

Cao et al. [17] designed a wireless portable monitoring system for respiratory diseases. The proposed system consists of two sensors nodes: the oximeter sensor node and the respiration-posture sensor node, both sensor nodes are integrated with Bluetooth transmitters and a PC or cell phone that connects with the Internet. The system measures user's respiratory airflow, blood oxygen saturation, and body posture, so it can serve as both sleep recorder and spirometer which could be applied for remote monitoring and diagnosis of OSA, COPD, and asthma.

Bellos et al. [18] designed and developed a system called CHRONIOUS, which offers an integrated platform that provide management and real-time assessment of the health status of the patient suffering from COPD. This is followed by a severity estimation algorithm which classifies the identified pathological situation in different levels and triggers an alerting mechanism to provide an informative and instructive

message/advice to the patient and the clinical supervisor. The CHRONIOUS system consists of two primary functional blocks the wearable platform and the SD, and two secondary blocks, the home patient monitor (HPM) and the external devices (which contain spirometer).

Seto et al. [19] developed DexterNet system, which is Wireless Body Sensor Network for the prevention and management of children's Asthma. The architecture of the system consists of three layers. First layer is the body sensor layer (BSL), it is responsible for monitoring of a child's activities, geographic location, and air pollution exposures occur. Second layer is the personal network layer (PNL), it is a wireless mobile device worn by the child summarizes the sensed data, and provides information feedback. Finally, the global network layer (GNL), in which a web server provides the information services that supports the healthcare management of asthma cases, prevention of asthma attacks, participatory sensing and the collection of anonymous sensor data for research into the risk factors associated with asthma.

Bumatay et al. [20] designed inexpensive external mobile device accessory (Peak Flow Meter) that records and stores the user's PEF, and graphs this data over time. Stored data could be forwarded by email to physicians to monitor the patient's PEF over time.

Kwan et al. [21] developed personal lung function monitoring devices for Asthma patients, which are portable external mobile device accessory that collects spirometry, peak expiratory flow, exhaled nitric oxide, carbon monoxide, and oxygen concentration information from patients. Results could be shared with physicians remotely.

D. Bae et al. [22] proposed a system framework for modeling and analyzing individual exposure to environmental triggers of asthma attacks. The system is able to retrieve an individual patient's location data (GPS data) and several environmental data (air pollution, tobacco smoke, temperature and humidity) through sensor equipped mobile devices. By using statistical methods and efficient data analysis algorithms, the system can retrieve intelligence information from relations between asthma and various environmental conditions as researchers claimed.

K. Dinesh Kumar [23] designed human health monitoring mobile phone application by using the wireless NanoSensor-based embedded system. In the proposed system, NanoSensor was placed in the mobile phones and smartphone application alerts

the patient and displays the body condition, causes and how to overcome problems without the need for physician guidance.

Bagchi and Chattopadhyay [24] developed an algorithm which monitors important spirometric values such as FEV1,FVC PEF continuously, so that any deviation from the safe limits will allow the system to send a warning sign to the physician's mobile and at the same time it will send numerical and graphical respiratory information of the subject to the web-server. The study was limited to two common respiratory diseases like chronic obstructive pulmonary disease (COPD) and chronic restrictive pulmonary disease (CRPD).

3.4   Usage of Smartphone Built-in Microphone to Perform Spirometry

A group of researchers benefited from the internal microphone of smartphone and used it to record patient's exhalations for further analysis on smartphone to measure lung parameters as Larson et al. [25] did. They developed an iPhone mobile application that performs spirometry sensing using smartphone's built-in microphone. The processing of the recorded signal is done on the cloud in order to report FVC, FEV1 and PEF lung measurements to the user. They evaluated their App on 52 subjects and the mean error when compared to a clinical spirometer was 5.1% for common measures of lung function.

Xu et al. [26] designed and developed Android mobile-phone based system for lung function diagnosis called mCOPD. The App is designed to diagnose COPD disease. It uses the built in microphone to record subjects' exhalation, the processing on the resulted signal is done on mobile and the App will provide user with FVC and FEV1 lung measurements. They evaluated mCOPD in controlled and uncontrolled environments with 40 random subjects. The average deviation of the data FEV1/FVC when compared to the clinical spirometer was 3.9%.

Stein [27] designed a smartphone App to be used for patients with COPD. It uses built-in microphone and sound analysis algorithms to test lung functions and reports FEV1 and FEF25-75% lung measurements. The App designed to work with distance between mouth and arm set manually to 30 centimeters.

Based on the published literature, mHealth deployment in assessing respiratory diseases has shown promising results, but still need more investigation in order to be considered as the coming successor of traditional monitoring methods of respiratory diseases. In our proposed system, we use the built-in microphone to record patient's

exhalations. Moreover, we conduct an experiment to build a model that find the relationship between the frequency response and the actual flow rate of recorded exhalation. Also, we use the built-in proximity sensor in order to adjust the distance between mobile and patient's face which is incorporated for the first time. The usage of proximity sensor will help us in several ways:

- It helps in recording clear exhalations.
- It helps in preserving the stability of the system, since patient will perform spirometry several times with the same behavior and accuracy.
- It helps in increasing the sensitivity level required for such medical systems.

We conduct a comprehensive testing on diagnosed COPD patients, diagnosed asthma patients, smokers, and healthy people.

Chapter 4:   Methodology of Diagnosing and Managing Respiratory Diseases

The purpose of this work is to develop a portable reliable system to diagnose and manage respiratory diseases COPD and Asthma. The system provides medical recommendations as well.

The motivating factors behind the approach taken in this work include:

- The wide spread of smartphone usage and its reasonable prices.
- The strong capabilities of smartphones.
- Open standards of mobile apps developing which allow designing and developing customized applications, and the flexibility of downloading apps on phones even though the patient bought new phone.
- The increasing prevalence of lung diseases COPD and Asthma.
- The 'progressive' feature of chronic diseases which requires regular checkups and follow in order to catch the disease and slow its progress.
- Patient's worries about time and high cost spent on medical centers visits for regular health status checkups.

The major tasks carried out in this research are the following:

1) Identify the symptoms that indicate the probability of lung diseases COPD and Asthma, and develop a Pretest Activity to be the first indicator about the presence of the disease.
2) Identify the methods used to extract the required physiological signals.
    - How to extract patient's exhalations and find lung measurements.
3) Develop an algorithm to analyze the collected physiological signals.
    - Analyze patient's exhalations.
4) Design a model that find the relationship between the frequency response of the recoded exhalation by the microphone and the actual flow rate of the exhalation and make use of this model to implement the Android application.
5) Implement an Android application that does the following:
    - Diagnose if the patient has COPD or Asthma.
    - Assess the severity of the disease.
    - Notify user about exacerbations and the need for hospitalization.
    - Provide the patient with medical recommendations.

6) Validate the proposed functionality of the application by running tests on real patients and comparing them against the GOLD standard.

7) Attempt to create a benchmark for Asthma and COPD patients for future research.

4.1 Pretest Probability of Lung Diseases COPD and Asthma

Both ginAsthma (Global Initiative for Asthma) [28] and GOLD (The Global Initiative for Chronic Obstructive Lung Disease) [10] have recommendations for the diagnosis of Asthma and COPD diseases. They indicate that any individual who has one or more of the listed indicators in their pocket guides should undergo the diagnosis process. Also, they recommend taking symptoms, medical history and life style in addition to a lung function test like spirometry into consideration in diagnosing lung disease. Furthermore, the nature of spirometry test sometime results is inadequate measurements especially if the patient didn't prepare and perform spirometry as recommended. The patient will not be under the supervision of a physician while doing the spirometry in our proposed system. Therefore, Pretest Activity will be conducted before the spirometry test in order to find the probability of an individual to have lung disease and consequently increase the accuracy of the system. The Pretest Activity is actually a questionnaire that includes questions about symptoms of Asthma and COPD, and frequency of these symptoms. The conclusion reached from the pretest is a part in the overall diagnosis of the disease. However, the Pretest Activity is critical to our system due to the following reasons:

- It increases the accuracy of the system and avoid false-negatives (sick people wrongly diagnosed as healthy) and false-positives (healthy people wrongly diagnosed as sick).
- It increases the accuracy of the system and distinguishes Asthma from COPD even Asthma and COPD sometimes have similar symptoms. The Frequency of symptoms, the time of occurrences of symptoms during the day, disease leading factors, patient age and response to medication will all differentiate Asthma and COPD mostly except in case there is overlap between Asthma and COPD.
- It assists in avoiding wrong diagnosis due to lack of preparation and perhaps faulty performance of spirometry test especially under the supervision of mobile device not physician.

Following are some questions collected from the COPD Assessment Test (CAT) [29] and Asthma self-assessment [30]:

1. How long have you been living in UAE?
2. Do you suffer from difficulty in breathing during dusty seasons in UAE?
3. Do you ever feel out of breath or short of breath?
4. Do you feel breathless when you walk up a hill or one flight of stairs?
5. Do you have cough?
6. Do you ever cough at night?
7. How often do you wheeze, or make an audible sound, when you breathe out?
8. How many nighttime awakenings do you experience?
9. Do you have limitation with normal activities?
10. Do you ever get a feeling of tightness round the chest?
11. Do your symptoms get worse if you are exposed to any of the following 'triggers':
    - Smoke or traffic fumes
    - Cold air or changes in temperature
    - Food additives
    - Intense emotions
    - Animals
    - Perfumes, room cleaners and sprays
    - Pollen grains or mold spores
    - Exercise
12. Do you seem to have chest infections more often than other people around you?
13. Is there a history of any of the following conditions in your immediate family:
    - Asthma
    - Pollinosis (Hay fever)
    - Eczema
    - Allergies

4.2 Methods of Extracting Physiological Signals

The diagnosis, classification, and management of COPD and Asthma diseases require extracting lung measurements and reading SpO2. Lung measurements are extracted from the patient's exhalation, and the SpO2 by measuring oxygen level in blood.

4.2.1.   Extracting oxygen saturation. Oxygen saturation level is usually measured by a sensor called pulse oximeter, it measures the level of oxygen in the blood (SpO2). In order to capture SpO2 using pulse oximeter, the patient should place it on a thin part of his body like fingerprint or earlobe, or across the foot for an infant. More details about the mechanism and our sensor choice will be discussed later in the system architecture.

4.2.2.   Extracting patient's exhalations. As we discussed in Section 3.4, different methods have been used to measure or record patient's exhalations in order to find lung measurements such as using an external microphone to record patient's exhalations and send them to mobile or PC for analysis [15]. The built-in microphone in smartphones could be used also to record exhalations [25-27].

In the proposed system, we use the smartphone built-in microphone to extract and record patient's exhalations and store them on mobile SD card for further analysis. The smartphone built-in proximity sensors is used to adjust the distance between Smartphone and patient's mouth. The used smartphone in our experiment is Samsung Galaxy S5, and the threshold of its built-in proximity sensors, which is described in Section 5.1.2, is 5 cm. Per Pulmonologists advice, the distance 5 cm is logically suitable for sensing clear and direct exhalation. Therefore, we designed the proposed system to work with distance.

4.3   Methods of Analyzing Collected Physiological Data

As discussed earlier in the definition of chronic lung diseases COPD and Asthma, patients typically suffer from difficulty in breathing and hence regular checkups of SpO2 and spirometry will assist the patient in diagnosing and managing his disease. For this reason, we use a microphone that is able to record patient's exhalations for further extraction of lung measurements and a pulse oximeter to measure oxygen saturation in the blood. As indicated in Section 2.4, pulse oximeter complements spirometry in case of chronic diseases [9]. Due to the importance of the pretest in increasing the accuracy of the system and reducing the false-negatives and false-positives, pretest probability plays a role in the final diagnosis in our system.

4.3.1.   Oxygen saturation. In the proposed implementation, a pulse oximeter is used to measure oxygen level (SpO2) before performing the spirometry test. The measurements from the pulse oximeter is saved to be used in:

- The diagnosis stage as described later in Section 5.4.

28

- The review of disease history and progress over time.
- The assessment of patient's response to medications over time.

In general, SpO2 of 92% or less (at sea level) suggests hypoxemia [9]. The following steps are followed to extract SpO2 using pulse oximeter:

1. Read oxygen level using a pulse oximeter and insert the value in the Pretest Activity.
2. For COPD patient, SpO2 of 92% or less requires the investigation of the need for long-term oxygen therapy [9].
3. For Asthma patient, SpO2 of 92% or less may indicate a need for oxygen supplementation.

4.3.2.   Patient's exhalations. After measuring SpO2, we next record the patient's exhalations three times as recommended by GOLD pocket guide [10] and store them as wave files on smartphone SD card. Possible range of breathing frequencies approximately lies between 100 Hz to 1200 Hz [52, 53]. Signal processing is performed to extract this range of frequencies, analyze the signal and calculate FVC and FEV1 lung measurements. Figure 3 shows the steps required to analyze the recorded exhalations. The resulted ratio FEV1/FVC and FEV1% are used in diagnosis and classification stages as discussed later in Sections 4.4 and 4.5 respectively.

4.4   Towards the Final Diagnosis

For the purpose of the final diagnosis, the results of the Pretest Activity namely the possible causing factors and the disease probability are taken into consideration. Next, the oxygen saturation is measured and the lung parameters FVC and FEV1 are computed. The subsequent step is to use this collected information and data to try and reach a definite diagnosis. The Pretest Activity results are used together with the computed FEV1/FVC ratio, and FEV1% value to reach a diagnosis as follow:

- FEV1/FVC > 0.7 and FEV1% predicted >80% with pretest possibility:

    Patient at risk and he might have Asthma, therefore he should repeat the test after exercising an effort or later when he has difficulty breathing in order to confirm the diagnosis.

- FEV1/VFC < 0.7 with pretest possibility:

    Patient has respiratory disease

    o If higher pretest possibility of Asthma: diagnose patient with Asthma.
    o If higher pretest possibility of COPD: diagnose patient with COPD.

- SpO2 of 92% or less with FEV1/FVC < 0.7: Patient will be notified that he suffers from exacerbation and may need oxygen supplementation.

Figure 4 is a flow chart illustrating the diagnosis flow of both diseases COPD and Asthma.

4.5   Classification of COPD and Asthma

Respiratory diseases COPD and Asthma are classified into different categories according to their severity. For a diagnosed COPD disease, according to GOLD pocket guide [10] it has four main categories depending on the value of FEV1% predicted: mild, moderate, severe and very severe. The classification criteria is given in Table 3.

Table 3: COPD severity ranges.

Severity	FEV1% predicted
Mild	>= 80
Moderate	>= 50 and < 80
Severe	>= 30 and < 50
Very severe	<30

For a diagnosed Asthma disease, the classification is based on FEV1% predicted, frequency of nighttime awakenings due to the symptoms of disease and interference of symptoms with normal activities [11]. Asthma has four different categories: intermittent, mild persistent, moderate persistent and severe persistent. The disease is categorized as shown in Table 4.

For example, in Table 4, if the patient performed spirometry test and had an FEV1/FVC ratio less than 70% and FEV1% predicted in the range of 60-80%, and if he suffers from minor limitation with normal activities and daily nighttime awakenings due to the disease symptoms, then severity is considered to be moderate persistent.

4.6   Accuracy Assessment

As discussed in Section 4.4, the proposed approach for diagnosis is based on the ratio FEV1/FVC and the classification is based on FEV1% predicted as well as data from the pretest. Therefore the two measured lung parameters FVC and FEV1 contribute to the diagnosis and classification stages. We will compare these two values with the corresponding values measured by using external clinical spirometer, in order to assess how close our results when compared to those obtained using proven experimental spirometers.

Table 4: Asthma severity ranges.

Severity	Age (years)	Nighttime awakenings	Interference with normal activities	FEV1% predicted
Intermittent	ALL	≤ 2 days/week	none	> 80%
	0-4	0		
	>= 5	≤ 2x/month		
Mild persistent	All	> 2 days/week but not daily	Minor limitation	> 80%
	0-4	1–2x/month		
	>=5	3–4x/month		
Moderate persistent	All	Daily	Some limitation	60–80%
	0-4	3–4x/month		
	>=5	> 1x/week but not nightly		
Severe persistent	All	Throughout the day	Extreme limitation	< 60%
	0-4	> 1x/week		
	>=5	Often 7x/week		

4.7   Validation

The main goal of this research is to develop a portable reliable system to diagnose and manage the respiratory diseases COPD and Asthma. Therefore, a comprehensive validation of the proposed system is required. The validation is performed by testing the application on real COPD and Asthma patients as well as healthy people, and checking the accuracy of the system when compared to the clinical diagnosis of patients. The validation and testing stage is co-supervised by a consultant Pulmonologists from Zahra and Oriana Hospitals. More on this will be discussed in Chapter 8.
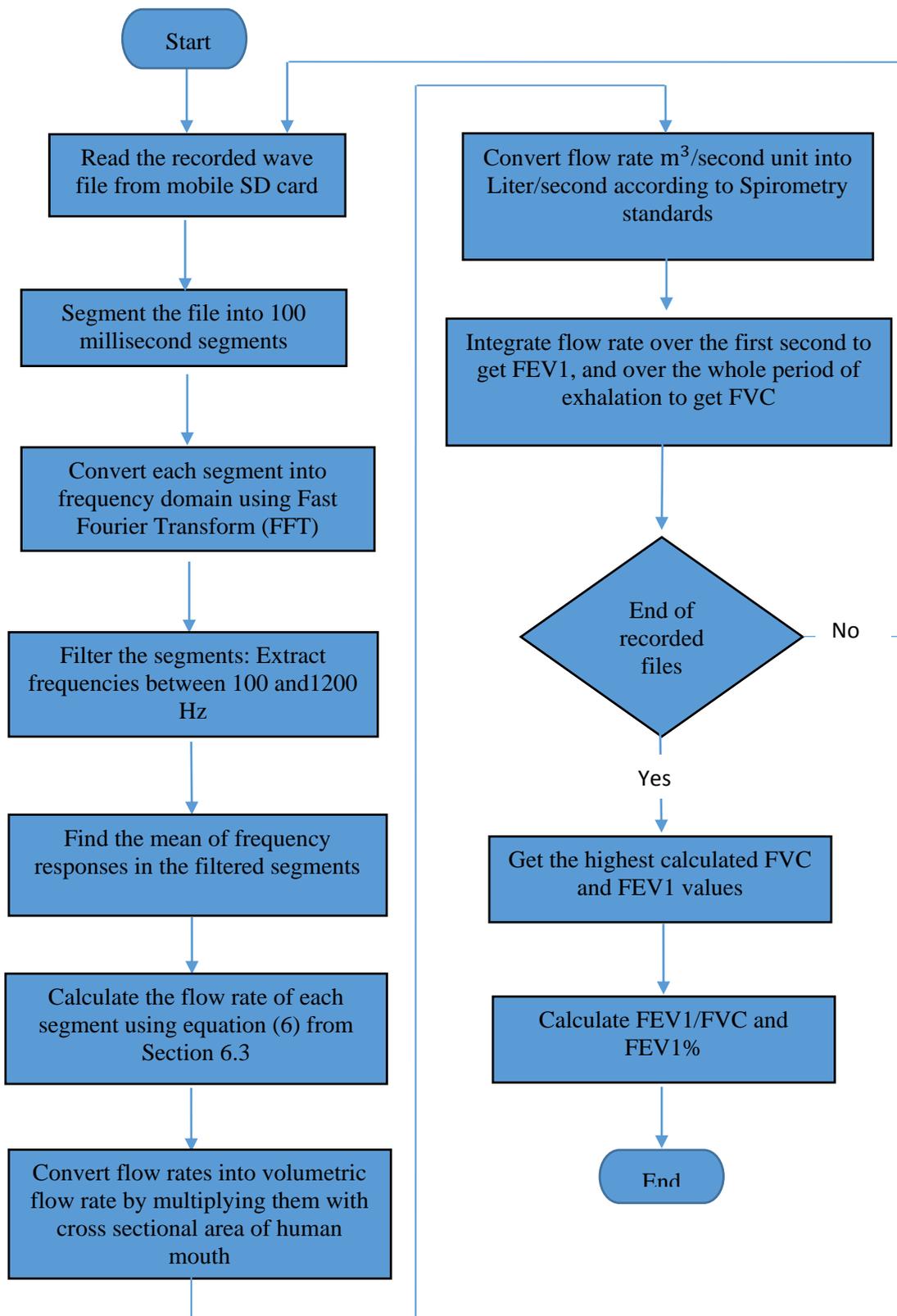
Figure 3: Flow chart explaining how to calculate the parameters FVC and FEV1.
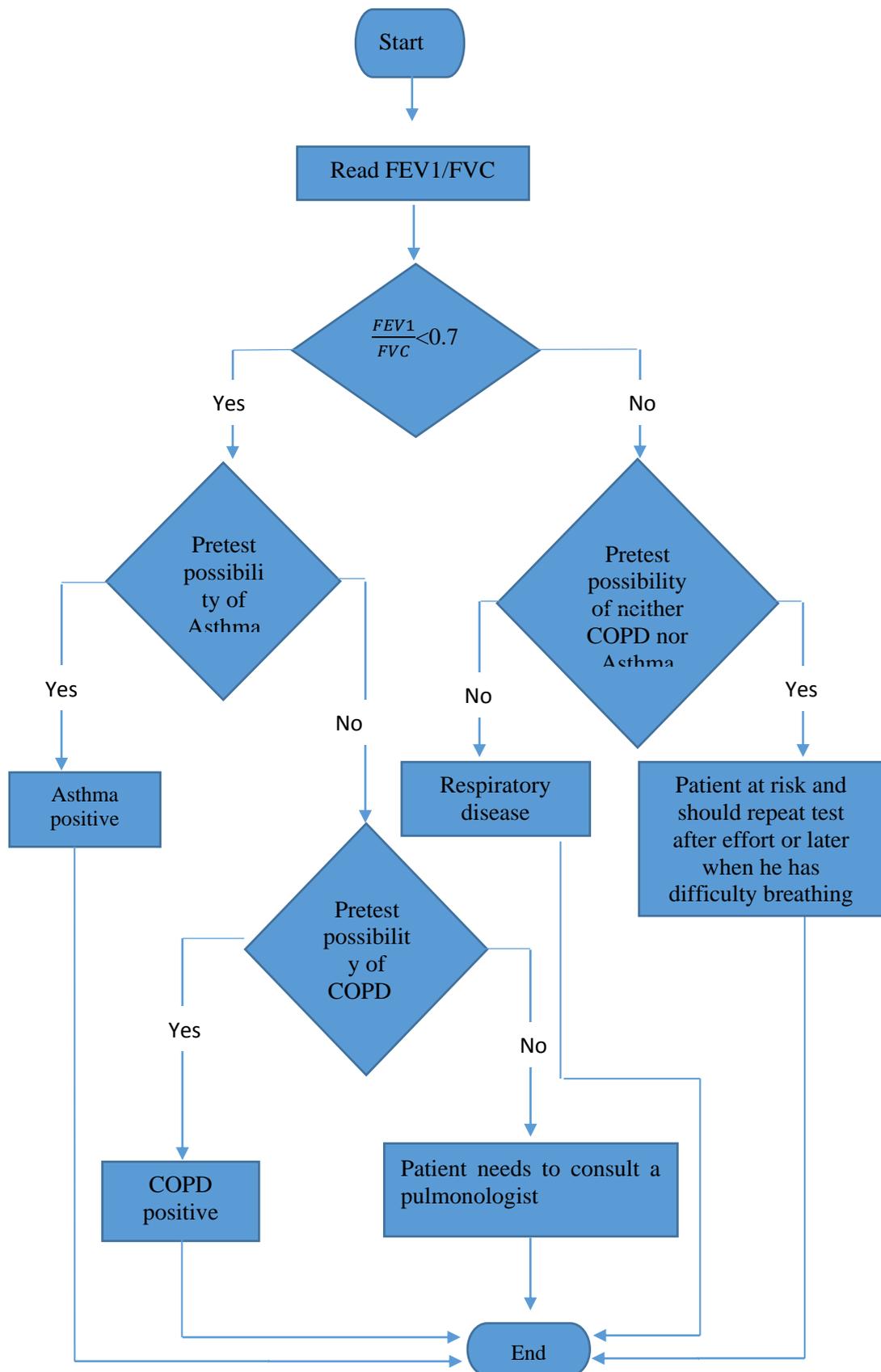
Figure 4: flow chart explaining how to diagnose COPD and Asthma.

Chapter 5:   System Architecture

In this Chapter, we will discuss the software and hardware components of the proposed system, describe the overall system architecture and introduce how modules are connected to each other. As seen in Figure 5, the system consists of (1) a smartphone as a central processing point, (2) a built-in proximity sensor used in determining the optimized distance between phone and patient's mouth for best results, (3) a built-in microphone to record the patient's exhalations and (4) a pulse oximeter to record the SpO2.
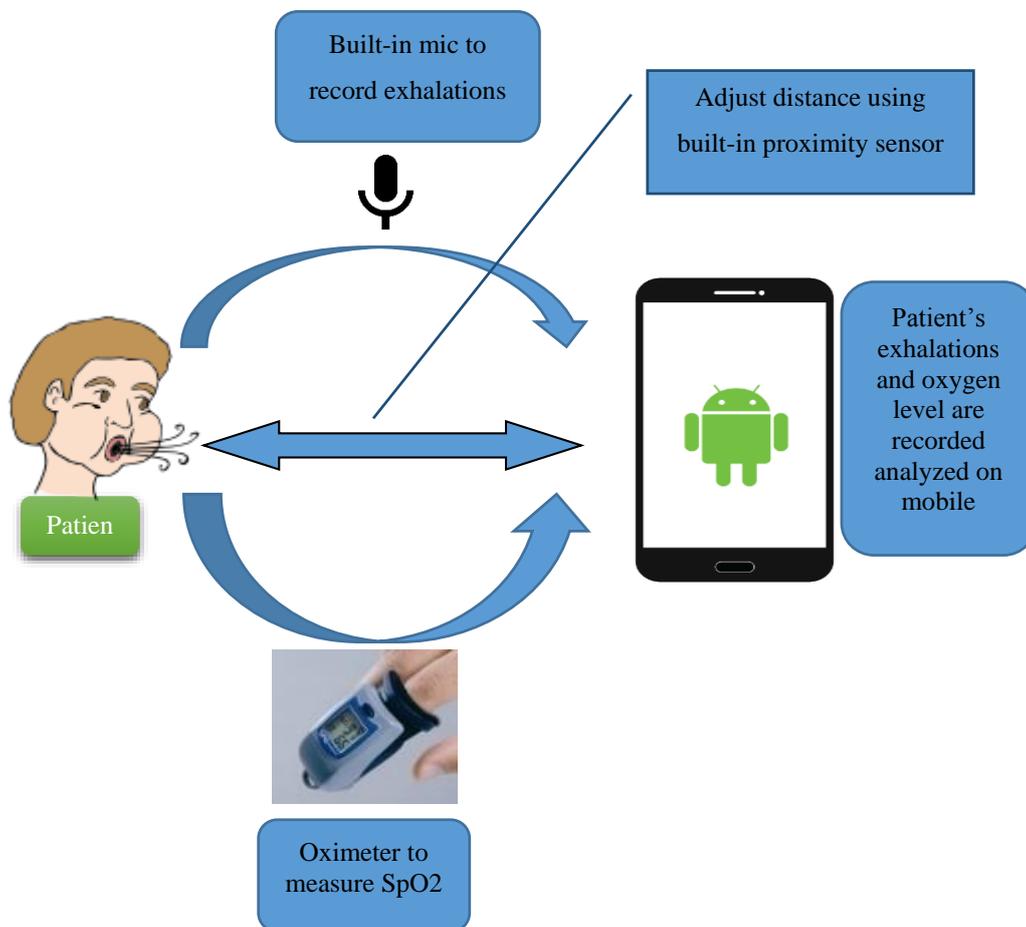

Figure 5: System architecture showing the main components and the data flow between them.

5.1   Hardware Components

There are four main components that interact with each other to extract data from the patient, analyze it, and display it to the user as shown in Figure 5. Following is a brief description of each component.

5.1.1.   The Smartphone. eMarketer [31], reported that number of smartphone users worldwide will surpass 2 billion in 2016 as we can see in Figure 6. The increasing widespread of smartphones in addition to the high capabilities, built-in sensors and user friendly interfaces make the smartphone a good choice to be the center of our proposed system. The smartphone used in this work is the Android-based Galaxy S5 manufactured by Samsung. The phone operates with Quad-core Krait 400, 2.5 GHz with an internal storage of 16 GB, 2 GB RAM, and an external storage of up to 128GB.

Figure 6: Smartphone users and penetration worldwide 2013-2018 [31].

5.1.2.   Built-in sensors. Two built-in sensors are used in the system implemented in this work:

- Microphone: it has the active noise cancellation feature, which helps in picking up the voice and ignoring the background noise.
- Proximity sensor: it is able to detect the presence of nearby objects without any physical contact. The proximity sensor is an interrupt based sensor, which gives only two values; 1 or 0. It responds to a change that is more than a threshold away from the target. The object being sensed is often referred to as the proximity sensor's target which is patient's face in our system. Different users may perform spirometry with different distances which leads to varying in the

accuracy. Adjusting distance by using the built-in proximity sensor will improve the accuracy and consistency of the proposed system.

5.1.3. **Pulse oximeter.** Pulse oximetry is a non-invasive method that enables rapid measurement of the oxygen saturation of hemoglobin in arterial blood [9]. The pulse oximeter shines light at two wavelength red and infrared, it shines through a part of the body that is relatively translucent and has good arterial pulsed blood flow like finger and earlobe. It measures the changing absorbance at each of the wavelengths, allowing it to determine the absorbance.

5.2 **System Software**

The following software development environments are used:

5.2.1. **Android Software Development Kit (SDK).** The core of our system, which is the Android mobile application, will be developed in java using Eclipse IDE with the Android Development Tools (ADT) plug-in [60].

5.2.2. **Matlab Environment.** Matlab is a multi-paradigm, high level, and numerical computation environment. It allows for analyzing data, developing algorithms, and creating user interfaces. As we will see in Section 6.2, analysis of collected data in experimental work is carried out using Matlab software which provides built-in signal processing functions that facilitate the analysis of audio files. The functionality of analysis software of our application is verified using Matlab before transporting and deploying it on the Android environment.

Chapter 6: Experimental Work

The main goal of our research is to develop a reliable portable system to diagnose and manage the respiratory diseases of COPD and Asthma. Our system utilizes the built in sensors in an Android-based smartphone to perform spirometry test. In spirometry, the patient's exhalation is analyzed to extract lung measurements. The smartphone's built-in MEMS microphone is capable of sensing direct airflow of human exhalation [26, 38]. In practice, we cannot directly extract the air flow from the recorded human exhalation signal. However, we can compute the time and frequency responses of the recorded exhalation signal using audio processing techniques. Towards achieving our goal, we designed an experiment to explore and find the relationship between the frequency response of a human exhalation recorded by mobile microphone and the actual flow rate during exhalation.

6.1   Experimental Setup

The objective is to find a relation between the audio signal response of mobile microphone and the flow rate. Therefore, we need a source of airflow, a device to measure the actual flow rate, and a mobile to record the airflow. For the source of airflow, we need a speed-stable airflow source with minimum possible noise and capability of adjusting the airflow speed; the DYSON AM06 [57] fan is selected for this purpose. Figure 7 shows the DYSON AM06 fan used in the experiment, which is a bladeless fan with 10 different levels of speed. Moreover, DYSON AM06 uses the air multiplier technology to create a powerful stream of uninterrupted airflow, and is 75% quieter than its predecessors.

In addition to DYSON AM06 fan, we used the AM -4201 [58] Anemometer which is shown in Figure 8. AM- 4201 Anemometer is capable of measuring flow rates ranging from 0.4 to 30.0 m/s with a resolution of 0.1 m/s. A GALAXY S5 Android-based smartphone was used in the experiment.

We developed an Android application that is capable of recording six seconds duration audio signal. The AudioRecord class which is described in Section 7.2.2 in detail is used to achieve audio capturing using mobile microphone. The designed Android application performs the following:

i.   Captures six seconds audio using AudioRecord class with a timer.

ii.   Writes data to a *wav* file.

iii.   Saves the *wav* on mobile SD card.

Figure 7: DYSON AM06Bladeless Fan.

Figure 8: AM- 4201Anemometer.

We next isolated the lower part of the DYSON AM06 fan in order to eliminate noise at higher fan levels as shown in Figure 9. Finally, we placed GALAXY S5 mobile beside the anemometer fan on a separate Table 5 cm away from DYSON AM06.The complete experimental setup is depicted in Figure 10.

6.2   Data collection and Analysis

Using the setup described above, we recorded 34 wave files at different fan levels and at different times during the morning, noon, afternoon, and evening in order to increase the accuracy of our experiment. While recording each wav file, we recorded

the actual flow rate value using the anemometer. The 34 wav files with their corresponding flow rate values are stored in a database. Using Matlab analysis, the recorded waveforms are analyzed in an effort to derive a relationship between flow rate (m/s) and a signal characteristic in the time-domain, frequency- domain, or both.

Figure 9: Isolation of DYSON AM06 Fan.

Figure 10: Experimental setup.

I. Time domain

To determine a relationship between signal characteristics and flow rate (as recorded by the anemometer) in time domain, two factors are considered: root mean square (RMS) and peak value attained by the signal. For each wav file, we truncated the first 2 seconds in order to eliminate the noise at the beginning of recording. Then, we applied a Butterworth filter in order to extract frequencies between 100 Hz and 1.2 kHz [43]. Finally, the RMS and maximum value attained by the recorded signal in each

file are calculated using equations (1) and (2). The correlation factor between RMS values and the flow rates was 0.8803, and between peak values and the flow rates was 0.5938. By comparing the two correlations factors, it is clear that RMS achieved a better relationship. Therefore, RMS value is chosen to establish a relation with flow rate in the time domain.

$$RMS = \sqrt{Mean(x^2)} \tag{1}$$

$$Peak = Max\ (x) \tag{2}$$

II.   Frequency domain

For all wave files in our database, we truncated the first 2 seconds in order to eliminate any noise at the beginning of recording. Signals were next transformed from time domain into frequency domain using Fast Fourier Transform (FFT).Research indicates that human speech and lung sounds and exhalations lie in a low frequency range mainly less than 3 kHz [26, 39, 40]. We applied a filter bank on the new transformed signal in order to extract frequencies in the following ranges 100-300 Hz, 300-600 Hz, 600-1200 Hz, 100-1200 Hz, 300-1200 Hz, 1-2 kHz, 1-1.5 kHz, 1.5-2 kHz, 2-3 kHz, 100 Hz-2 kHz, 100 Hz-2.5 kHz and 100 Hz-3 kHz. We next calculated the mean of the frequency responses of each frequency range. Finally, we calculated the correlation factors between mean of frequency response of each range and the actual flow rates values. The highest correlation factor obtained was 0.904 for the range 100 Hz- 3 kHz, and the second highest one was 0.8913 for the range 100 Hz-1.2 kHz. However, since lung sounds are mainly below 1.2 kHz [41, 42], we chose the relationship that is based on the second highest correlation factor.

By comparing the correlation factors obtained in the time domain and the frequency domain, the relationship between the frequency domain factor (which is mean of frequency responses between 100 Hz-1.2 kHz) and the flow rate is stronger than the relation between the RMS time domain factor and the flow rate. Moreover, frequency domain analysis is preferred over the time domain analysis for MEMS microphones since time domain analysis may lead to saturation problems. Even though, this saturation may lead to the occurrence of spurious high frequencies, this will not have a noticeable effect since we are interested in lower frequencies. Therefore, the relation between mean of frequency responses in the range 100 Hz- 1.2 kHz and the flow rate was selected as the basis for deriving the relationship between the frequency responses of patient's exhalation and the actual flow rate.

Regression analysis techniques are used to find the relationship and thereafter an equation that relates flow rate to the mean of frequency responses between 100 Hz and 1.2 kHz. Using the data points shown in Figure 11, and using Matlab we applied different fitting techniques. Moreover, we evaluated the goodness of each fitting curve using the root mean square error (RMSE) as given in equations (3), (4), and (5).

$$RMSE = \sqrt{MSE} \qquad (3)$$

$$MSE = \frac{1}{m} \times \sum_{i=1}^{m} Ei \qquad (4)$$

$$Ei = (Expected flowrate - Actual flowrate)^2 \qquad (5)$$

The fitting techniques investigated are:

i. linear regression

In linear regression, we usually find the straight line that fits best for a set of data points, where the dependent variable (Y) is flow rate m/s and the independent variable (X) is the frequency response. According to the data points, the RMSE of the best linear regression is 0.3172. Figure 12 shows the best linear regression fit for the data set.

ii. Quadratic regression

In quadratic regression, we find the parabola line that fits best for a set of data points, where the dependent variable (Y) is flow rate m/s and the independent variable (X) is frequency response. The RMSE of the best quadratic regression obtained here is 0.2108. Figure 13 shows the quadratic regression relationship of the model.

iii. Exponential fitting

In exponential fitting, we find the exponential function that fits best for a set of data points, where the dependent variable (Y) is flow rate m/s and the independent variable (X) is frequency response. The RMSE of the best Exponential regression was 0.4281. Figure 14 shows the exponential regression of the model.
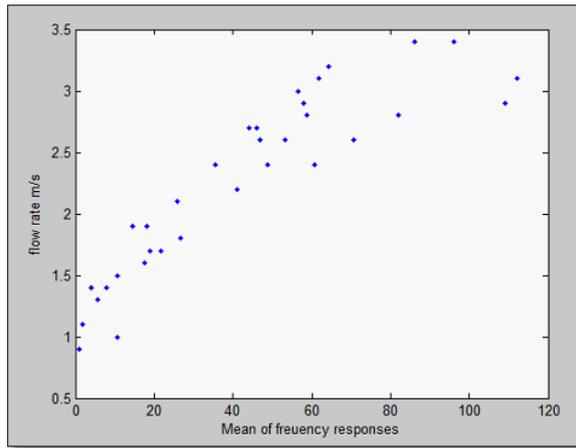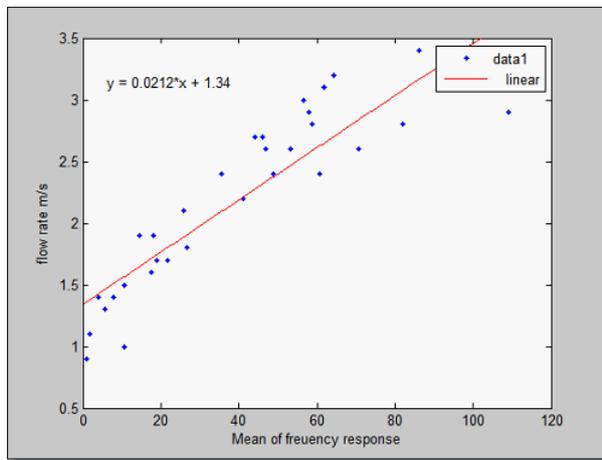
Figure 11: Distribution of data points.

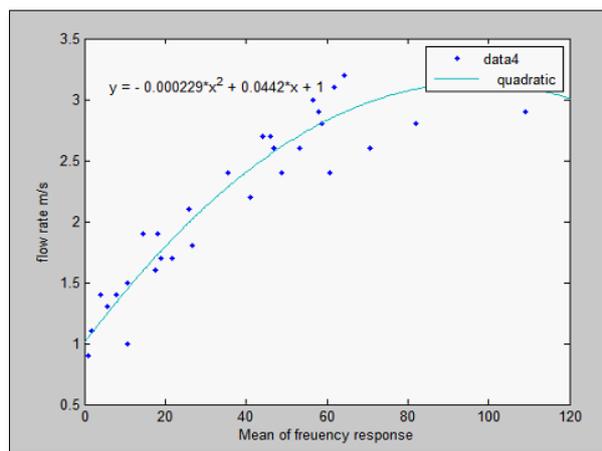

Figure 12: Linear Regression.
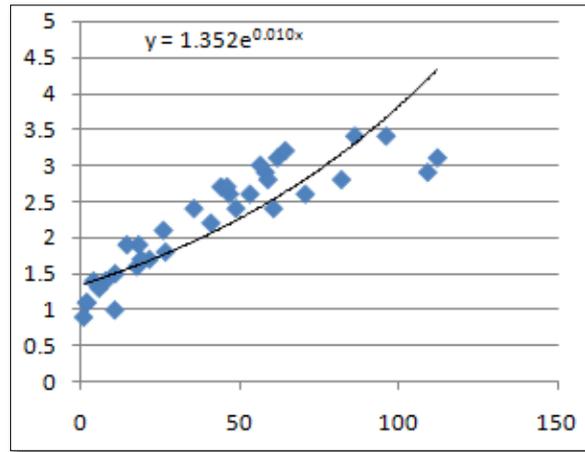

Figure 13: Quadratic Regression.

Figure 14: Exponential Regression.

6.3 Experimental Results

In the previous section, we found that the least RMSE value corresponds to fitting curve obtained using the quadratic regression. Hence, using the quadratic fitting, the relationship between the flow rate and the mean of frequency responses is computed as given in equation (6):

$$Y = -0.000229 \times x^2 + 0.0442 \times x + 1.002 \qquad (6)$$

Where Y: flow rate m/s.

x: the mean of frequency responses between 100 Hz and 1.2 kHz.

6.4 Issues Faced During Experimentation

The main issues we faced are related to the equipment used and the environment where the experiment is conducted and measurements are taken.

I. The DYSON AM06 fan noise at higher speed levels

The first step in the experiment is to find a noiseless, stable airflow source with different speed levels. We chose DYSON AM06 fan for this purpose. We visualized the recorded airflows in Matlab, and we noticed that fan noise increases when increasing the speed level, mainly above level five. The solution for the above mentioned problem was isolating the lower part of DYSON fan as shown previously in Figure 9. We recorded new airflows from the isolated fan and we visualized them using Matlab. The new recordings are clearer than the previous ones as we can see the difference between Figure 15 and Figure 16.

II.   Limited speed levels of DYSON AM06 fan

Data collection for a variety of settings would help increase our confidence in the validity of the proposed model. DYSON AM06 fan has only 10 different levels of speed. Therefore, we repeated the experiment at different day times morning, noon, afternoon, and evening since the environment nature such as air temperature and speed affect the flow rate of DYSOM AM06 fan air.

III.   Noise presence in experiment environment

During the experiment, data collection required an extremely quiet environment since we are working with audio signals with low amplitudes. Several filters were applied on the recordings in Matlab in order to exclude any possible noise outside the possible range of human exhalation frequencies. On the other hand, if the noise lies in the same range of human exhalation frequencies it is difficult to exclude it. Therefore, we ensured an extremely quiet environment.
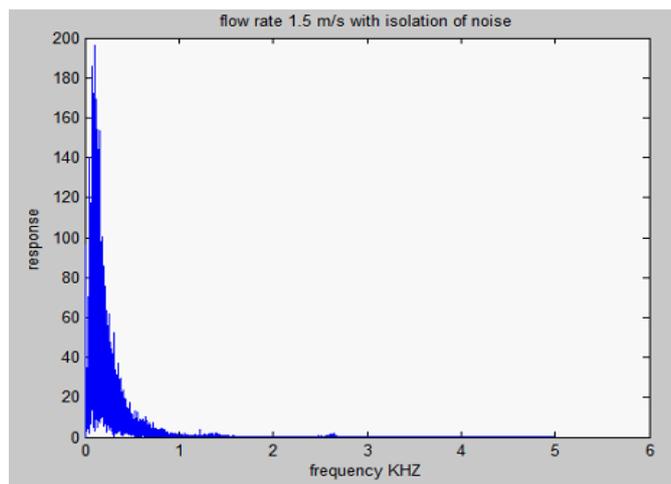

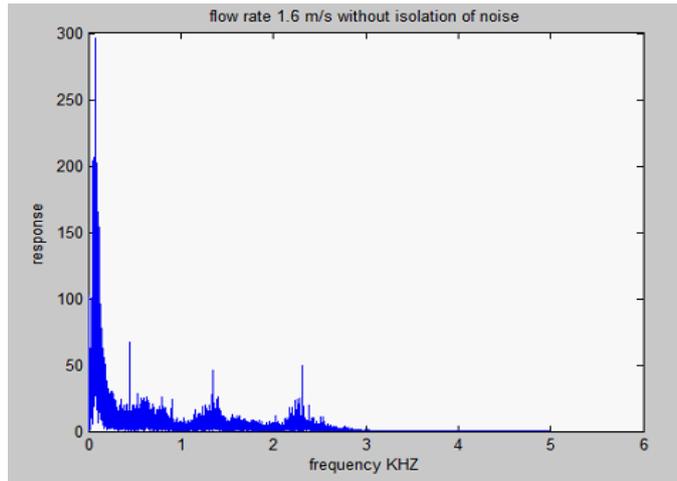Figure 15: Recorded airflow from isolated DYSON fan.

Figure 16: Recorded airflow from non-isolated DYSON fan.

Chapter 7:   Implementation: The Mobile Application

In Chapters 4, 5, and 6 the methodologies, system architecture, and model derivation have been explained in detail. In this Chapter, we discuss the design and implementation of the various mobile application components, and the interaction between these components will be detailed.

7.1   Software Development Environment

The development of our system is achieved in two phases: system prototype design and final system design. The Matlab environment is used for the first phase, and Java programming environment embedded within the Android Software Development Kit (Android SDK) is used for the second phase.

Matlab is a multi-paradigm environment and high level language that allows for numerical computation, programming, and visualization. By using Matlab, we can visualize and analyze data, apply different machine learning techniques, develop algorithms, and create applications and models. Several researches showed how Matlab techniques could be used effectively for audio signal processing [34] and other researchers employed audio signal processing Matlab techniques in their experiments [32,33].

In the development of our system, Java programming environment embedded within Android Software Development Kit is used. The Android SDK includes libraries and tools that allow building, running, debugging, and testing of an Android-based platform application. Android SDK was chosen for the development of our proposed system because it is open source; which means developers can easily download, modify, and distribute any software. Additionally, growing memory resources and availability of faster processors in modern Android-based mobile phones make it efficient and effective for audio processing platforms [35, 36]. Moreover, Android dominated the smartphone market in the past five years with a share of 82.8% according to statistics from the International Data Corporation (IDC) Worldwide Quarterly Mobile Phone Tracker [37].

7.2   Application Components

The proposed mobile application consists of four main activities: Pretest Activity, Sensing Activity, Diagnose Activity, and Report Activity. Typically, an application consists of several activities interacting with each other. Each activity is an

application component with a Graphical User Interface (GUI) that interacts with the user. Figure 17 shows the main activities of the application and their interactions.

Figure 17: Main activities of the application and their interactions.

7.2.1. **Pretest Activity.** Pretest Activity consists of three parts: Collection of basic personal information, reading SpO2 value, and a questionnaire. The basic personal information includes age, height, weight, gender and ethnic group. The SpO2 is measured via external device. The questionnaire is used to assess the possibility of an individual having the disease. The questionnaire includes 13 basic questions about symptoms of respiratory diseases, which are collected from different respiratory diseases agencies reports. The answers of the questionnaire are compiled and forwarded to the Diagnose Activity to be used in the analysis and diagnosis phases.

The Pretest Activity has a significant role in increasing the accuracy of the system and reduces the number of false-positives diagnoses as discussed previously is Section 4.1. Figures 18 and 19 are screenshots from the Pretest Activity.

Figure 18: A sample screenshot of Pretest Activity.

Figure 19: A sample screenshot of Pretest Activity.

7.2.2. **Sensing Activity.** The Sensing Activity is the main activity in the application. It is responsible for collecting the required physiological signals from an individual for the purpose of spirometry test. Since we aim to collect exhalation of an individual, the Sensing Activity uses the AudioRecord class. The AudioRecord class is responsible for recording the exhalation of an individual. Exhalation is extracted from an individual by placing the smartphone directly opposite to an individual face, and the individual should perform a strong exhalation after a deep inhalation as required for the spirometry test. Accordingly, the built in microphone of the smartphone will sense the performed exhalation. In the Android environment, audio recording is achieved by

AudioRecord class, which allows recording from the audio hardware which is the built in microphone in our case. Moreover, AudioRecord class offers flexibility for programmers in choosing the formats and options of the recording. Also, it saves raw data in uncompressed format, which allows the programmer to process the audio data, write to a file, and display it as a waveform. The following steps are followed to record audio signal using the built in microphone and the AudioRecord class:

i. Create an instance of the AudioRecord class.

ii. Specify the parameters of the AudioRecord class as follow:

    a. The source of audio is the built in microphone.

    b. The value of sample rate is 44100 Hz.

    c. The value of channel is CHANNEL_IN_MONO.

    d. The value of the audio encoder is ENCODING_PCM_16BIT.

    e. The value of buffer size is determined by the AudioRecord class which is the min buffer size that is associated with the above parameters, so it is guaranteed that recording will work on all devices.

iii. Invoke startRecording() method to start the recording.

iv. Invoke AudioRecord.read() method to read uncompressed data.

v. Invoke stop() method to stop recording.

The raw data resulted from recording audio is saved temporarily in wave file on smartphone SD card. The exhalation period of an individual usually last for several seconds only, so the size of the resulted file is less than 1Mega-Byte. In our application, an individual should repeat exhalation three times, in order to increase the accuracy of the system. Therefore, the maximum required size on SD card is less than 3 Mega-Bytes. The saved wave files will be read and analyzed in the Diagnose Activity, and at the end of this activity these wave files are deleted from SD card.

7.2.3. **Diagnose Activity.** The Diagnose Activity is responsible for analyzing the readings collected during the Sensing Activity, and processing the information collected during the Pretest Activity. The four major components of this activity are: Analyzing Pretest Activity Data, Analyzing Oxygen Saturation, and Analyzing Recorded Exhalations, and Concluding the Final Diagnosis. Figure 20 shows these parts.
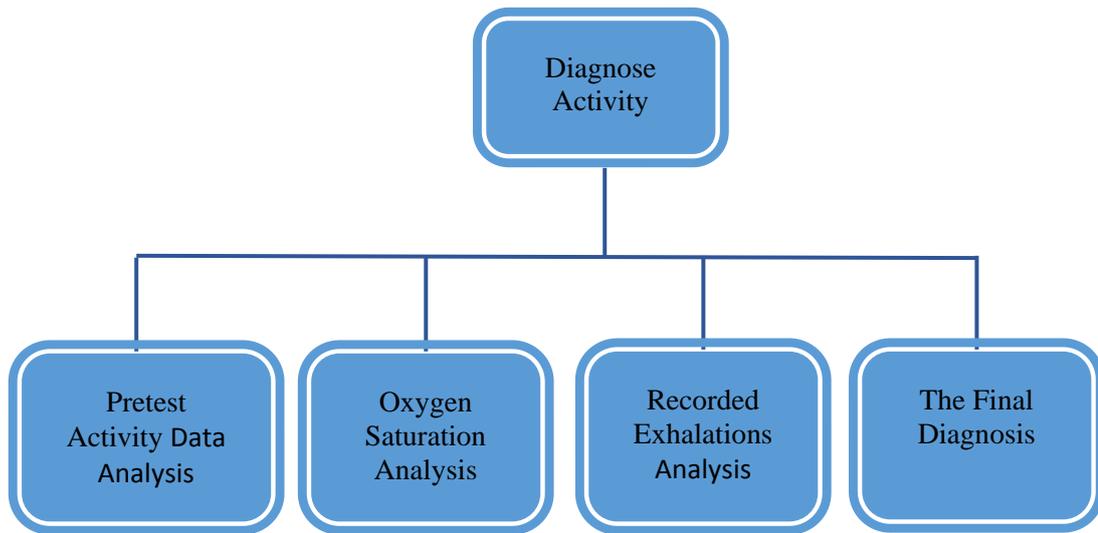
Figure 20: Main components of the Diagnose Activity.

I.   The Pretest Activity Data Analysis Component

The answers to the questionnaire in the Pretest Activity are passed to the Diagnose Activity. In the Diagnose Activity, two probabilities are calculated which are: COPD probability, and Asthma probability. The Diagnose Activity loops over the answers of the questions and increase one of the two probabilities depending on the answer. For example, the following question from the Pretest Activity "Which group of the following triggers that cause worsening of your breath? " has three possible answers which are: (1) Allergens, cold air, and exercise, (2) Respiratory tract infections such as pneumonia and the flu, and (3) None. If the answer is (1) then Asthma probability is increased, if the answer is (2) then COPD probability is increased, and none of these two probabilities is increases in case the answer is (3). The results of this component are the two probabilities.

II.   The Oxygen Saturation Analysis Component

The SpO2 value is measured by an external sensor and the measured value is entered by the patient manually during the Pretest Activity phase. The value is checked and if it is less than 92%, a Boolean variable is assigned to true, and the app will warn the patient later in the Report Activity since he may suffers from a poor blood oxygenation, which is called hypoxia, and may need oxygen supplementation. The output of this component is the Boolean value.

III.   The Recorded Exhalation Analysis Component.

Analyzing the recorded exhalations is based on the algorithm described in Section 4.3.2 and illustrated in Figure 3. The algorithm requires filtering the signal to

extract frequencies between 100 Hz and 1200 Hz. Because there is no specific library in the Android SDK for signal processing, we implemented the required filtering functions in Android. We have implemented filter bank in order to extract possible exhalation frequencies that are between 100 Hz and 1.2 kHz. The outcomes of this component are FEV1% value and FEV1/FVC ratio.

IV.   The Final Diagnosis Component.

This component accepts the results from the two previous components: The Pretest Activity Data Analysis Component, and the Recorded Exhalation Analysis Component. This component contains an implementation of the algorithm described in Figure 4. Based on the two inputs of this component, and the analysis of the algorithm, the final diagnosis could be one of the following: Asthma positive, COPD positive, or negative outcome. The final diagnosis is shown on the Report Activity.

7.2.4.   Report Activity. The Report Activity is the last screen that will be displayed to the user, in which all the related spirometry results and recommendations will be summarized. The report page contains the following:

- Spirometry parameters: FVC, FEV1 and ratio FEV1/ FVC.
- Diagnosis result: whether or not the user has COPD or Asthma.
- Disease severity: The level of the disease if the diagnose was positive. COPD Levels are: mild, moderate, severe and very severe and for Asthma are: mild intermittent, mild persistent, moderate persistent and severe persistent.
- SpO2 warning: In case the user suffers from a poor blood oxygenation.

Figure 21 shows sample of the Report Activity and how the different parameters and diagnosis are displayed.

Figure 21: A screenshot for Report Activity.

Chapter 8:   Testing and Discussion of Results

In this Chapter, results obtained while testing the MobSpiro application using samples collected from human subjects are presented and discussed. Initially, we will explain the protocol used for samples collection and provide a brief description of the collected samples.   Next, we discuss the results obtained using these test samples. Moreover, we will discuss the factors that affected the results, and their contribution to the accuracy of the application. We will calculate several clinical measurements which reflect the reliability and accuracy of our proposed system. Furthermore, we will discuss the problems faced during samples collections and testing, and how they affected the accuracy of the system.

8.1   Samples Collection

To obtain reliable and representative results, samples variety is a must. Therefore, the samples used in this work include patients, at risk smokers and healthy individuals. This variety of our samples in gender, age, and health conditions helps in studying the accuracy of the proposed system, and in developing techniques for future improvements of similar applications. The subjects tested are coached on how to conduct the test correctly and they performed the spirometry test twice, once using the MobSpiro application on GALAXY S5 smartphone, and another as a reference test using a Clinical Spirometer for comparison purposes. In this work, patients are selected from two hospitals, Oriana hospital and Al-Zahra' hospital in Sharjah under the supervision and guidance of Pulmonologists. Smokers and healthy individuals were volunteers from AUS community.

The handheld spirometer used is Spirobank 2 [59]. Studies conducted on Spirobank 2 and other office Spirometers indicate that the user friendliness and quality of these office Spirometers especially Spirobank 2 make them acceptable for the detection of respiratory diseases COPD and Asthma [44-46]. Moreover, office Spirometers are helpful in early detection of COPD and Asthma [47]. Accordingly, Spirobank 2 is selected as the reference spirometer in our testing in the case of smokers and healthy people. In collecting the samples from subjects, we followed the following protocol:

1. Subjects are asked few questions about disease symptoms and family history of respiratory diseases in order to fill the Pretest Activity.

2. Subjects are asked to measure their SpO2 using an oximeter.

3. Subjects are asked to perform spirometry on handheld Spirometer or clinical Spirometer (for hospital subjects).

4. Subjects are asked to perform spirometry using the MobSpiro application by taking a deep inhalation and blowing as hard as possible on the mobile and repeat this action 3 times.

Patients' personal details except for their age and gender are not recorded. We tested the application on 25 subjects. Ten of them are patients already diagnosed with Asthma and COPD from Oriana and Zahra' Hospitals in Sharjah, 5 smokers some of them with few symptoms of respiratory diseases, and 10 healthy with no symptoms. Table 5 shows the age and gender of the subjects from the three categories.

8.2   Testing Results and Diagnosis

8.2.1.   Spirometry parameters results. The results displayed in this subsection are based on the processing of the recorded patients' exhalations as described in Section 5.3.2. The three parameters FVC, FEV1, and the FEV1/FVC ratio are computed for both cases, the standard spirometry and the MobSpiro application. The graphs shown in Figures 22, 23, and 24 show the differences in FVC, FEV1, and FEV1/FVC ratio respectively between the clinical Spirometer and the MobSpiro application for all subjects. From the data of Figures 22, 23, and 24 the calculated mean percent error between FVC data resulted using the MobSpiro application and the clinical spirometer is about 4.6%; the mean percent error between FEV1 data resulted by our MobSpiro application and the clinical spirometer is about 3.1%; and the mean percent error between FEV1/FVC ratio data resulted by the MobSpiro application and the clinical Spirometer is approximately 3.5%.

8.2.2   Diagnosis Outcomes. The final diagnosis of MobSpiro application depends on the pretest possibility of the diseases (Asthma and COPD), and the resulted spirometry parameters. Smokers and healthy subjects with IDs from 1 to 15 in Table 5 had negative diagnosis of COPD and Asthma by both the MobSpiro application and the Clinical Spirometer. Table 6 shows the diagnosis results of MobSpiro application and the clinical diagnosis of patients (IDs 16- 25 from Table 5). All patients were diagnosed correctly by the MobSpiro application except one patient (Samples from subject 19). Subject 19 was diagnosed with Moderate COPD by the MobSpiro application, but clinically he was diagnosed with Moderate Persistent Asthma. Actually, MobSpiro

application depends on FEV1/FVC ratio, FEV1%, and the pretest possibility in diagnosis and classification of disease. On the other hand, clinical diagnosis also depends on FEV1/FVC ratio, FEV1%, symptoms and history, but it may also depend on chest radiograph or the post bronchodilator test which was described in Section 2.7. In some cases, chest radiograph or the post bronchodilator test could be the only differentiator between Asthma and COPD, which unfortunately cannot be included in our proposed system.

8.3   Analysis of Human Exhalations

In this subsection, we will use data from one sample to present the process of diagnosing a respiratory disease using the application. Moreover, we will show a recorded exhalation and discuss the stages it goes through to reach the final results in our proposed application.

Figure 25 shows the exhalation signal for one of the samples used in this work. The Y-axis represents the amplitude of the signal, and the X-axis represents the time in seconds. We applied the steps described in the algorithm of Section 4.3.2 and illustrated in Figure 3, on this signal in order to obtain the flow-time curve which is shown in Figure 26, where the Y-axis represents the flow rate in meter/second and the X-axis represents the time in seconds. The final volume-time curve is shown in Figure 27, where the Y-axis represents volume in Liter and the X-axis represents Time in seconds. The spirometry parameters FVC and FEV1 are shown in Figure 27.

According to the results of the above sample, FEV1/FVC is 82% which indicates a healthy sample.

8.4   Factors Affecting the Results

The implementation of our algorithm, which was described in Section 4.3.2, required specifying a constant that represents the cross sectional area of a typical human mouth. The cross sectional area of mouth is required to convert the flow rate into volumetric flow rate, and thus finding lung parameters. The patient during spirometry test blows hard, and the cross sectional area of mouth opening during blowing is the required constant in our case. Practically, this constant cannot be exactly the same for different people since this constant depends on several factors such as gender, age, and body composition. Unfortunately, we could not find existing studies in literature related to this topic. In our system, we took into consideration the gender and age factors. Regarding age factor, we considered two age stages, namely childhood and adulthood.

Both genders are considered also. Accordingly, we specified four constants in our testing stage for this purpose as seen in Table 7. We estimated these four constants by considering the cross-sectional area from three subjects in each group and then finding the average cross sectional area.

Table 5: Subjects Details

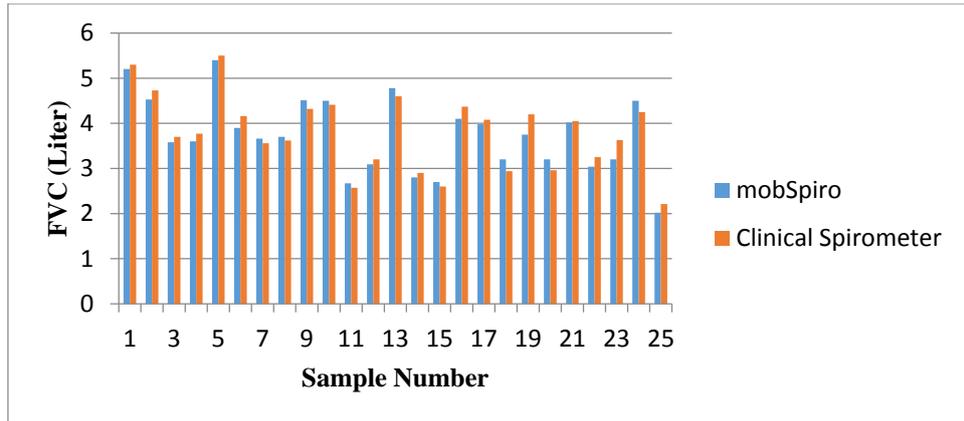| Sample ID	Age	Gender
Smokers		
Subject 1	56	Male
Subject 2	47	Male
Subject 3	38	Female
Subject 4	31	Female
Subject 5	24	Male
Healthy		
Subject 6	66	Male
Subject 7	54	Female
Subject 8	48	Male
Subject 9	40	Male
Subject 10	35	Male
Subject 11	34	Female
Subject 12	31	Female
Subject 13	28	Female
Subject 14	12	Male
Subject 15	10	Female
Patients		
Subject16	Female	63
Subject 17	Male	51
Subject 18	Female	48
Subject 19	Male	40
Subject 20	Female	30
Subject 21	Male	25
Subject 22	Female	23
Subject 23	Female	18
Subject 24	Male	17
Subject 25	Male	8

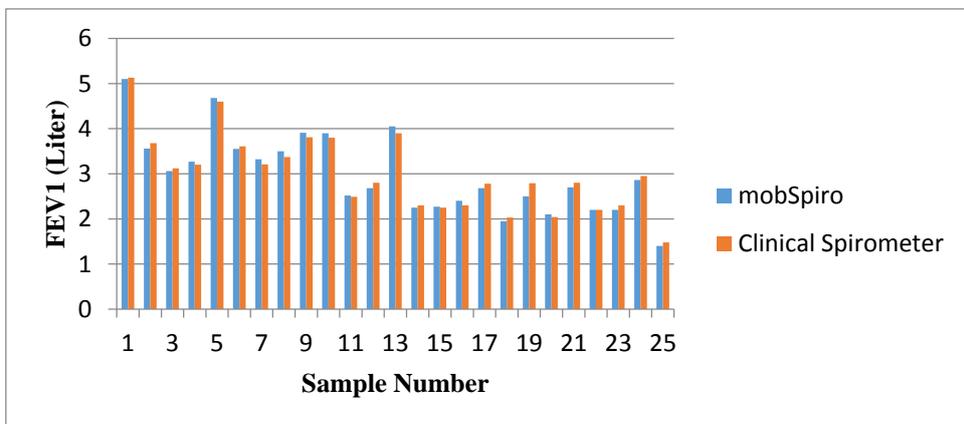Figure 22: FVC differences between real Spirometer result and MobSpiro result.

Figure 23: FEV1 differences between real Spirometer result and MobSpiro result.
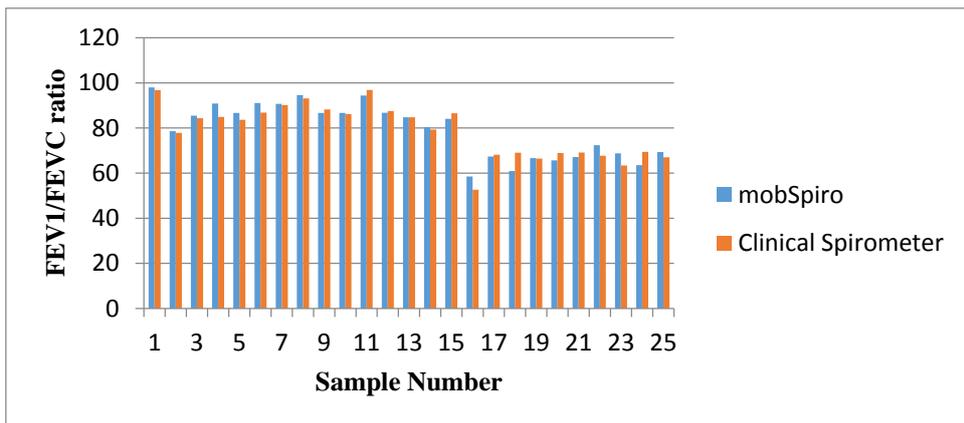

Figure 24: FEV1/FVC ratio differences between real Spirometer result and MobSpiro result.

Table 6: Diagnosis results of the patients.

Sample ID	FEV1/FVC MobSpiro	FEV1 % MobSpiro	Pretest possibility of COPD	Pretest possibility of Asthma	Clinical Diagnosis	MobSpiro diagnosis	Correctly diagnosed
Subject 16	58.5	95.3	True	False	Mild COPD	Mild COPD	True
Subject 17	67.3	78.9	True	False	Moderate COPD	Moderate COPD	True
Subject 18	60.9	98.5	True	False	Mild COPD	Mild COPD	True
Subject 19	66.6	74.4	True	False	Moderate persistent Asthma	Moderate COPD	False
Subject 20	65.6	68	False	True	Moderate persistent Asthma	Moderate persistent Asthma	True
Subject 21	67.1	60.8	False	True	Moderate persistent Asthma	Moderate persistent Asthma	True
Subject 22	71.2	79.1	False	True	Moderate persistent Asthma	Moderate persistent Asthma	True
Subject 23	68.7	76.6	False	True	Moderate persistent Asthma	Moderate persistent Asthma	True
Subject 24	63.5	82.4	False	True	Intermittent Asthma	Intermittent Asthma	True
Subject 25	69.3	87.1	False	True	Intermittent Asthma	Intermittent Asthma	True

Figure 25: Exhalation signal of the sample.

Figure 26: Flow rate vs Time.

Figure 27: Volume vs Time.

Table 7: Cross section area of mouth for different groups.

	Female	Male
Childhood	Group (1) 0.0007meter^2	Group (2) 0.0008 meter^2
Adulthood	Group (3) 0.000855 meter^2	Group (4) 0.001 meter^2

8.5   Comparison with Published Results

Portable devices have been used to perform spirometry tests as explained in Chapter 3. In this section, we present a comparison between the results of the system implemented here, and the results of similar portable devices as discussed in the literature. Table 8 displays the mean percent error in FVC, FEV1, and FEV1/FVC obtained using our system as well as the results of the previously published work.

By comparing the results obtained using MobSpiro to other systems, we notice that our data include samples collected from 10 patients, but some of the reported work

in the literature used random volunteers and didn't necessarily ensure the presence of patients subjects in their set. Moreover, one of the systems, spiroSmart by Larson et al. [25], does the processing in cloud and not locally on the smartphone. The spirometry test is designed to work with a distance equal to 30 cm for the system implemented by Stein [27], with arm length for the spiroSmart, and for unspecified close distance for the COPD work [26]. For our proposed system, the proximity sensor was used to adjust and identify an optimal distance at the beginning of the test. Actually, the distance between smartphone and patient's mouth during the spirometry test is considered a critical factor.

8.6   Issues Faced during Testing

Samples collection and testing was not an easy task during the implementation of the system. We faced several issues and limitations which affected the size of tested subjects, especially the patient's category, since for accuracy a larger population is always desirable. Other issues are related to the environment, the patients' attitude, the pulmonologists' patience in cooperating with us, and the sometimes the performance of spirometry test itself.

Table 8: A comparison between mobile-based spirometry systems.

Previous work	Number of samples	Number of patients	Mean percent error in FVC	Mean percent error in FEV1	Mean percent error in FEV1/FVC
Larson et al. spiroSmart [25]	52	Unspecified	5.0%	3.5%	3.6%
Xu et al.mCOPD [26]	40	Unspecified	6.5%	3.6%	3.9%
Stein [27]	12	2	< 10%	< 10%	< 10%
MobSpiro	**25**	**10**	**4.6%**	**3.1%**	**3.5%**

I.   Noisy environment

In our application, we record patient's exhalation using the built in microphone of the GALAXY S5 smartphone in a regular room in a hospital or clinic. Even after filtering when preprocessing the recorded exhalation, noise still affects the final results of spirometry. The filters exclude frequencies outside the possible range of human exhalation frequencies, but noise frequencies that lie in the same range of exhalation

frequencies cannot be eliminated. To ensure the result of spirometry test done using our application is reliable, an individual should perform it in a quiet controlled environment. Fortunately, we collected samples from smokers and healthy people in a quiet, controlled environment. On the other hand, while collecting samples from patients in hospitals, where sometimes couldn't find a quiet, controlled environment. Therefore, we notice that accuracy of our system when tested on smokers and healthy people in controlled environment is relatively better than the accuracy of the system when tested on patients in uncontrolled environment as seen previously in Section 8.2.

II.   Consistency of patient's behavior

The most reliable approach to assess the accuracy of our application is by comparing its results to those of Clinical Spirometer results. During the testing, the patient performs spirometry on both Clinical Spirometer and the MobSpiro application, and the results of both tests are recorded. In general, spirometery test accuracy depends largely on the behavior of the user, i.e. the depth of inhalation and the strength of exhalation. Unfortunately, some patients in both hospitals were tired after performing the test on the Clinical Spirometer, so they performed the spirometry on our application less enthusiastically. Practically, we cannot enforce the patient to do spirometry exactly the same on both devices. Accordingly, this issue has affected the accuracy of our system to some extent.

III.   Cost of spirometry test at hospitals

We strived to add more patients from both hospitals to our samples collection, but unfortunately we could not achieve that. Cost of spirometry test at hospital is considered high, therefore a pulmonologist cannot ask patient who recently did spirometry in a previous visit to repeat it again. A pulmonologist may depend on symptoms and medication effects and trial and error when diagnosing the patient, in case the patient cannot bear the cost of spirometry test.

IV.   Doctors and patients cooperation

During sample collection in hospitals, it was important to have cooperative pulmonologists and patients. Some Pulmonologists during their office hours typically have many patients and prefer continuing their work without interruption. Therefore, it was difficult to expect full cooperation from them during sample collection phase. Moreover, some of patients were kind and cooperative, and some were in a hurry and don't have time to repeat the spirometry test on our smartphone.

8.7   Performance Tips

Spirometry test is an effort based medical test. Therefore, the effort and cooperation of the patient plays a basic role in increasing the accuracy of the test. Also, the MobSpiro application is designed to work in a specific manner. The Following are few tips that should be followed by the user to ensure the reliability of the spirometry test using our MobSpiro or a similar application.

I.   Fixed distance during spirometry test

The distance between sound source and mobile microphone affects the strength of the recorded signal. Therefore, in the experimental work, we collected data at a fixed distance (5 cm) between DYSON AM06 fan and mobile. Also, we designed the MobSpiro application to record subject's exhalation at a fixed distance (5 cm) between subject's face and mobile. MobSpiro app adjusts the distance at the beginning of the test by the help of the built-in proximity sensor. User can help in increasing the accuracy of the spirometry test by keeping the distance as adjusted at the beginning and for the whole duration of the test and following the instructions provided in our application.

II.   Performing spirometry as perfectly possible

In medicine, the assurance of a high quality spirometry test is still a challenge. Spirometry is considered of value if it is performed correctly and results clearly interpreted [48]. Patients who receive training on how to perform spirometry test effectively can achieve higher quality spirometry tests than others [49, 50].   In spirometry, patient needs to take a deep inhalation and then exhale strongly as much as possible. Therefore, patient behavior plays a basic role in increasing the accuracy of the results by following. As recommended by American Thoracic Society, a minimum of three acceptable maneuvers should be performed in a spirometry test [51]. One maneuver includes taking a deep inhalation and exhaling as strong as possible. Moreover, minimum FVC exhalation is 6 seconds. If the duration of FVC exhalation is less than 6 seconds, resulted FVC is considered an unreliable parameter [51].

Chapter 9:   Conclusion

Chronic obstructive pulmonary disease (COPD) and Asthma are chronic lung diseases, which are characterized by coughing, wheezing, chest tightness, and shortness of breath. Severity level of COPD disease ranges from mild, moderate, and severe to very severe depending on specific lung measurements. For Asthma, severity level ranges from mild intermittent, mild persistent, and moderate persistent to severe persistent. Spirometry remains the golden standard for diagnosing and staging COPD and the recommended test for Asthma diagnosing and monitoring. Traditional methods of diagnosing and monitoring COPD and Asthma require either buying portable Spirometers, which are considered expensive compared to moderate income, or regular visits to physician in medical centers, which are considered time consuming and expensive. Due to the pervasiveness of smartphones and their powerful computational capabilities, we implemented a design that takes advantage of the built-in sensors in the smartphone to extract and analyze physiological signals in order to diagnose, stage, and monitor COPD and Asthma diseases.

Following a thorough review of published literature in respiratory diseases and the methods by which they are diagnosed and managed, we discussed the design and development phases of a mobile application that is able to read the physiological signals of a patient using built-in sensors, and analyze the collected data to diagnose, stage and monitor the disease.

The developed smartphone application has performed as expected in recording patient exhalation and extracting lung function measurements from the patients and analyzing the collected data solely on the smartphone. We tested the application on 25 subjects. The results showed that 96% of test samples were correctly diagnosed, and the mean percent error between FVC, FEV1, and FEV1/FVC ratio data resulted by our MobSpiro application and the clinical Spirometer is 4.6%, 3.1%, and 3.5% respectively. These results prove the effectiveness of the proposed system when compared to the clinical Spirometer and emphasize the role that smartphones may play in healthcare in the coming future.

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Vita

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