Intelligent Sensing Anywhere

Look4MySounds

Sound Platform for Remote Auscultation

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Abstract

Respiratory diseases are pathologies that affect the air passages, including the nasal passages, the bronchi and the lungs. Their variety can go from acute infections, such as pneumonia and bronchitis, to chronic conditions, like asthma and chronic obstructive pulmonary disease (COPD). These pathologies result of changes in the lung structure or airways obstruction, causing additional respiratory sounds (such as crackles and wheezes) superimposed on normal ones.

Auscultation through the stethoscope is the most important and established non-invasive method to distinguish between normal and abnormal sounds. However, this is a subjective tool that extremely relies on medical experience and hearing capabilities. Besides that, one of the basic requirements of this examination procedure is the need to maintain a doctor-patient interaction. In many situations, it reveals unreachable and expensive for both patient and healthcare unit. Recently, due to the concern in errors and costs reduction, while improving the care quality, there was a significant increase of studies on computer-assisted acquisition and analysis of respiratory sounds. In addition, the remote monitoring is becoming an interesting and useful technology in health care services due to its clinical, economic and social benefits.

The aim of this project is to develop an autonomous, portable and inexpensive sound platform for remote auscultation of respiratory sounds. The system will allow continuous monitoring of chronic diseases in a domestic environment over extended periods of time to access its severity and progression, avoiding constant patient displacement to healthcare units. Besides that, the screening of pulmonary conditions and/or pathologies through the sounds, which allows the early detection of potential danger situations, will also be a possible. The sound platform prototype includes: three boards that work integrated, a stethoscope with a microphone incorporated to acquire the respiratory sounds and a memory card to store them. The respiratory sound data is then classified through an algorithm implemented in a microcontroller.

The present document describes the entire system specifications, the algorithm implemented and the experimental evaluation/validation in real life situations, which points towards the commercialization potential of the developed prototype.

Resumo

As doenças respiratórias são doenças que afectam as vias respiratórias, incluindo as vias nasais, os brônquios e os pulmões. Estas podem ser agrupadas em duas grandes categorias: infecções agudas, como a pneumonia e a bronquite; e condições crónicas que incluem a asma e a doença pulmonar obstrutiva crónica (DPOC). As alterações estruturais dos pulmões e a obstrução das vias respiratórias que resultam em doenças causam sons respiratórios adicionais (como as crepitações e os sibilos) que se sobrepõem aos sons respiratórios normais.

A auscultação, através do estetoscópio, é o mais importante e estabelecido método não invasivo para distinguir entre sons normais e patológicos. No entanto, é uma ferramenta subjectiva que depende muito da experiência médica e das capacidades auditivas de cada um. Para além disso, o principal requisito deste procedimento é a necessidade de manter uma interacção médico-paciente. Em muitas situações, isto torna-se inacessível e dispendioso tanto para o paciente como para a unidade de saúde. Nos últimos anos, devido à preocupação na redução de erros e custos enquanto se melhora a qualidade dos cuidados de saúde, tem-se verificado um aumento significativo de estudos sobre a aquisição e análise de sons respiratórios assistidas por computador. Para além disso, a monitorização remota está a tornar-se uma tecnologia interessante e útil na área da saúde devido aos seus benefícios clínicos, económicos e sociais.

O objectivo deste projecto é desenvolver uma plataforma de som autónoma, portátil e económica para auscultação remota de sons respiratórios. Este sistema irá permitir a monitorização contínua de doenças crónicas num ambiente familiar durante longos períodos de tempo de modo a avaliar a severidade e progressão da doença, evitando assim as constantes deslocações dos pacientes às unidades de saúde. O rastreio de condições/patologias pulmonares através dos sons, ajudando na identificação precoce de situações de perigo, também será possível com este equipamento. A plataforma de som inclui três placas que funcionam integradas, um estetoscópio com um microfone incorporado para a aquisição de sons e um cartão de memória para os armazenar. Os sons respiratórios são depois classificados através de um algoritmo implementado num microcontrolador.

Através deste documento, pretende-se descrever as especificações de todo o sistema, o algoritmo implementado e a avaliação/validação experimental em situações reais tendo em vista a potencial comercialização do protótipo desenvolvido.

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Acronyms

Abbreviation	Definition
OSAS	Obstructive Sleep Apnoea Syndrome
ISA	Intelligent Sensing Anywhere
WHO	World Health Organization
COPD	Chronic Obstructive Pulmonary Disease
PC	Personal Computer
M2M	Machine-to-Machine
R&D	Research and Development
CI	Centro de Instrumentação
GEI	Grupo de Electrónica e Instrumentação
UC	Universidade de Coimbra
HC	Hospital dos Covões
CHC	Centro Hospitalar de Coimbra
DSC	Digital Signal Controller
DC	Direct Current
kB	Kilobyte
GB	Gigabyte
GPRS	General Packet Radio Service
INE	Instituto Nacional de Estatística
FDA	Food and Drug Administration
RP	Remote Presence
POTS	Plain Old Telephone Services
DSL	Digital Subscriber Line
ISDN	Integrated Services Digital Network
IP	Internet Protocol
NASA	National Aeronautics and Space Administration
PLC	Power Line Communications
PHS	Personal Handy-phone System
PPP	Point-to-Point Protocol
LCD	Liquid Crystal Display
CORSA	Computerized Respiratory Sound Analysis
FT	Fourier Transform
FFT	Fast Fourier Transform

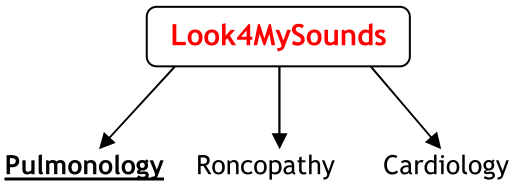
IFFT	Inverse Fast Fourier Transform
LED	Light Emitting Diode
AR/MA	Auto-Regressive/Moving Average
TEWA	Time-Expanded Waveform Analysis
TP	True Positives
FN	False Negatives
TN	True Negatives
FP	False Positives
GUI	Graphical User Interface

1. INTRODUCTION

1.1 Look4MySounds Project

The idea of a sound platform for remote auscultation arose following the Sleep@Home project context, developed in the previous two years. The goal of the Sleep@Home was the home screening of Obstructive Sleep Apnoea Syndrome (OSAS). The system prototype was composed of a video camera, an oximeter and a video server where the data was stored. The physicians pointed as main limitation of this system the need to listen the patient's breathing. For example, snore during sleep time, is a significant feature of respiratory problems, often associated with Sleep Apnoea. Based in these medical advices, ISA decided to create a new project that could diagnose this disease, but also many others where the sounds analysis is important.

The Look4MySounds project is intended to cover three biomedical applications: pulmonology, roncopathy and cardiology. The pulmonology application is presented along this thesis.



1.2 Motivation

Respiratory diseases are a leading cause of hospitalization and death. The diseases that reveal the most worrying numbers are asthma, chronic obstructive pulmonary disease (COPD) and pneumonia. The World Health Organization (WHO) estimates that, in 2007, 300 millions of people in the world have asthma and 255 000 people died of asthma in 2005. Besides that, 210 million people suffer from COPD and 3 million died in 2005. WHO predicts that COPD will become the third leading cause of death in 2030. Additionally, pneumonia is a largest worldwide cause of death in children. Statistics reveal that this disease kills 1,8 millions of children (under the age of 5 years) every year, more than AIDS, malaria and measles combined [1,2].

In many situations is complicate to provide the required medical monitoring of patients, mainly by lack of human resources and infrastructures, but also by the difficult access to health services of a considerable number of people (mostly elderly). Furthermore, the governmental politics require that health entities increase their productivity and, at the same time, impose a spending restraint in their services. The daily life activities, the stress and the lack of time are also reasons for many people to not control their vital signs in a medical care unit. These signs may be indicative of a possible disease.

Concerning errors and costs reduction while improving the care quality, wireless technologies are becoming interesting and useful medical solutions. The remote monitoring, with its clinical, economic and social benefits, enables the vital signs monitoring of patients from their homes by healthcare providers. In fact, if diagnosed in time, many diseases can easily be treated at home with antibiotics and a supervision of the patient's respiratory sounds. The access to patients' data is simplified, being only necessary when an alarm is emitted or just for diagnostic routine purposes. In the latter situation, another advantage to the patient is that they avoid constant displacements to healthcare units just to deliver measured values.

Advanced techniques in signal processing, combined with data remote transmission, allow the development of portable systems with low power, great autonomy and more comfortable for household.

1.3 Objectives

The aim of this project is the development of an autonomous, portable and inexpensive sound platform for remote auscultation. The system must be able to acquire, store and process respiratory sounds. In addition, each type of pathologic sound should be distinguished. The sound data must be saved into a memory card. It should also be possible to transfer the data to the patient's personal computer (PC) by a RS-232 serial port or remotely sent to a doctor or a healthcare unit. The respiratory sounds should be collected through a stethoscope with a microphone incorporated.

1.4 Audience

Along this document is reported what was done during the project in order to reach the main goal proposed. All the research, the execution, the knowledge acquired and the decisions made will be evaluated by supervisors who followed the entire system development process.

1.5 Document Structure and Organization

The present document is divided in 9 organized chapters. This section makes a brief description of each one.

1 – **Introduction** – describes the main purposes of a product like this on the market. Also, the objectives of the master's project are provided;

2 – **Project Management** – refers to the team members, including supervisors and entities involved in the project. The tasks division and its initial/final planning were presented as well;

3 – **Theorical Background** – provides all the information related to the respiratory sounds field. The anatomy of the lungs, the respiratory diseases and associated sounds as well as the auscultation technique used to acquire the patient's sounds will be described in this chapter;

4 – **Look4MySounds System -** reports a brief description of the system. All the components of the acquisition solution will be enunciated and the general architecture will be presented;

5 – **Related Works** – contains the problem analysis and a general view of the equipments for remote transmission/classification of respiratory sounds. The final section summarizes the advantages that the pretended solution may offer when comparing with the already existing;

6 – **Experimental Data** – refers to the subjects data used to perform the evaluation/validation of the prototype. Furthermore, the conditions in which the tests were made will be described. The statistical results obtained after algorithm conclusion and a discussion of the same is also presented;

8 – **Conclusions** – final impressions concerning the system (hardware plus software) developed during the year. A doctor's appreciation will also be presented;

9 – **Future Work** – this chapter concludes the project report with some issues that the student considers important to develop in the future to increase the robustness of the equipment.

2. PROJECT MANAGEMENT

2.1 Project Members

A Biomedical Engineering student, from the Faculty of Sciences and Technology – University of Coimbra, and their supervisors, composed the project team (Table 1). The student and the Engineer Inês Fonseca, her technical supervisor, carried out the development of the sound platform (software and firmware modules). The supervisors had an important role in the orientation and coordination of their work.

Table 1 - Project team.

Name	Contribute	Email contact
Ana Margarida Martins	Student	ammartins@isa.pt
Engineer Inês Fonseca	Technical Supervisor	ifonseca@isa.pt
Engineer Soraia Rocha	Supervisor	srocha@isa.pt
Engineer Catarina Pereira	Supervisor	cpereira@isa.pt
Engineer José Luís Malaquias	Supervisor	jmalaquias@isa.pt
Professor José Basílio Simões	Supervisor	jbasilio@isa.pt
Professor Carlos Correia	Supervisor	correia@lei.fis.uc.pt
Doctor Helena Estevão	Medical Supervisor	
Doctor José Moutinho	Medical Supervisor	

2.2 Tasks Division

The assignment of the tasks that Margarida and Engineer Inês Fonseca would perform was made at the beginning of the project. In the first semester, both team members were responsible for the development of respiratory sounds classification algorithms. During this period, they implemented several computer-assisted diagnosis techniques, taking into account methods already used in the literature. However, the results of the implemented algorithms did not work with the sounds collected with the student’s PC at HC (the same pathology gave different results for each patient). So, a redefinition of Margarida’s tasks was accorded and, from the middle of the second semester, she became the only responsible for the implementation of a simple algorithm for respiratory sounds classification.

Table 2 – Tasks assignment.

Project Members	Assigned Tasks
Ana Martins	• Collect respiratory sounds from healthy people and patients at the Hospital; • Analysis of the sounds data and identification of the obvious pathologies; • Programming the sound platform with an algorithm for respiratory sounds classification.
Inês Fonseca	• Programming the sound platform to acquire and store respiratory sounds; • Firmware implementation to remote communication.

2.3 Entities Involved in the Project

2.3.1 ISA

Intelligent Sensing Anywhere (ISA) is a spin-off company of the University of Coimbra founded in 1990. Currently, it is an award-winning global company specialized in Telemetry and Machine-to-Machine (M2M) Communications.

The company has a Research and Development (R&D) department that works focused in providing complete solutions in several fields like telemetry, industrial automation, environment and healthcare. With a team of highly specialized engineers, which has been growing since its formation, ISA made possible the integration of several students in its software team to help in market viability studies and in the development of simple solutions with commercialization potential.

In the first semester, the Engineers José Luís Malaquias and Catarina Pereira were responsible for the supervision at ISA. In the middle of the second semester, with the arrival of the Engineer Soraia Rocha, she became the most effective supervisor of the project. Several meetings were arranged to briefs presentations of the project state and to clarify some doubts. These meeting were always very profitable in order to point new directions for the work progression.

After the change of ISA installations to the current address, the student began to develop the work, twice a week, in company desks reserved for temporary workers, benefiting of a closer accompaniment by the supervisors.

Entity Name	Main Responsible	Website
ISA	Engineer José Basílio Simões	http://www.isa.pt

2.3.2 CI-GEI

CI is a research group integrated in GEI, which had been recently created in the Physics Department of the University of Coimbra (UC). Its research areas include Atomic and Nuclear Instrumentation, Biomedical Instrumentation, Plasma Physics Instrumentation, Optical Signal Processing and Telemetry and Industrial Control. CI was the institution responsible for the connection between ISA and UC.

The supervisor at CI was Professor Carlos Correia. His knowledge and assistance was important in the signal processing field. Professor Carlos Correia was always available to point towards new directions of work.

Most of the work was developed in this research centre, mainly when the student was not in ISA installations.

Entity Name	Main Responsible	Website
CI-GEI	Professor Carlos Correia	http://lei.fis.uc.pt

2.3.3 HC

HC is a general Hospital that is integrated in CHC. The CHC mission is to provide differentiated healthcare throughout the cycle of human life, from prevention to rehabilitation, as a regional and national reference centre in diverse medical areas, such as cardiology, neurology, pulmonary, among with many others. It also made possible the investigation, education and formation. HC includes the Sleep Studies Laboratory, were Doctor José Moutinho works, and the Pulmonology Service, where the respiratory sounds from patients interned were collected. Doctor José Moutinho, with his knowledge and extensive experience, made the entire medical accompaniment helping in the auscultation process definition and the respiratory sounds classification collected.

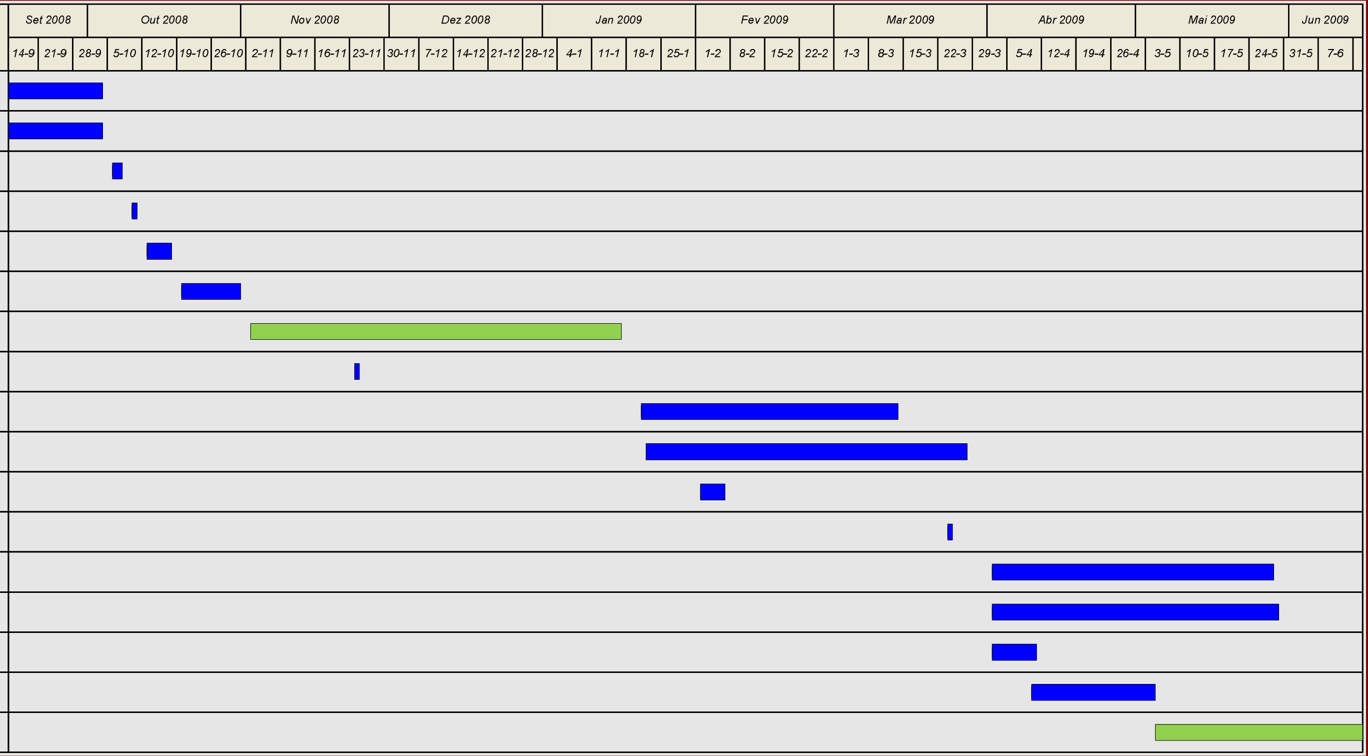
Entity Name	Main Responsible	Website
HC	Doctor Rui Pato	http://www.chc.min-saude.pt

2.4 Scheduling

2.4.1 Initial Planning

The initial scheduling was defined by the Engineer Inês Fonseca with the supervision of the Engineer José Malaquias.

ID	Task Name	Start	Finish	Duration
1	Lecture of the colleagues' thesis from previous years	15-09-2008	03-10-2008	15d
2	Study Sleep Apnoea disorder	15-09-2008	03-10-2008	15d
3	Research on sound platforms to screening/diagnosis OSAS	06-10-2008	07-10-2008	2d
4	Integration on the Look4MySounds project	10-10-2008	10-10-2008	1d
5	Study the relevant terms covering the respiratory sounds field	13-10-2008	17-10-2008	5d
6	Research methods for respiratory sounds analysis	20-10-2008	31-10-2008	10d
7	Implementation of algorithms to respiratory sounds classification	03-11-2008	16-01-2009	55d
8	Participation in the Portugal Tecnológico (Lisbon)	24-11-2008	24-11-2008	1d
9	Collect patients respiratory sounds at Hospital with the PC/Audacity software	21-01-2009	13-03-2009	38d
10	Analysis of the recorded sounds and test in the implemented algorithms	22-01-2009	27-03-2009	47d
11	Preparation for the first project presentation	02-02-2009	06-02-2009	5d
12	Participation in the FENGE (Coimbra)	24-03-2009	24-03-2009	1d
13	Collect patients' respiratory sounds at the Hospital with the sound platform	02-04-2009	28-05-2009	41d
14	Analysis of the recorded sounds and identification of the pathologies	02-04-2009	29-05-2009	42d
15	Study the viability of a sound platform to record respiratory sounds	02-04-2009	10-04-2009	7d
16	Implement the most reliable algorithm in C code	10-04-2009	04-05-2009	17d
17	Port the algorithm to the sound platform	05-05-2009	15-06-2009	30d

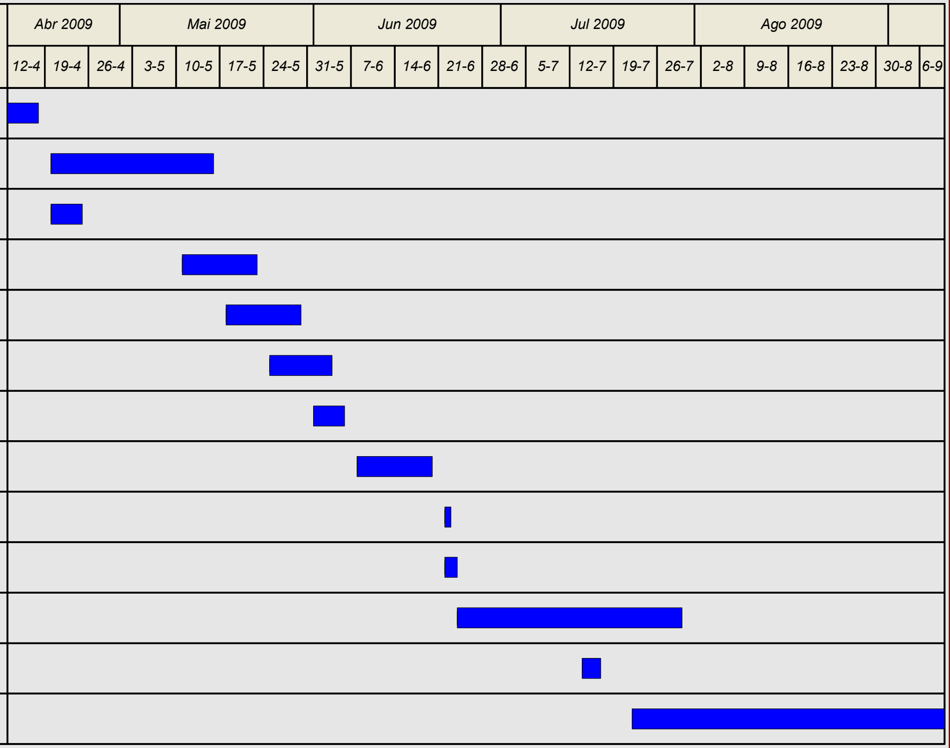


The tasks 7 and 17, marked with green colour, were carried out by the student and her technical supervisor, Engineer Inês Fonseca.

2.4.1 Final Planning

As it was already mentioned in the chapter 2.2, the results of the implemented algorithms were not the expected. So, in the beginning of April, Margarida's tasks were redefined by the Engineer Soraia Rocha.

ID	Task Name	Start	Finish	Duration
1	Test the algorithm implemented by Inês Fonseca for respiratory phases detection	13-04-2009	17-04-2009	5d
2	Development of an algorithm in Matlab for respiratory sounds classification	20-04-2009	15-05-2009	20d
3	Elaboration of the project's technical specifications document	20-04-2009	24-04-2009	5d
4	Draft of a Graphical User Interface (GUI)	11-05-2009	22-05-2009	10d
5	Algorithm optimization (noise filtering stage)	18-05-2009	29-05-2009	10d
6	Preparation for the second project presentation	25-05-2009	03-06-2009	8d
7	Intensive study in C programming language	01-06-2009	05-06-2009	5d
8	Convert the implemented algorithm to C	08-06-2009	19-06-2009	10d
9	Participation in the Innovation Days (Lisbon)	22-06-2009	22-06-2009	1d
10	MPLab User's Guide and dsPICs programming study	22-06-2009	23-06-2009	2d
11	Implement the algorithm in C to the dsPIC	24-06-2009	29-07-2009	26d
12	Elaboration of the User's Guide document for the Look4MySounds project	14-07-2009	16-07-2009	3d
13	Project final report	22-07-2009	09-09-2009	36d



3. THEORETICAL BACKGROUND

3.1 Lungs: Anatomy and Physiology

The human lungs are a pair of organs responsible for the respiration, i.e. transport the oxygen (O_2) from the atmosphere to the bloodstream and release carbon dioxide (CO_2) from the bloodstream to the atmosphere. This process of gas exchange is accomplished for small amounts of other gases, floating bacteria, and viruses. So, the lungs also protect the body against these airborne irritants and infections agents.

The lungs are spongy and cone-shaped; they extend from the trachea to below the heart and occupy most of the thorax.

During respiration, which includes inspiration and expiration phases, the air enters the body through the nose or the mouth and travels down the throat and trachea into the chest through the bronchi. The bronchi subdivide into successive generations of narrower and shorter branching tubes. The final destination for inhaled air is a network of about 3 millions air sacs, called alveoli. Movement of the air into the lungs is controlled by the respiratory muscles of the thorax, the diaphragm and the muscles that move the ribs [3,4].

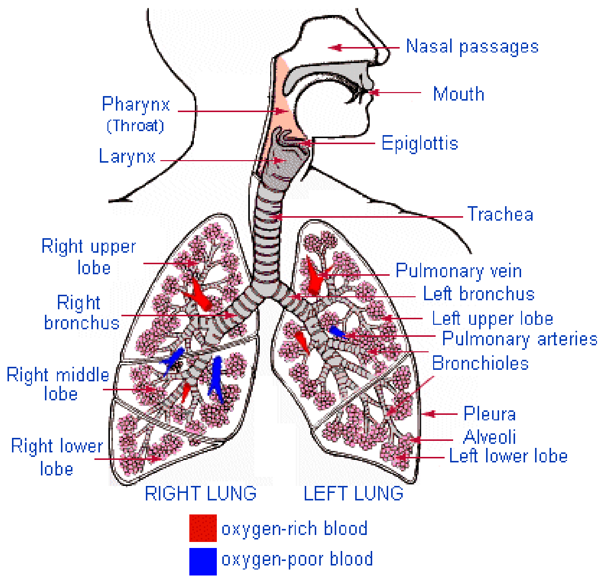


Figure 1 – Lungs anatomy.

3.2 Respiratory Diseases

Medical problems at birth or during infancy and growth can affect lung development. Also, later in life the lungs may be damaged by smoking, occupational exposures, or accidents. These abnormalities allow air pollutants to break through the lung's defences and the result can be respiratory diseases [3].

Respiratory diseases are pathologies that affect the air passages, including the nasal passages, the bronchi and the lungs. They can be classified in many different ways: by the organ involved, by the pattern or symptoms or by the cause of the disease. However, the most common fall into two broad categories: acute infections, such as pneumonia and bronchitis, and chronic conditions, like asthma or chronic obstructive pulmonary disease [2,5].

Pneumonia is a disease that results from the infection of the lung tissues by certain germs, such as bacteria, viruses, and fungi. As microorganisms multiply, the alveoli become inflamed, red, and accumulate fluid. It is difficult for the person to breathe properly and may lead to death within 3-4 days, if not treated. Fever, chills and cough are also symptoms of this disease. It can affect people of any age, although it is more serious in the very young (children under 5 years of age) and people over the age of 65 [2,6].

Bronchitis is an acute inflammation of the mucous membranes of the bronchi. The thin mucous lining of these airways become irritated and swollen. People who have bronchitis often have a cough that brings up mucous, wheezing (subject described in the following chapter), chest pain or discomfort, a low fever, and breathlessness. Bronchitis can be classified into two categories, acute and chronic; each one has unique etiologies, pathologies, and therapies. Both adults and children can have this disease [6,7].

Asthma is a chronic (long-term) lung disease in which the airways (bronchi) are reversibly narrowed. It is characterized by current attacks of breathlessness and wheezing. Asthma affects people of all ages, but it most often starts in childhood [2,6].

Chronic obstructive pulmonary disease (COPD) is a progressive disease in which airways become narrowed. The most common symptoms of COPD are breathlessness, excessive sputum production, wheezing, and a chronic cough. Cigarette smoking is the leading cause of COPD. Long-term exposure to other lung irritants, such as air pollution, chemical fumes, or dust, also can trigger an abnormal inflammatory response of the lung. In contrast to asthma, the limitation of airflow is poorly reversible and usually gets progressively worse over time [2,6].

According to WHO, pneumonia, asthma and COPD are under-diagnosed and under-treated diseases, creating a substantial burden to individuals and families and possibly restricting individuals' activities for a lifetime [2].

3.3 Respiratory Sounds

Respiratory sounds are all the sounds related to respiration that can be heard or detected at the mouth, over the trachea or the chest wall. They can be classified as normal sounds (also called breath sounds) or adventitious sounds. The adventitious sounds are related to additional sounds superimposed on breath sounds. They can be continuous sounds (like wheezes, rhonchus and stridor) or discontinuous sounds (such as crackles). The presence of these sounds usually indicates a pulmonary disorder. The most common and more studied noises are wheezes and crackles [5,8,9]. So, this thesis will focus on these sounds. Rhonchus has similar features to wheezes and some physicians do not distinguish between them. Stridor is a very rare sound and usually is associated with children.

3.3.1 Normal Sounds

The breath sounds are created in the airways due to air velocity and turbulence that induce vibrations in the airway walls. In inspiration, the air moves into progressively smaller airways with the alveoli as its final location. In expiration, the air is moving in the opposite direction towards progressively larger airways. Less turbulence is created, thus expiratory breath sounds are quieter than inspiratory sounds [10].

Normal sounds are traditionally organized into 4 categories: tracheal breath sounds, vesicular breath sounds, bronchial breath sounds and bronchovesicular breath sounds. The classification is based on their intensity, pitch, location, and inspiratory to expiratory ratio [10,11].

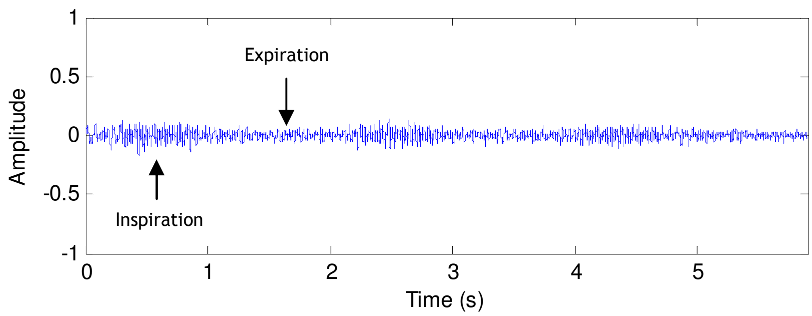


Figure 2 – Normal sound signal[1].

[1] Henceforth, the different respiratory sounds shown were acquired with the Look4MySounds hardware.

3.3.2 Adventitious Sounds

Wheezes are continuous sounds characterized mainly by their pitch and duration. The frequency of this pathologic sound lies within 100 and 2500 Hz, with a fundamental frequency between 400 and 1000 Hz. Wheezes, predominant of expiratory phase, are very often approximately by a pure sinusoidal signal, which justifies their musical character. According to Computerized Respiratory Sound Analysis (CORSA) guidelines, the dominant frequency of this adventitious sound is over 100 Hz and the duration is greater than 80 ms. Wheezes are produced when air passes through slightly occluded airways, causing the walls of the airways to oscillate. They usually identify the presence of an obstructive pathology, for example, asthma or COPD [5,12].

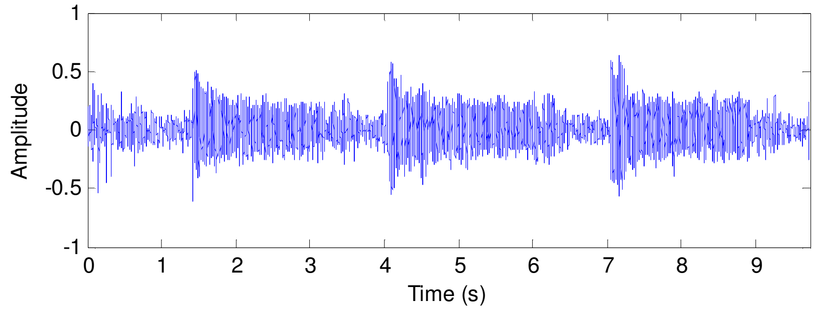


Figure 3 – Wheezes signal.

Crackles are discontinuous, explosive, non-musical sounds characterized by their specific waveform, duration, and location in the respiratory cycle. Concerning the last two features, crackles can be *fine* (short duration and typically occurs in the inspiratory phase) or *coarse* (long duration and is present in both respiratory phases). The crackles can be heard over the chest wall and are produced by the sudden opening of peripheral airways (especially the alveoli) from fully a deflated state. However, they also can be heard over the trachea and, in these cases, are produced by the passage of air bubbles through partially obstructed main airways. The principal pathologies where these adventitious sounds can be found are pulmonary fibrosis, bronchiectasis, COPD and pneumonia [5,8,10].

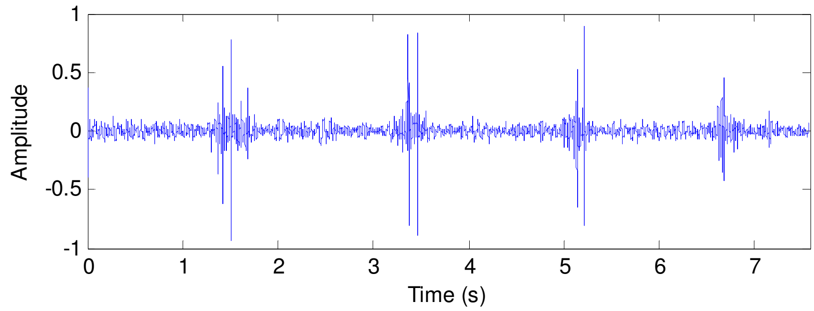


Figure 4 – Crackles signal.

3.4 Auscultation Technique

Auscultation is one of the most important and effective technique employed by a physician to evaluate the patient's respiratory function. The examination symmetrically is used to allow comparing and detecting unilateral injuries. However, in terms of positions to place the stethoscope there is no consensus in the literature. The opinion differs from doctor to doctor, institution to institution, paper to paper. So, it was decided to adopt the technique used by the Doctor José Moutinho, the pulmonology specialist that made all the medical accompaniment of the project.

1. Anterior (3 positions switching between the right and left side)

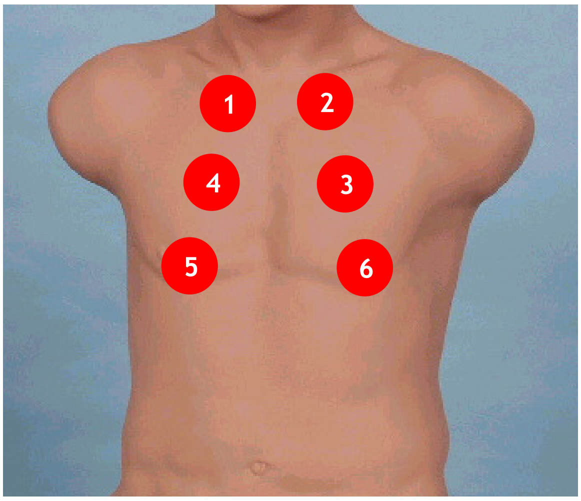


Figure 5 – Locations for auscultation on the anterior chest.

2. Lateral (3 positions switching between the right and left side)

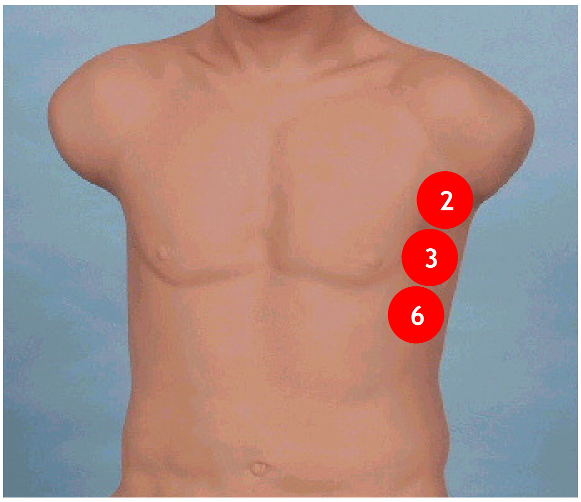


Figure 6 – Locations for auscultation on the lateral chest.

3. Posterior (4 positions switching between the right and left side)

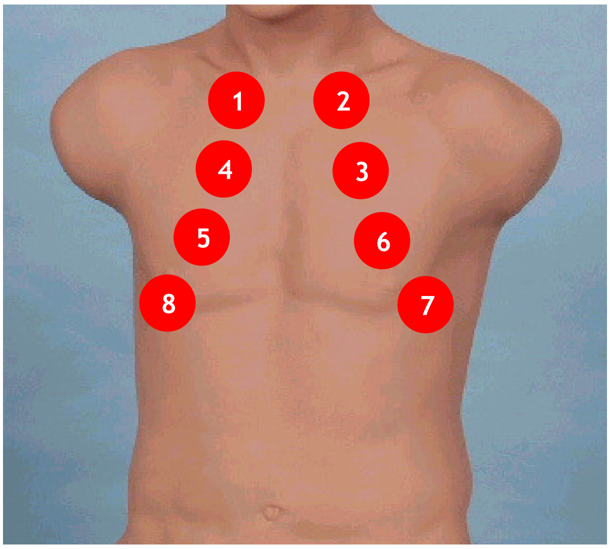


Figure 7 – Locations for auscultation on the posterior chest.

During the auscultation, the stethoscope must be in contact with the patient's skin whenever is possible to avoid the rubbing of the clothes against the stethoscope. This may lead to a misinterpretation of the sounds as being abnormal. Besides that, the stethoscope is pressed firmly. Thus, the respiratory sounds are clearer, less suitable to background noise and the friction due the stethoscope contact with the skin decreases. It is also important to acquire the sound in a silent environment, without television/radio noise or people talking.

The patient must be in a proper position, i.e. sitting up in bed or chair. All the twenty sounds are collected with the patient breathing normally through the mouth. It is required that the patient remain silent while being auscultate.

4. LOOK4MYSOUNDS SYSTEM

4.1 Hardware Requirements

The Look4MySounds system was designed to be as portable and autonomous as possible to enable the patient's sounds monitoring at his own home. So, the system hardware only requires a sound platform, a memory card and a stethoscope. The sound platform was chosen by the Engineer José Malaquias after a pre-selection of the student Eduardo Domingos. The prototype includes three boards from Microchip® that work integrated:

1. Development Board: Explorer 16 Development Board® [13]
2. Audio Board: Audio PICtail Plus Daughter Board® [14]
3. Cards Board: PICtail Daughter Board For SD&MMC Cards® [15]

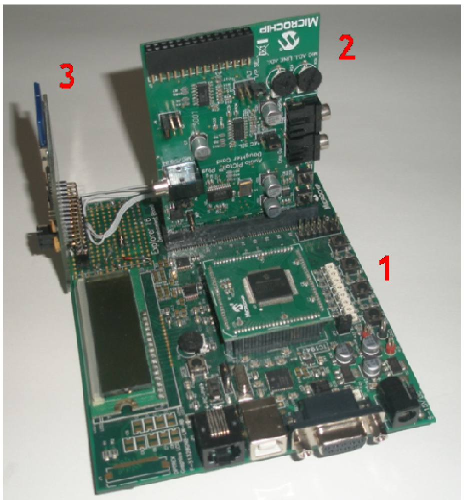


Figure 8 – Sound platform prototype.

The first board includes the dsPIC33F Digital Signal Controller (DSC) and is responsible for the communication between the other two boards. The audio board is responsible for the sound acquisition through the stethoscope, which is connected on the left side of the board. The last board allows reading and writing data on the memory card.

The sound platform is powered by 9V (DC) voltage, provided by a power supply home plugged (220V) (for more details see the annex Sound Platform Prototype Specifications).

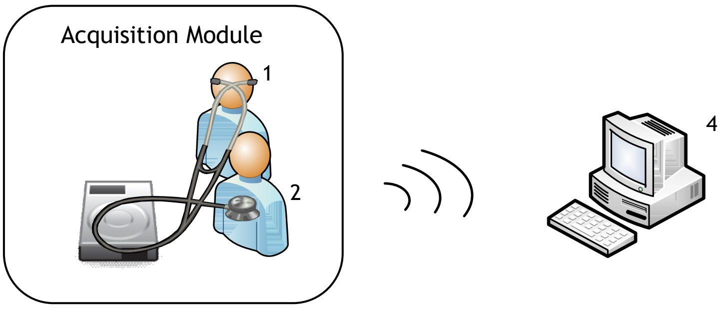
A Littmann Select Stethoscope® was chosen for the respiratory sounds acquisition [16,17]. This simple stethoscope offers reliable and clear acoustics to healthcare professionals listening to lung, heart or blood pressure sounds. In order to amplify the sounds, an electret microphone, suitable to acquiring the sounds frequency range, was introduced in the stethoscope.

The sounds are stored in a memory card SD with 2 GB from the SanDisk® [18].

Figure 9 – a) Stethoscope with a microphone incorporated; b) Memory card.

4.2 System Architecture

Look4MySounds is a system that understands two sides of interaction: patient and healthcare provider. The first step of the process is the patient's respiratory sounds acquisition with the help of a family member, taking into account a pre-defined order of auscultation. The sounds are stored in a memory card folder and, when the sounds recording finish, the algorithm will classify all the sounds recorded. In addition, a brief medical report with all the classifications is made. This information and the sound data could be transfer to the patient's PC by a RS-232 serial port or remotely sent to a doctor or a healthcare unit. The healthcare provider receives the data and takes the procedures that seem necessary. The wireless technology that will be used for data remote transmission is under study by the Engineer Inês Fonseca. However GPRS could be a possible solution.



Legend: 1-Patient; 2-Patient's Family Member; 3-Sound Platform; 4-Doctor/Healthcare unit.

Figure 10 - Look4MySounds physical architecture.

5. RELATED WORKS

5.1 Problem Analysis

The Europe is facing relevant demographic changes that will cause a major impact on the whole society. From 2005 to 2030, the number of people over 65 years old will rise by 52,3%, while the age group of 15-64 will decrease by 6,8% [19]. In Portugal, the scenario is identical. According to INE, in 2008 for each 100 juveniles there were 114 elders [20]. The increase in life expectancy is one of the main causes of this phenomenon.

In 1920, the life expectancy was 35,8 and 40,0 years for men and women, respectively. In 2008 reached to 75,4 years for men and 82,0 years for women. In addition, INE studies predict that in 2060, these values will increase more than 5 years in both sexes [21].

The incidence of chronic diseases augments with the people's age. Due to this fact, it is essential to provide long term observation to those patients. Their fragile health, and the tendency to chronic diseases, made this age group one of the most sensible that must be closely observed by caregivers.

The most well established and used medical technique is the examination through the stethoscope. One of the basic requirements of this procedure is the need to maintain a doctor-patient interaction. Consequently, patients who need frequent – perhaps even daily - examinations are faced with the burdensome prospect of frequently visiting their doctor at a hospital or clinic. These geographic constraints are particularly difficult to patients who live a long distance from healthcare units and, consequently, have difficulty in moving (most elderly people). Additionally, in Portugal, the large majority of elder people have low pensions and the daily visits to the doctor become too expensive.

Nowadays, and due to the economic constraints along with all the others, there is an urgent need to increase the quality of care while reducing costs and errors.

5.1.1 Costs Context

In what concerns to respiratory diseases monitoring, up to 84% of direct costs associated with COPD are due to patients' hospitalization. The total costs of asthma in Europe is €17,7 billion per year, and the productivity lost is estimated at €9,8 billion [22,23].

As the number of people requiring healthcare is increasing, while the number of healthcare providers is diminishing, the healthcare units are encouraged to reduce the length of patient's stay. Besides that, when is required to hire a caregiver to visit or stay with the patient at his home, the costs are intolerable for many people. Another relevant point is the waiting lists to get a regular visit for the physician. On units that are visited by a large number of patients, it is essential to regulate the patients' appointments concerning the gravity of the disease of each person.

Accordingly to governments and healthcare units, it is critical the need to focus on products that can supervise remotely the patients maximizing, thus, the relation between costs and benefits. Wireless solutions, that combine remote monitoring equipment with communications technologies, seem to be very promising. In the patient point of view, this means fewer offices and emergency room visits, reducing the inherent duration of hospitalization as well as the travel time and costs. These technologies, from the physician side, mean a more efficient case management for each particular patient [24].

Monitoring the progression of diseases, based on a remote notion, can lead to better treatment of the disease. These equipments will also incentive a preventive healthcare system, avoiding the increasing of chronic diseases gravity. Besides that, the pos-treatment at home, in a comfortable and domestic environment, can lead to an acceleration of the patient's recovery.

5.1.2 Diagnosis Context

As it was already mentioned, the auscultation through the stethoscope is one of the most important and established non-invasive method to distinguish between normal and abnormal sounds. Despite being a low cost instrument, this is a subjective tool that extremely relies on medical experience and hearing capabilities [25,26]. Developing the skill to make a good diagnosis takes years of study and practice. Acquiring expertise in identifying some lung sounds requires experience that many physicians do not have the opportunity to acquire. Concerning this, recently, there was a significant increase of studies on computer-assisted acquisition and analysis of respiratory sounds. Moreover, applications, including diagnosis establishment, monitoring and data exchange through Internet, for example, are obviously complementary tools to objective and automatic auscultation sound analysis.

5.2 State of the Art

5.2.1 RP-7™

The RP-7™ Remote Presence System is a registered trademark of *InTouch Technologies* [27]. *InTouch Health*® (founded in January 2002) is a leading provider of Remote Presence (RP) telehealth solutions that empower physicians to easily and more frequently visit with hospital-based patients. This system is the first FDA-cleared Remote Presence devices, which allows direct connection to Class II medical devices [28].

The RP-7 robot, designed to increase patient-physician communication by improving physician efficiency, quality of care and patient satisfaction, looks similar to a large wireless mobile platform with a flat screen monitor mounted on top as the "head." When in use, the physician's face is displayed on the computer monitor. One of the recent advances in the robot technologies is the incorporation of an electronic stethoscope (made by *RNK Products, Inc*) that allows listen patient's breath and heart sounds.

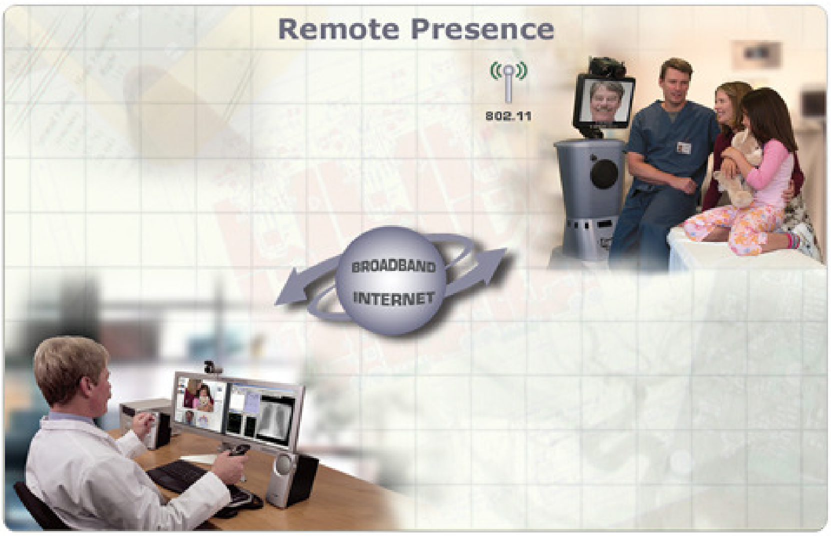


Figure 11 – RP-7^{TM} Remote Presence System.

The Robot's panoramic Virtually There visualization system, combined with the Holonomic Drive System, the SenseArray System 360, and the control interface, allows physicians, patients and hospital staff to have an interactive experience [27].

Figure 12 – Robot's panoramic Virtually There visualization system.

Using a ControlStation, the remote physician, which may be in his home or office, manoeuvres the RP-7® Robot through a joystick while interacting with patients, family members and staff. There are three varieties of ControlStations: Laptop, Desktop or ControlStation Kit. All of these include the Remote Presence software, camera, microphone, speaker and joystick. The camera, speaker and microphone allow real-time, high-quality, two-way audio and video communication [27,29].

Figure 13 – a) LapTop ControlStation; b) DeskTop ControlStation.

The Shawnee Mission Medical Centre (SMMC) at Kansas City was the first hospital in the world to acquire this new version of RP-7 [29].

The robot can be leased for about 2110€ a month and the company believe that the Hospital can benefit of over 6 millions of euros annually [27].

5.2.2 CareTone®

American TeleCare's® patented family of CareTone® Telephonic Stethoscopes allows high-quality, real-time heart, lung and bowel sounds to transmit over ordinary (POTS) or digital (DSL, ISDN, T1) telephone lines. *American TeleCare, Inc.* is an established leader in the TeleHomecare field providing solutions combined sophisticated technology with sound clinical expertise to develop systems for patients and health care providers [30,31].

The CareTone consists of a sending and receiving unit that enables a doctor or other healthcare provider to perform a stethoscope examination on a remotely-located patient. The sending unit contains a high-quality chest piece, a power indicator light and a stereo jack for headphones in consultations where there is a clinician at both the remote and central sites. The receiving unit includes headphones, volume control and a switch to select either bell or diaphragm frequency sounds [32].

The acoustic stethoscope sounds are converted into electrical signals, and then transmitted over a conventional telephone line. At the doctor's location, the signals are shifted down to their original frequencies and then converted back to audible sound for the doctor's analysis [32].

American TeleCare's CareTone IP Software enables the transmission of auscultation sounds from the CareTone (ordinary telephone line) and CareTone Ultra Digital (digital telephone line) Telephonic Stethoscopes over an IP network [30].

Figure 14 – CareTone® Telephonic Stethoscopes devices.

The good quality of this industry-leading stethoscope has been recognized by institutions such as NASA, which employed the device in its space shuttle program. The CareTone also has been integrated into many institutional and prison telemedicine programs both at the USA national and international panorama [30].

Table 3 - CareTone® specifications.

Dimensions	2.6x9.3x1.4 mm (BxLxT)
Weight	362,87 gr
Power	+12 V DC
Interface	RJ-11C to POTS (ordinary telephone line)
FDA Clearance Device	Class II
Frequency Range	Bell-20 to 250 Hz Diaphragm-20 to 500 Hz

5.2.3 Web-based Remote Digital Stethoscope

The Electronic Engineering Department of the Fu Jen Catholic University in Taiwan presents a Web-Based remote digital stethoscope that stores, transmits and processes both breathing and heart sounds.

The prototype system consists of a traditional stethoscope, a microphone, a sound card, and a headphone. In the network hardware, the system uses a power line communication (PLC) to take the place of the Ethernet, because it does not require constructing new wires. Besides that PLC module supports good expansibility and compatibility. The users use a browser in his PC to connect the Web page server to get the patient's digital sound signals from a remote location.

In order to medical professionals and patients conveniently use the network to transmit the digital sound files; it was designed two programs, the "Dialup Network" and "FTP". The "Dialup Network" program can let users use the remote dialling network service function in Microsoft Windows. The doctors can use a modem or a PHS cell-phone to connect to the Remote Access Server by the Point-to-Point Protocol (PPP). When the Internet is available, they can use the Wireless WAN network environment through PHS. The reason for the PHS be selected is because it is low power with a small amount of interference to the medical instruments. With the "FTP" program the patients and medical professionals can upload and download the digital sound files.

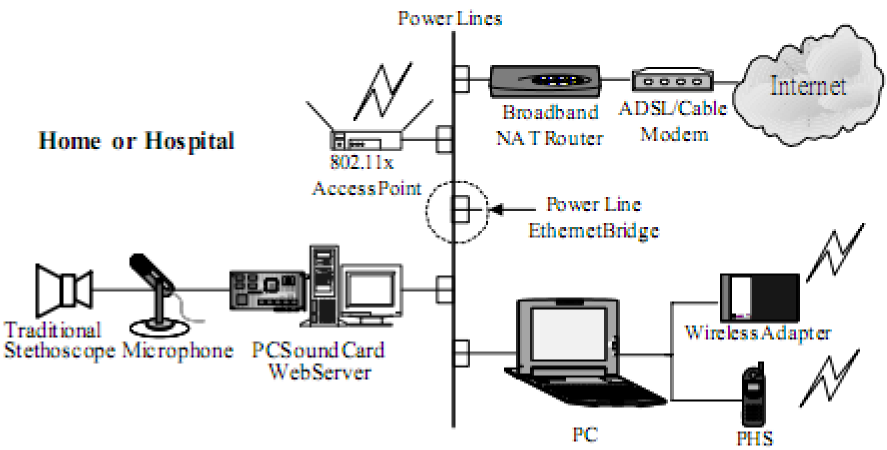


Figure 15 – System architecture of the Web-based remote digital stethoscope.

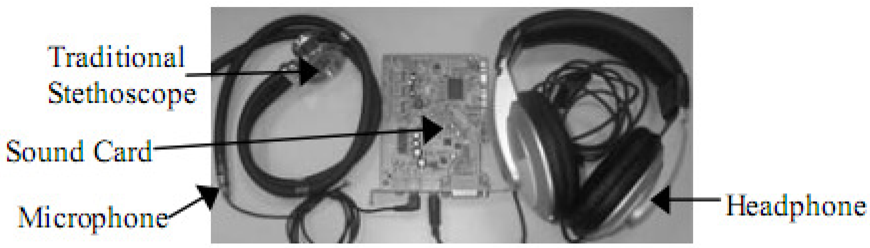


Figure 16 – The interface hardware of the design.

Table 4 – Hardware modules specifications.

	Microphone	Headphones
Frequency Response	380 Hz to 15 KHz	20 Hz to 20 KHz
Impedance	>10 Ω	32 Ω
Sensitivity	-65 dB	116 dB

Sound Card (typical PC interface)	
Sample frequency	8 to 48 KHz
Sample default format	16 or 24 bits
Signal-to-Noise Ratio	100 dB
Cross Talk	-100 dB
Total Harmonic Distortion+Noise at 1 KHz	0.004%
Frequency Response at -3 dBr	<10 Hz to 22 KHz

Data acquisition software was developed under Windows platform and includes two programs. The first one, “Digital Stethoscope Recorder”, controls the remote PC to record and save sounds files, and the other one, “Digital Stethoscope Player”, is responsible for playing the sounds files.

The remote digital stethoscope use software and hardware with low cost components and is assembled both at home and at a healthcare unit [33].

5.2.4 Intelligent Stethoscope

Bloodline Technology holds a patent for an intelligent stethoscope to perform auscultation and automatically diagnose lung, heart and vascular disorders through the body sounds.

The body sounds are recorded from many locations on the body and all of the sounds are categorized according to specific characteristics to form an array of information. This array is compared with stored arrays of information through a waveform analysis procedure in conjunction with a medical algorithm. The latter arrays are indicative of known abnormalities, when an array match is determined, the operator is informed and the diagnosis is displayed.

The system consists of a conventional stethoscope, acoustically coupled to an electronic interface. The audio signals are processed and digitized via a sampled analogue to digital waveform acquisition procedure. The digitized audio is stored in data base memory for further analysis, while simultaneously being displayed on a LCD. A keypad to control the operation of the microprocessor based stethoscope is also part of the device. And, a peripheral data port is used for the transfer of data base memory to a digital plotter, and/or storage in a larger memory media. The system is powered from rechargeable batteries, and controlled by an intelligent power control system [34,35].

5.3 Review of the System

The three first systems presented in the previous section are available on the market and allow remote auscultation of respiratory sounds using different types of data transmission. The first one is a mobile wireless platform, the second transmit the information over telephones lines and the third uses the Microsoft Internet Explorer browser to control the remote PC in order to record and save the sound files. It must be regard that none of them made automatic classification of the sounds collected.

The main limitation of the RP-7^{TM} Remote Presence System is the need of a healthcare provider in the patient's home to perform the stethoscope examination. In our system, a family member can easily place the stethoscope in the chest positions pre-defined by the doctor. The robot price is expensive for a healthcare unit and is not easy to support the costs associated with the robot services. Look4MySounds is an inexpensive product that includes low-cost technologies. Therefore, any institution may acquire and borrow it to the patient take to his home or even any consumer can buy it with a medical prescription.

The CareTone® and the Web-based Remote Digital Stethoscope are non-expensive devices that allow the remote sending of the sounds to the doctor. Indeed, these mechanisms are very appealing in terms of reducing the patient's costs due to the healthcare unit travelling. However, they do not make an improvement for the doctor's side since he will always have to hear and analyze the patient's sounds. In here, the Look4MySounds project presents the same advantages of the both systems, coping also their main limitations.

The last device of the state of the art is a stethoscope that automatically classifies respiratory sounds but do not have the remote component, being only for medical use. Regarding the sounds recognition, this equipment has a great disadvantage in relation to Look4MySounds. The need to have an extensive database to allow the comparison of recorded arrays with saved arrays that represent known abnormalities. Moreover, the price of these intelligent stethoscopes is high, rounding the 2000 or 3000 euros.

6. RESPIRATORY SOUNDS CLASSIFICATION

The main purpose of the project is the development of an algorithm to detect pathologies in respiratory sounds and also discriminate them as wheezes or crackles, the most common types of adventitious sounds in respiratory diseases.

The original code was implemented on a PC (Pentium Dual Core@2.0GHz) using Matlab 7.5.0. After the experimental evidence of the algorithm efficiency, the Matlab code was converted to C programming language, using Dev-C++, and, finally, implemented in the dsPIC through the MPLAB IDE 8.20 program.

The algorithm is divided into three main stages, which are summarized below:

1. **Wheezes Classification** – the first step detects and classifies the sound as containing wheezes taking into consideration their continuity properties and duration.

2. **Noise Filtering** – this step reduces or even eliminates the friction of the signal due the stethoscope contact with the skin, allowing the algorithm to better distinguish between normal sounds and sounds with crackles.

3. **Crackles Classification** – the last step classifies the sounds as normal or containing crackles using an approach based on the histogram’s entropy.

In the algorithm presented for respiratory sounds classification, the properties of each sound were explored in the most efficient way in order to perform a reliable detection of the pathologies. A method to reduce/eliminate the noise, caused by friction between the skin and the stethoscope, was also developed due its frequent interference in the signal. This sometimes led to wrong diagnosis, even by a specialist.

As the final goal is to process the sounds in the dsPIC, the methods used should be quickly and not expensive in terms of memory consuming. In this chapter, it is explored the resolution of some problems concerning the wheezes detection in the dsPIC due to the lack of memory available.

6.1 Wheezes Classification

In the past decades, a variety of techniques have been employed by researchers to analyze and classify wheezes. They range from Fourier transform (FT) [12], linear prediction of coefficients [36][37], genetic algorithms [38], neural networks [38] and wavelets [39][40][41]. These methods rely extensively on the fields of digital signal processing and machine learning.

The most commonly used signal-processing tool is the FT (equation (6.1)), which represents the signal in terms of its frequency components. Time-frequency analysis is particularly useful in the application of respiratory sounds analysis because of its ability to temporally resolve the frequency components of a signal, giving rise to a more accurate representation of a typically non-stationary data.

$$X(\omega) = \sum_{n=0}^{N-1} x[n] e^{-\frac{i2\pi\omega n}{N}} \tag{6.1}$$

Based on this approach, it was decided to analyze wheezes using this method, not only because it is a simpler and a much studied concept, but also because dsPIC, with it memory available, would be able to process this transform, unlike other heavy and complex techniques such as wavelets or genetic algorithms.

Machine learning techniques, like linear prediction of coefficients or neural networks, refer to teaching a system to assign class labels to data samples using an existing set of labeled data. Although these methods are revealing promising techniques, a large and validated database is needed. The number of respiratory sounds (and patients) required to build a reliable database [42] would take more than one year to collect, being incompatible with the project duration.

6.1.1 Implementation

To describe the implementation details of the wheezes classification process it is assumed that the input of the algorithm is the respiratory sound containing wheezes, as shown in Figure 17.

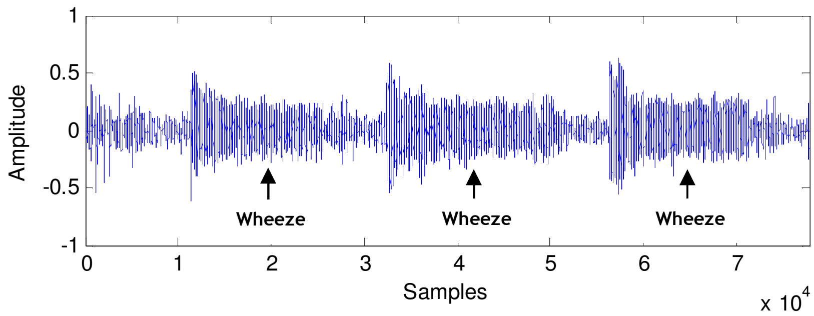


Figure 17 – Plot of the signal input. Wheezes epochs are pointed out by arrows.

The scalogram computation for a time-scale analysis of wheezes is the first step of the process. Wheezes analysis through a scalogram was chosen, instead the periodogram or spectrogram analysis mentioned in [12][39] because, after explore the three techniques, it was concluded that the scalogram provides a much clear representation of wheezes. Scalogram eliminates most of the undesired information allowing a better study of wheezes continuity properties. Besides that, studying features in 56 scales it is simpler than working within a frequency range of 100-2500 Hz that contains this adventitious sound.

Although MathWorks® provides a built-in function (*wscalogram.m*), it was decided to use Kovesi's scalogram [43]. This function is simpler and faster, being as well efficient. One more advantage is the fact that sometimes it is impossible to access the code of Matlab's built-in functions. Using Kovesi's scalogram, the posterior conversion to C language will be simplified since all the code can be directly accessed. This function requires some default specifications, which include the number of scales used to represent the respiratory sound. It was empirically determined that 56 scales allow to have a sufficient representation of the signal. This scalogram calculates phase and amplitude of one-dimensional signal. However, to perform the algorithm only the amplitude output is enough. Thus, the phase component was removed from the code.

After the computation of the Fast Fourier Transform (FFT) of the signal, a Gabor filter is computed in each scale of the signal's representation. The filter is used to select the most meaningful frequency components of the signal at each level of scale. After multiply the original signal FFT with the Gabor filter, the Inverse Fast Fourier Transform (IFFT) is applied to reconstruct the signal (see the annex Matlab Pseudo-code for further details about the scalogram computation).

Comparing the Figures 20 and 21, it can be seen that obvious differences exist between wheezes and crackles scalograms. Unlike crackles, which are characterized by rapid amplitude deviations in time-domain, wheezes have a large amplitude deviation. Figure 22 describe the scalogram of the normal sound signal shown in Figure 2 (Chapter 3.3.1), where the hot colours segment represents the inspiratory phase.

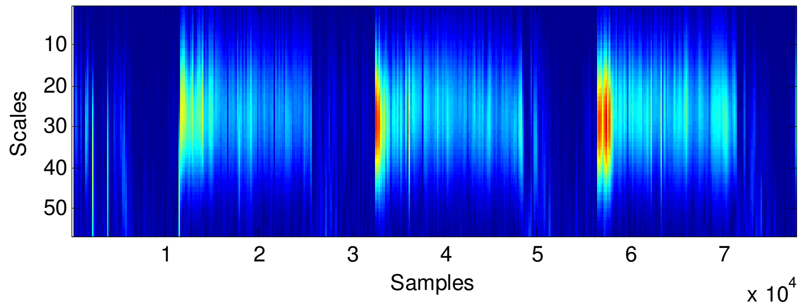


Figure 18 – Scalogram of a sound with wheezes.

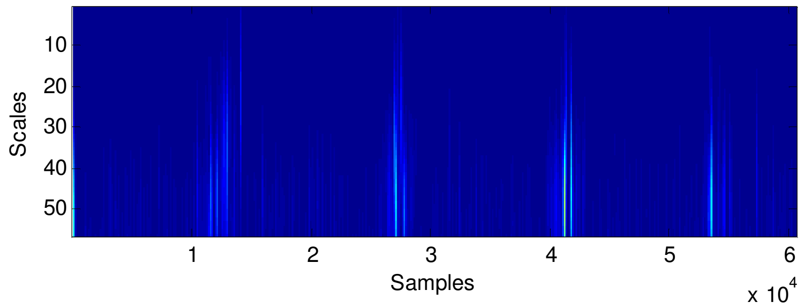


Figure 19 – Scalogram of a sound with crackles.

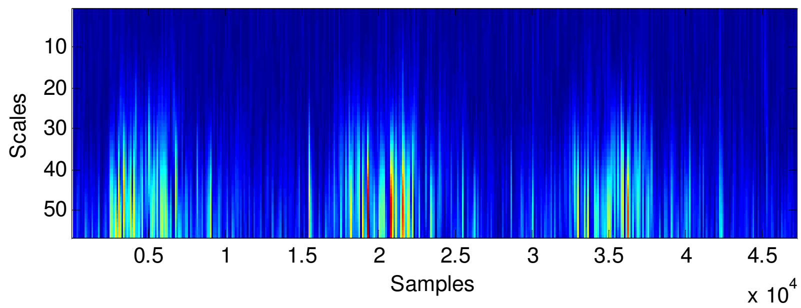


Figure 20 - Scalogram of a normal sound.

The next step is where the background contributions of the scalogram are removed. For this, an amplitude-threshold (0.023) empirically obtained is used. If the contributions of the scalogram are lower than this threshold, they are set to 0, removing the undesired signal components. The other components are equalized to a constant value, 0.5, to then analyze the isolated wheezes continuity (Figure 21). This whole process will allow the automatically selection of the scale where the signal presents more number of samples. No precautions are needed with crackles or normal sounds, since the scalogram of these sounds, in a large number of cases, are more discontinuous.

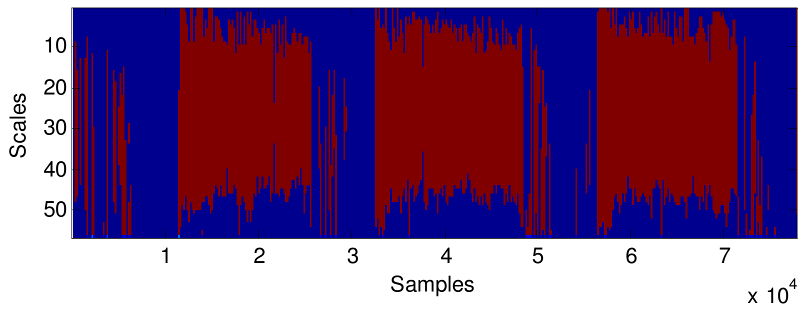


Figure 21 – Wheezes continuity properties.

Biomedical signal processing is a hard task to achieve. Each breath sound has its own properties that can differ from the same pathologic sound of the same patient. As stated before, the selection of the scale is automatically done by choosing the one which have the maximum mean of continuous samples. With the scale selected, many sounds were tested (Table I of the annex Algorithm Tests) in order to verify the differences in the number of continuous samples between the various sounds types.

The experimental tests reveal the obvious differences in the continuity properties of each sound. As the crackles present continuity values higher than 640 samples, a simple criterion based on the wheezes duration (greater than 80 ms) referred in section 3.3.2 was not enough. So, a criterion based on the wheezes durations (between 80 and 250 ms) explained in [5] was defined:

$$duration(samples) = \frac{(0{,}08 + 0{,}250) * 8000}{2} = 1320 \tag{6.2}$$

where 8000 stands for the sampling frequency of the acquired sounds. Therefore, if the signal amplitude presents higher continuity than this value (equation (6.3)), it is classified as a sound with wheezes.

$$duration(samples) \geq 1320 \tag{6.3}$$

The final goal of the project is to process the sounds on the dsPIC. Although the technique adopted allows a good classification of the wheezes collected, it turns out to be a method very expensive in terms of memory available on the dsPIC. In this case, the signal was treated in segments of 256 samples. For example, in a sound with 64000 samples (the minimum size of the respiratory sounds acquired), 250 FFTs and IFFTs are needed, for each one of 56 scales. Thus, when the code was implemented in the dsPIC, it presented lack of memory to store all the information processed.

Due to this set back, a simple solution that can give similar results to those obtained in Matlab was explored. Even if the wheezes automatic detection is usually made in the frequency domain (as the original code made in Matlab does) it was implemented in the sound platform a convolution with the same filter with the signal. In fact, if the frequency spectrum of two signals is multiplied in the frequency domain, this corresponds to a convolution between the two signals in the time domain (equation (6.4)) [44].

$$Y(\omega) = X(\omega)H(\omega) \leftrightarrow y[n] = x[n] * h[n] \tag{6.4}$$

In here, a default scale was selected to handle the sounds. The filter representation in time domain, to convolve it with the sound signal, was obtained through the Matlab IFFT function. The next steps are equal to those explain before, with the amplitude-threshold (0.012) being empirically selected to this new case and then converted to integers range (0.012*32767=393). As it will be seen in the next chapter, this turns out to be a good solution.

6.1.2 Flowchart

Figure 22 shows the flowchart of the wheezes classification stage for the code implemented in Matlab and in the dsPIC. The algorithm inputs are the respiratory sound file in wave format, the sampling frequency and the sound length. The system output is the classification of the sound, which can be visualized in the sound platform (LED9) if a wheeze is detected. In this case, the algorithm stops the analysis of the respiratory sound and starts to analyze the next sound.

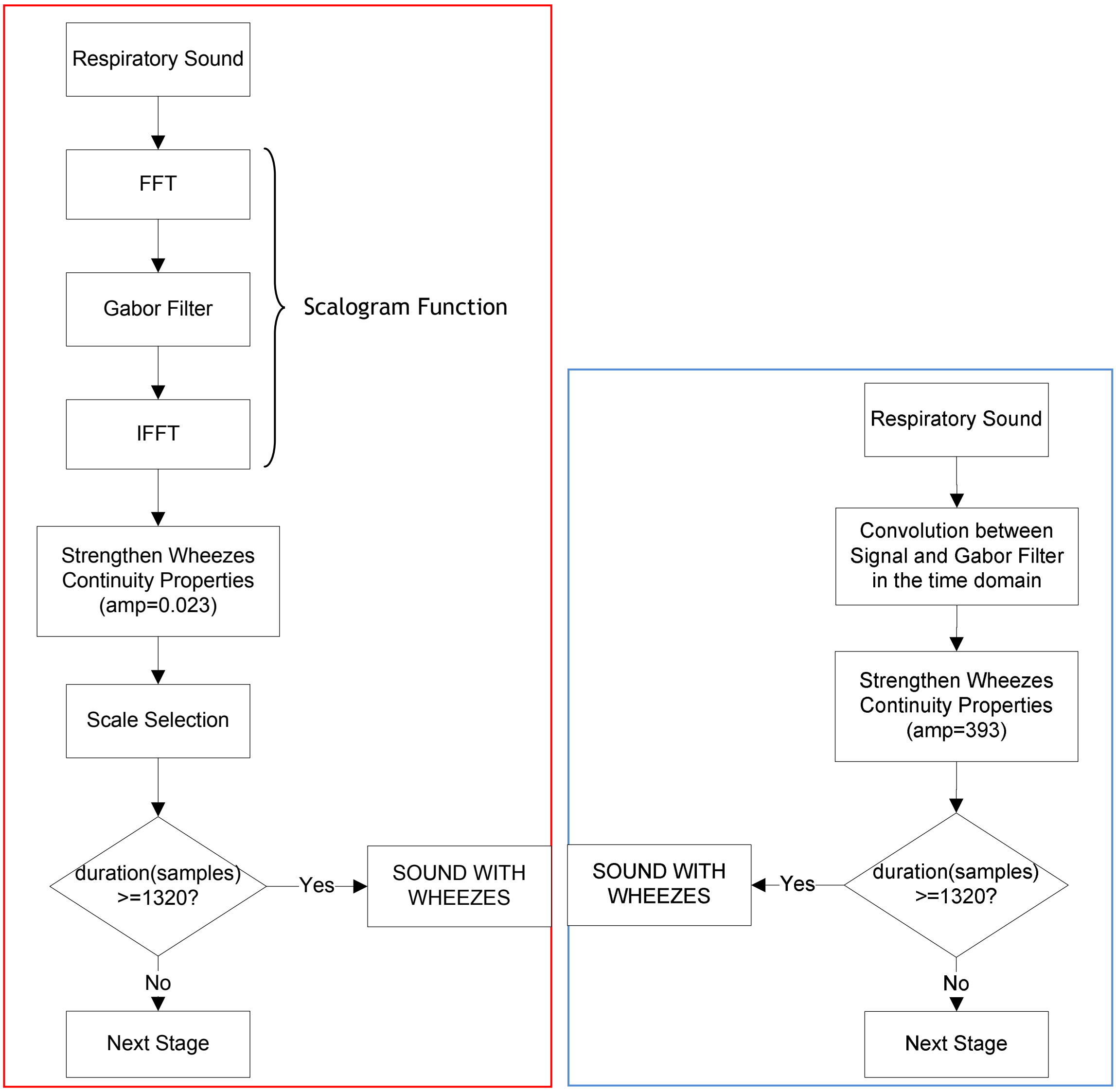


Figure 22 – Wheezes classification flowchart: a) Matlab; b) dsPIC.

6.2 Noise Filtering

The “cleaning” of the respiratory sounds is one of the most important parts of the algorithm. Two different noises are present in the recordings: the friction due the stethoscope contact with the skin and the heart sounds. These artifacts introduce perturbations during the sounds analysis, resulting in wrong classifications, even by a specialist.

Heart sounds spectrum is located between 20 and 100 Hz. The main components of respiratory sounds are also located in this frequency range. Among several methods that have been tested, the better results were obtained with adaptive filtering and auto-regressive/moving average (AR/MA) estimation [5]. During the project, the same elimination technique of the friction noise was applied to the heartbeat but without success. The resulting signal did not have quality to be classified. So, as a matter of time, and because the cardiac sound affects at most two sounds (in twenty) recorded closely to the six position on the anterior side (section 3.4), this task was left for future work.

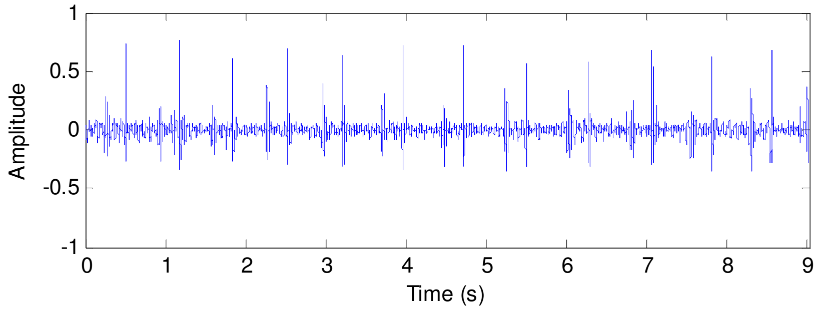


Figure 23 – Heart sound signal overlay on the respiratory sound.

The friction noise exhibits isolated peaks where the signal rapidly falls of in amplitude. This type of artifact is present in many recorded sounds and makes the algorithm to classify the normal sounds as sounds with crackles.

It must be regard that the algorithm only performs this step if no wheezes are detected. In fact, it is clear that the scalogram eliminates most of the undesired information related to the background noise, and because of that the friction noise does not affect the wheezes classification performance.

6.2.1 Implementation

The first step of this stage is the detection of signal peaks (local maxima) [45]. The input threshold (0<delta<1) was tested with many sounds and the best value, that efficiently detects all the peaks due the friction, was found: delta=0.3. This means that it is required a difference of at least 0.3 (amplitude) between the peak and its neighbourhood in order to declare it as a peak. Local minima are also detected in the function, but it was concluded that only the maxima is needed to remove the sound friction. The local maxima are stored in a matrix with the amplitude of the peaks and the corresponding indices (X-value).

During the selection of the delta value, it was observed that, in some normal sounds (as the illustrated in Figure 24), no maxima was detected due to the low amplitudes covered by the signal. So, in this case, the sound is classified as normal and the sound analysis process finish.

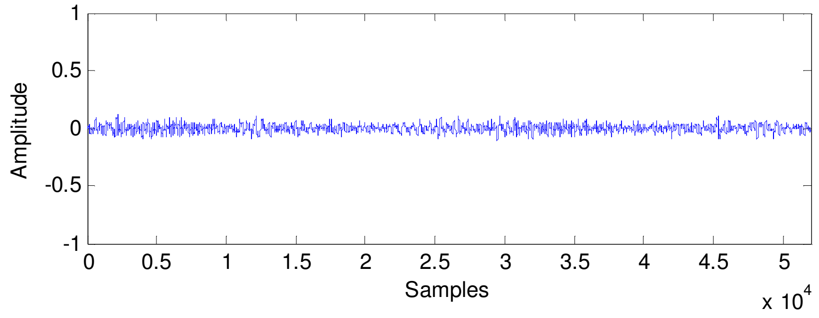


Figure 24 – Normal sound where no peaks are detected.

After finding the peaks, each one is selected and the 30 samples back and forward of the respective index are equated to the sound mean. At this point, the friction noise is reduce or eliminated.

The following block of three graphs describes how this stage performs in normal sounds.

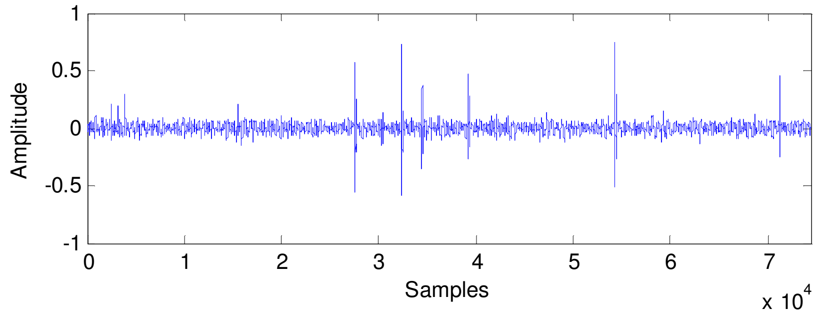


Figure 25 – Normal sound with noise.

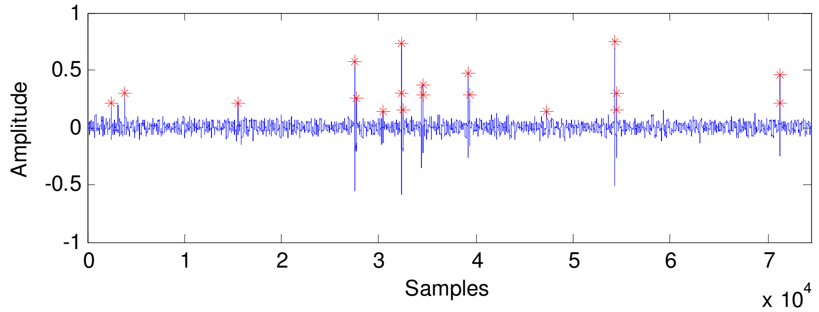


Figure 26 – Peaks detection. The local maxima are plotted as red stars.

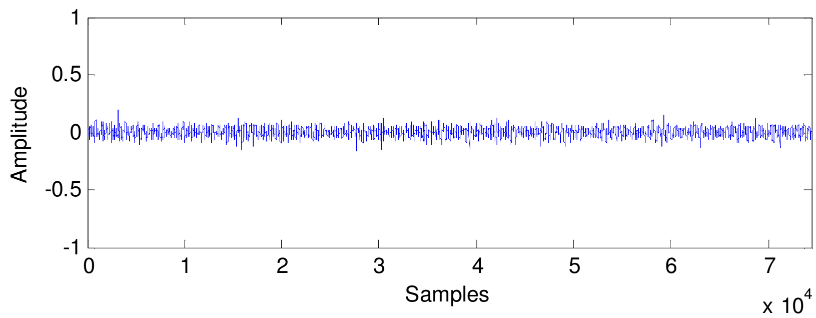


Figure 27 – Sound with noise removed.

In sounds with crackles, as the illustrated in Figure 28, the noise filtering output is different from the obtained in normal sounds. As many maxima are detected in close samples (Figure 29), the result is a distorted signal with failures (Figure 30) that will be classified, in next stage, as pathologic. This is not the case on normal sounds where local maxima appear as isolated peaks. Here, the signal remains almost equal after their elimination.

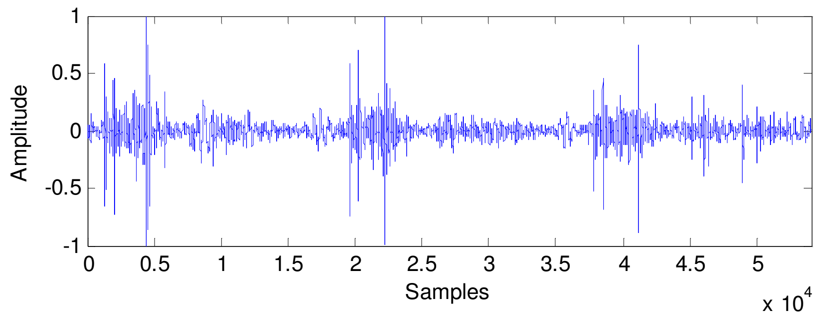


Figure 28 – Sound with crackles.

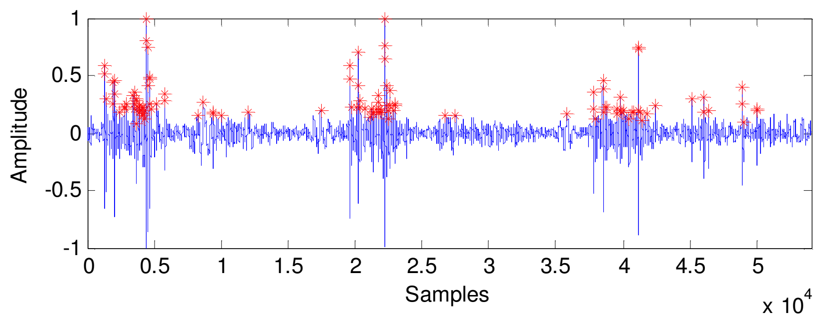


Figure 29 – Peaks detection. The local maxima are plotted as red stars.

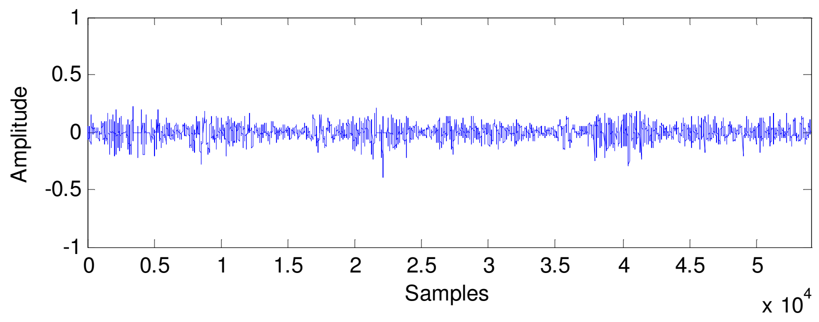


Figure 30 – Sound with noise removed.

This stage of the algorithm was implemented in the dsPIC without changes. Only the variable delta to selected the peaks of the signal was converted to fall in the -32768<integer<32767 range (0,3*32767=9830).

6.2.2 Flowchart

Figure 31 illustrates the flowchart of the noise filtering stage performed in the dsPIC. The input of the algorithm is the respiratory sound file in wave format and the threshold for peaks detection. The output is the sound with the friction reduced or, in some cases, completely eliminated.

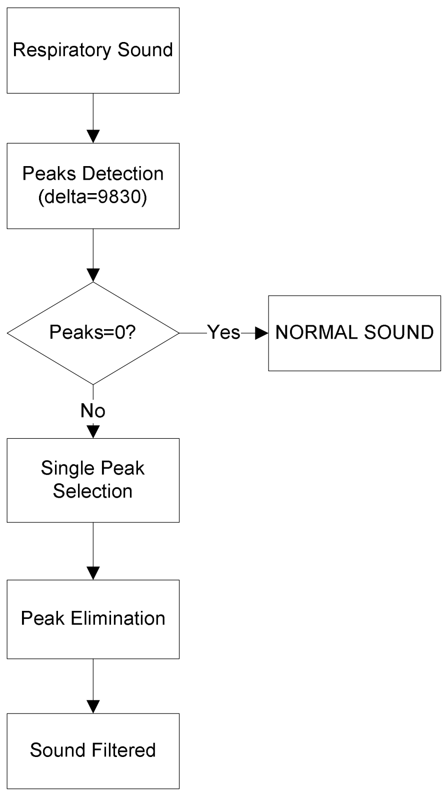


Figure 31 – Noise filtering flowchart.

6.3 Crackles Classification

One technique that is found to be particularly useful in crackles characterization is called time-expanded waveform analysis (TEWA). This adventitious sound have a distinct morphology when observed in TEWA; a sudden short deflection followed by deflections with greater amplitude [12][46]. Other analysis methods like wavelets [47][48][49], fuzzy non-stationary filter [50], neural networks and genetic algorithms [38] have also been presented in the literature.

Once again, considering the final goal of the project, a simple and robust algorithm based on the histogram's entropy was developed. After many experiences and tests, it was concluded that the proposed solution could provide good results.

6.3.1 Implementation

When a normal sound acquired with the sound platform is compared with one that present pathologic sounds, it is noticeable the difference between them. The histogram processing is a classic tool to summarize and display data. On the other hand, the entropy, with its basis on thermodynamics concepts, allows measuring the system disorganization. In fact, it can be observed, when comparing two sounds (normal and crackles), that both have different levels of entropy, being the pathologic sound more susceptible to be a disorganized distribution. In this section it is presented the strategy followed to distinguish crackles from normal sounds, which uses the entropy of the histogram to achieve it.

To describe the implementation details of the crackles classification process it is assumed that the input of the algorithm is a respiratory sound containing crackles, as shown in Figure 32.

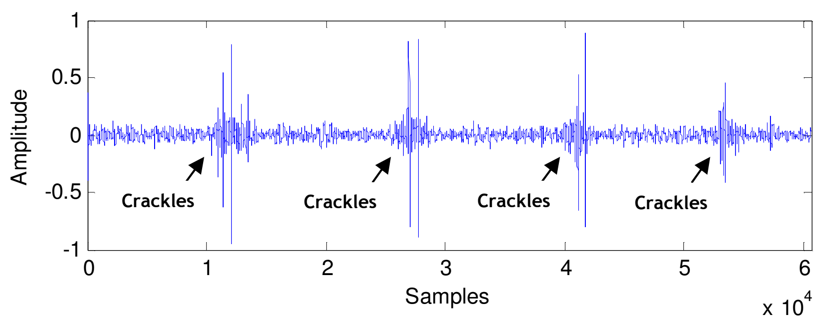


Figure 32 – Plot of the signal input. Crackles are pointed out by arrows.

The first step of the algorithm is the computation of the ideal number of bins for the histogram to each sound. In here, several methods from [51] were tested to check which allows a better discrimination of the sound data. The one that reveal more different features between normal sounds and crackles was the Scott's criteria [52], given by:

$$h = \frac{3{,}5\sigma}{n^{1/3}} \tag{6.5}$$

This formula gives the bin width, where σ and n are the standard deviation and the length of the signal, respectively. From h, the number of bins is determinate by:

$$k = \frac{\max(sound) - \min(sound)}{h} \tag{6.6}$$

After obtained the number of bins (k), each sample value is used to assign it to the respective bin using the following formula:

$$bin = \frac{sample - \min(sound)}{h} \tag{6.7}$$

For each sample that falls into a bin, the number of elements of that bin is incremented by one.

The friction elimination of the respiratory sound changes considerable the amplitude spectrum of the source signal (Figure 30). Actually, the output signal is a distorted version of the original sound. The entropy, along with the measure of the signal disorder, provides a representation on the log scale that allows a more efficient classification of the pathologic sounds, since small differences between the histograms will be more noticeable. The entropy of the histogram is computed taken into account the signal histogram characteristics. Then, the histogram is normalized[2] to the unit length to be treated as reflecting the probability distribution of the signal [53]. Considering this assumption, the overall entropy (S) of histogram (h_{norm}) is computed by:

$$S = \sum_{j=1}^{k} quo[j]\log(quo[j]) \tag{6.8}$$

where $quo[j] = abs(h_{norm}[j] - mean(h_{norm}))$ and $j = 1,\ldots,k$ bins.

[2] Henceforth, when histogram is mentioned should be understood normalized histogram.

As it can be verified in Figure 33, the graphic of a normal sound (represented in Figure 27) histogram's entropy has more components above the initial/ending line than the sound with crackles.

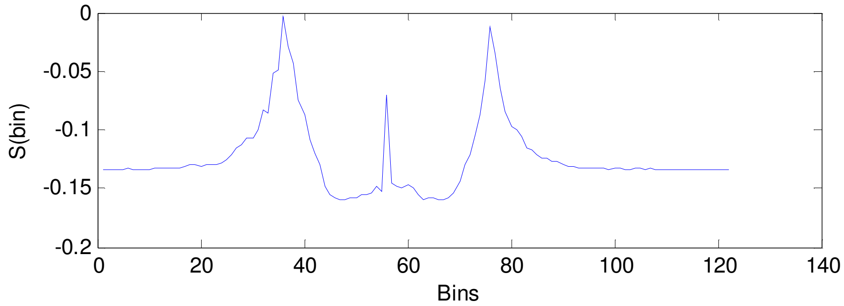


Figure 33 – Normal sound histogram's entropy.

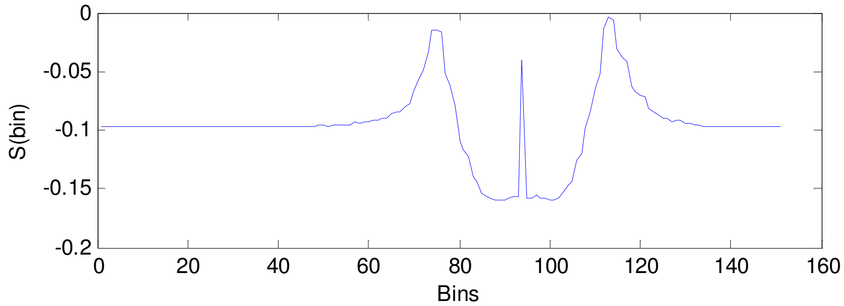


Figure 34 – Histogram's entropy of a sound with crackles.

From experimental evaluation of this method (Table II of the annex Algorithm Tests), it was observed that if the modulus of the histogram's k^{th} bin entropy (aux) is higher than the absolute value of the difference between the same histogram bin and the mean of the histogram (quo), the sound has crackles. The criterion states that:

$$-aux[k] > quo[k] \tag{6.9}$$

where $aux[k] = -quo[k]\log(quo[k])$.

After the implementation of the above method to discern if a sound is pathologic or normal, it was concluded that, although this method allows a fairly well classification of the sound, the rate of success was not the desired for the project purposes because some obvious crackles do not obey to equation (6.9).

In order to improve the classifications success rate, without increasing significantly the computational time and to make use of the entropy procedures adopted, a new criterion was established. Considering the entropy of each bin of the histogram, the entropy's mean is computed. The usual methods employ the modulus of equation (6.8) to compare the disorder of the systems. In this case, since the number of bins of the histogram change from sound to sound, the use of the entropy's mean appears to be more reasonable. After testing normal sounds and sounds with crackles that not obey to the first criterion (Table III of the annex Algorithm Tests) it was observed that it could be defined a threshold of 0,10 (entropy's mean) to distinguish the sounds in consideration. The final criterion is given below:

$$-\frac{1}{k}\sum_{j=1}^{k} quo[j]\log(quo[j]) \leq 0{,}10 \qquad (6.10)$$

If the sound obeys this criterion, it is classified as a sound with crackles.

Concerning the implementation on the dsPIC, the proposed stage of the algorithm was implemented in a straightforward manner. Only the threshold of the entropy's mean, used as the second criterion of this algorithm stage, was converted to the integers range (0,10*32767=3277). No problems with memory constraint as in the wheezes classification stage occurred here.

6.3.2 Flowchart

Figure 35 represents the flowchart of the crackles classification stage implemented in the dsPIC. The inputs of the algorithm are the respiratory sound file in wave format with the noise removed and the sound length. The system output is the classification of the sound, which can be visualized in the sound platform (LED8) if a crackle is detected.

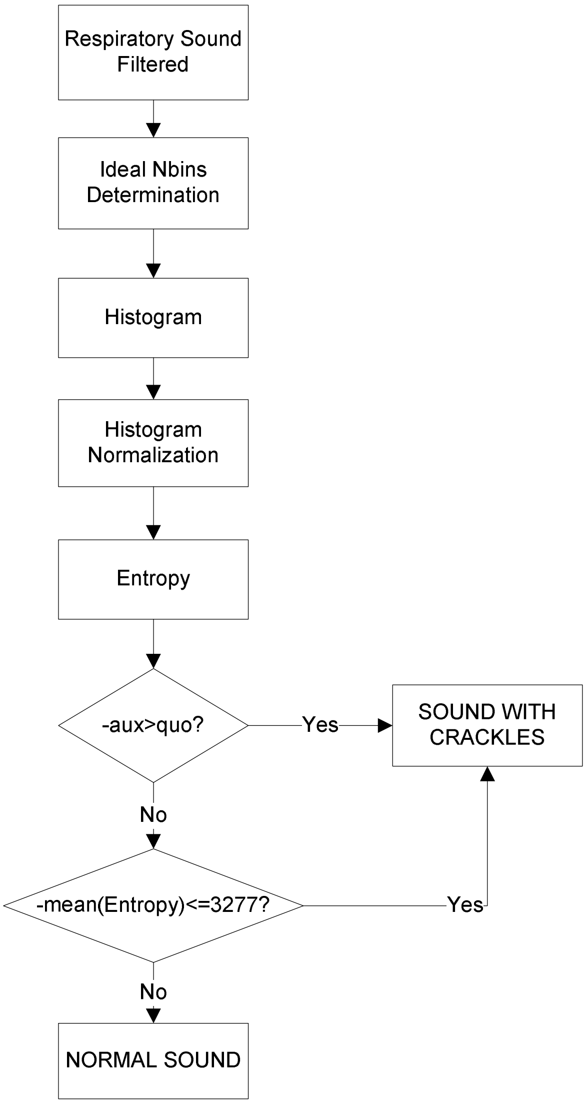


Figure 35 - Crackles classification flowchart.

6.4 General Flowchart

The flowchart of the final algorithm for respiratory sound classification implemented in dsPIC environment is illustrated in figure 36.

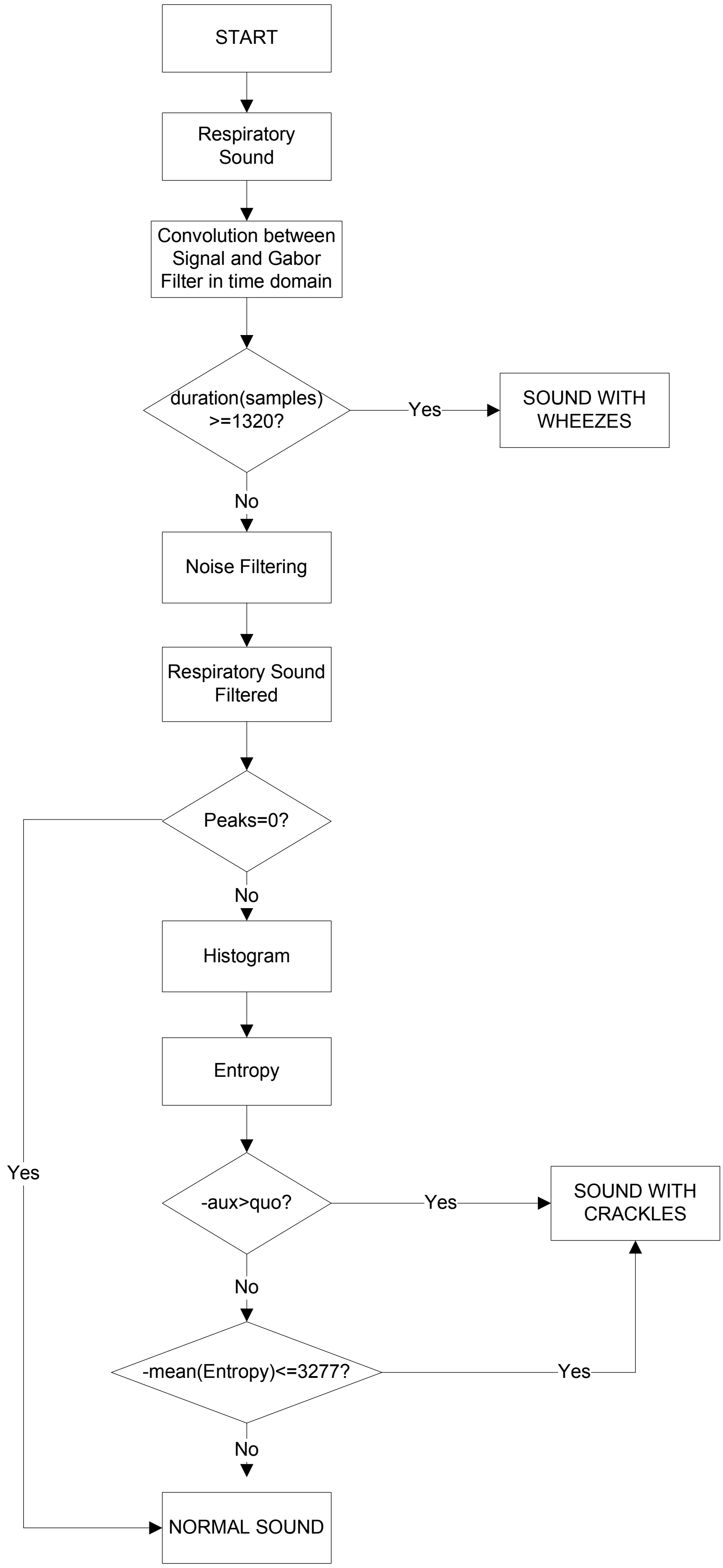


Figure 36 – Algorithm flowchart implemented in the dsPIC.

7. EXPERIMENTAL DATA

In order to evaluate the performance of the proposed algorithm, 440 respiratory sounds from 22 people (12 men and 10 women) with ages between 12 and 91 years old were collected. 6 normal subjects and 16 pathological subjects with different types of respiratory diseases, such as asthma, COPD, bronchitis, pneumonia and bronchiectasis, were studied during the analysis.

The normal class was recorded at student's home in a quiet room. The pathologic class, which includes 13 patients with crackles and 3 'wheezing' patients, was recorded at Pulmonology Service of HC. In this case, the sounds were acquired during the morning when the patients have clearer adventitious sounds due to the presence of mucus that obstruct the airways. The major disadvantage of recordings is at this time of day was the background noise in the room, which coincides with the time when the healthcare providers handle for the breakfast, the hygiene and the treatments of the patients. The patients with adventitious respiratory sounds were indicated by the Doctor Ana Filipa, who did the pre-auscultation and the identification of the type of disease, as well as the related adventitious sounds. When the doctor was not available, other specialists' doctors helped in this task.

The sounds were acquired with the hardware presented in chapter 4 at 8 kHz of sampling frequency and a resolution of 16 bits. Each person's sound has a duration approximated to 10 seconds, including 3 to 4 respiratory cycles.

The sounds recordings were performed between the 2nd of April and the 28th of May. Afterwards, the Pulmonology Service entered into building improvement works and it became impossible to record sounds with quality for analysis, due to the excessive environment noise.

Since the main purpose of the sound platform is the home use by the patients, a favorable environment to record the respiratory sound data can be easily created. Therefore, from the universe of the collected sounds only the ones with no significant background noise and no heart beating were used to evaluate the algorithm for sounds classification, which totalize 378 of the 440 collected. This means that an average of 17 respiratory sounds per person was used for analysis.

7.1 Algorithm Performance

Concerning the evaluation of medical devices, the rate of true positives detections (diseases) and true negative detections (non disease) are broadly the most used [5][25]. This type of measures allows the user to easily perceive the effectiveness of a certain medical method. As so, sensitivity and specificity are the statistical measures employed to evaluate the performance of a binary classification test.

The sensitivity (also called recall rate) measures the proportion of actual positives which are correctly identified as such (e.g. the percentage of pathologic sounds that are correctly identified); and the specificity measures the proportion of negatives correctly identified (e.g. the percentage of healthy sounds correctly identified). In theory, an optimal prediction should achieve 100% sensitivity (i.e. predict all people from the sick group as sick) and 100% specificity (i.e. not predict anyone from the healthy group as sick).

$$Sensitivity = \frac{True\ \ Positives(TP)}{True\ \ Positives(TP) + False\ \ Negatives(FN)} \tag{7.1}$$

$$Specificity = \frac{True\ \ Negatives(TN)}{True\ \ Negatives(TN) + False\ \ Positives(FP)} \tag{7.2}$$

The system evaluation (hardware plus software for sounds classification) was performed using 378 respiratory sounds from the 22 patients collected (Table IV of annex Algorithm Tests).

Table 5 - Algorithm general performance.

Algorithm \ Medical Diagnosis	POSITIVE	NEGATIVE
POSITIVE	TP=121	FP=6
NEGATIVE	FN=27	TN=224
	SENSITIVITY=81,8%	**SPECIFICITY=97,4%**

Table 6 – Algorithm stages performance.

Algorithm stages	TOTAL(CORRECT CLASSIFICATIONS)	PERFORMANCE
WHEEZES	20 (17)	85.0%
CRACKLES	128 (101)	78.9%

7.2 Discussion of the System Validation

The presented method for respiratory sounds classification is a simple and fast technique that reveals a good rate of classification. The whole system (sound acquisition plus classification) performs better than some methods proposed in the literature [5].

In the experimental tests, sounds from the same patient were considered. It must be regarded that not all the auscultation positions of a sick patient presents pathologic sounds superimposed in the regular breath sound. For example, if the patient has an injury on the left lung, usually only the sounds recorded at the left side present adventitious sounds. So, the sounds acquired on the right side will be normal. In addition, if the patient has a disease that causes coarse crackles, the pathologic sounds will appear in the inferior auscultation positions.

All the obvious pathologic sounds are detected. This means that if the doctor specifies the place where the adventitious sound is more intense, the algorithm is able to accurately detect it. The sounds recorded in close positions could also present pathologies. However, these signals are not as intense as in the place specified by the doctor. The 18% of sensitivity loss is exactly due to this fact. It must also be regarded that in all the patients at least 2 sounds are classified as pathologic. This is meaningful in the sense that, if a patient has a disease the algorithm is able to detect it. The doctor will be informed about how many pathologic sounds the patient has and takes the procedures seem necessary.

Regarding the normal sounds of all the people collected, only 6 from 230 were misclassified. This means that the algorithm is very robust in the normal sounds classification not only due to their inherent features but also because the noise (friction) is filtered before the analysis. Nevertheless, if this artifact is too intense, the noise filtering stage does not remove completely this misleading artifact. Another relevant point, according to Doctor Moutinho, is that smoking people, although not present a respiratory disease diagnosed, may have sounds with similar profile to crackles.

The replacement of the FFT technique for the convolution method in time domain due to the lack of dsPIC memory available makes some changes in the algorithm results. In fact, 3 sounds that were misclassified in the Matlab code are on the dsPIC correctly classified as wheezes. On the other hand, 2 sounds with crackles are wrong detected in the wheezes classification stage. This is in contrast with the Matlab results, where any crackle are detected as wheeze.

The measure of the overall accuracy is computed using the coefficient between the total number of correct classifications and the total number of observations in test:

$$Accuracy = \frac{TP + TN}{TP + TN + FN + FP} \quad (7.3)$$

Given the previous formula, it can be concluded that the algorithm for respiratory sound classification provides an accuracy of 91,3%. Comparing with other methods, the algorithm developed reports one of the highest rate of success of recent publication studies in automatic computer-assisted diagnose tools for respiratory sounds [5].

7.3 Graphical User Interface (GUI)

Under the project purpose, a simple and intuitive graphical user interface (GUI) was developed in Matlab environment to present the algorithm results to the student's supervisors. The GUI allows the selection of a patient and the visualization of the data related to the sound patient selected. This interface also provide an easy and fast way to supply useful information, such as the patients included in the system and the sounds available of each one. Some functionalities of the GUI are presented in the annex GUI Functionalities.

8. CONCLUSIONS

Along the document are reported the steps done to develop a system able to acquire, store and automatic classify respiratory sounds, distinguish them in normal and pathologic sounds (wheezes or crackles).

During this year, several methods reported in [39][54][55] were implemented in order to perform the computer assisted diagnosis. However, these algorithms do not show the desired results when classifying sounds collected at HC. Therefore, a method based on the scalogram strategy was implemented to detect wheezes and another based on the histogram's entropy was employed to make the distinction between sounds with crackles and the normal ones. The original code was implemented in Matlab environment because it is a more intuitive language and more easily show graphics and variables values. The intermediary conversion to C language allowed the implementation of basic routines. In the dsPIC final code all the variables were processed as integers, instead the float type used in Matlab code. As so, the thresholds and the constants were multiply by the factor 32767, the limit of the integer range (-32768<integer<32767). This approximation was used to allow the comparison between the variables' values obtained in the Matlab and in the MPLAB programs ensuring that the implementation was being well done.

In order to evaluate the performance of the method, both healthy subjects and patients with various respiratory diseases were tested. The algorithm presents a sensitivity of 82% and a specificity of 97%, being the overall accuracy of the system equal to 91%. Comparing with other methods, the algorithm developed reports one of the highest rate of success of recent publication studies in automatic computer-assisted diagnose tools for respiratory sound [5].

In a meeting with Doctor José Moutinho, he considered the sounds recorded by the hardware of high quality. He mentioned that the sounds allow to clearly identifying the most evident adventitious sounds. He also shows a great enthusiasm with the final results of the classification algorithm, saying that these are good results for an automatic technique for respiratory sounds discrimination.

The experimental evaluation/validation in real life situations allows to conclude that, after the remote transmission of sound data is finished, the low-cost prototype developed has a good commercialization potential on the healthcare market.

9. FUTURE WORK

The first improvement in the system/algorithm point that needs to be overcome is the noise issue caused by the friction between the skin and the stethoscope. The noise filtering stage proposed in the algorithm performs correctly in many respiratory sounds. However, when this artifact is too intense, the algorithm starts to lose the effectiveness.

The heart sound overlay in some respiratory sounds, which lead to wrong classification by the algorithm proposed, is other issue that can be study in the future. As mentioned in the section 6.3, a method for reduce this artifact was tested. Nevertheless, the resulting sound had not quality to be classified and is always detected as a pathologic sound. So, as a matter of time project, this task was sideline.

The relationship between respiratory sounds and airflow during the inspiratory/expiratory phases has always been of researchers' and physicians' interest. The phase at which the adventitious sounds occur is important to the doctors in order to better discriminate the different lung diseases. For example, wheezes are predominant of the expiration. The crackles, if they are fine appear in the inspiration and the coarse are present in both phases. Also in several clinical applications, such as sleep disorders (sleep apnoea) and monitorizations of ill patients, the presence/absence of breathing provides crucial information about the patient condition. During this year, an algorithm for respiratory phase's detection through sound data analysis, without airflow measurements, was developed [56]. However, the results were not the expected. Various problems related to the threshold definition and the index determination of the start/end of each phase has not been achieved. Thus, a future point of work, in order to solve this issue that the physicians consider important, is the optimization of the algorithm implemented or the use of a thermocouple in the user's nose to measure the respiratory flow.

The development of an algorithm to differentiate fine and coarse crackles would be interesting to help the doctor to better relate the patient's sounds with a disease, since these two types of sound occur in different pathophysiological conditions. Patients with pulmonary fibrosis usually have fine crackles and patients with chronic bronchitis have mainly coarse crackles.

Under the project, a graphical user interface was developed in Matlab environment to present the algorithm results to the student's supervisors. Designing a new GUI as a windows application would allow to the physician the access and visualization of the data of each patient.

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11. ANNEXES

11.1 Sound Platform Prototype Specifications

Explorer 16 Development Board:

- dsPIC33FJ256GP710:

MIPS	Pins	Program Flash Memory (kB)	RAM (kB)	16-bit Timer	Input Capture	Output Compare (std. PWM)
40	100	256	30	9	8	8

Codec Interface	ADC	UART	SPI	I^2C	Enhanced CAN	I/O Pins (Max)
1	2 ADC, 32 Ch	2	2	2	2	85

- Powered between 9V a 15V (DC), preferably by 9V;
- RS-232 serial port;
- Temperature sensor;
- Connectivity USB support by PIC18LF4550;
- LCD;
- Buttons (4) e LEDs (8);
- Oscillator: the microcontroller has 2 circuits of oscillators connected. The primary oscillator uses a crystal of 8 MHz, while secondary uses a crystal of 32,768 kHz. The PIC18LF4550 has its own crystal of 20 MHz;
- PICtail™ Plus Card Edge Modular Expansion Connectors.

Audio PICtail Plus Daughter Board:

- Codec: WM8510
  - Allows various sampling rates (8000, 11025, 16000, 22050, 24000, 32000, 44100 e 48000 kHz);
  - Communicates with dsPIC33F through the I^2C module.
- 4 Mb of Serial Flash;
- Works with Explorer 16 through PICtail Plus interface;
- Powered through Explorer 16.

PICtail Daughter Board for SD and MMC Cards:

- Supports different types of SD cards;
- Powered through Explorer 16.

11.2 Matlab Pseudo-code

In the section 6.1.1 was describe the implementation details of the wheezes classification stage. For better understanding of what was written, below is present the Matlab pseudo-code for sound scalogram computation. The signal variable is taken as the recorded sound.

```
%Initialize variables needed
nscales=56; minwavelength=4; mult=1.05; sigmaOnf=0.55;
ndata = length(signal); %Length of the respiratory sound recorded

signalfft = fft(signal);            %Take FFT of signal

radius=[0:fix(ndata/2)]/fix(ndata/2)/2; %Frequency values 0 - 0.5
radius(1) = 1; %Fudge to stop log function complaining at origin.

%Computing the respiratory sound scalogram
wavelength = minwavelength;

for row = 1:nscales
    fo = 1.0/wavelength;        %Centre frequency of filter.
    logGabor(1:ndata/2+1)    =    exp((-(log(radius/fo)).^2)    /    ...
(2*log(sigmaOnf)^2));
    logGabor(1) = 0;            %Set value at zero frequency to 0
%Multiply filter and FFT of signal, then take inverse FFT.

    EO = ifft(signalfft .* logGabor);
    amplitude(row,:) = abs(EO);      %Record the amplitude of the result
    wavelength = wavelength * mult; %Increment the filter wavelength.
end
```

11.3 Algorithm Tests

Table I - Experimental tests to define the threshold for wheezes classification stage.

Sounds	Continuous Samples
Wheezes	
Bernardes	1759
Luís	3478
Lucília	3777
Moltina	4971
Crackles	
Conceição	874
Carminda	995
Maria	1268
Normal	
Daniel	240
Margarida	250
Miguel	265

Table II - Experimental tests to define the first criterion of the crackles classification stage.

Sounds	aux	quo
Obvious crackles		
António	-0,0816	0,0710
Carminda	-0,0657	0,0508
Joaquim	-0,0941	0,0900
José	-0,0896	0,0828
Vitória	-0,0875	0,0796
Normal		
Catarina	-0,1336	0,1785
Daniel	-0,1391	0,1972
Ilda	-0,1172	0,1346
Margarida	-0,1500	0,2473
Miguel	-0,1227	0,1477

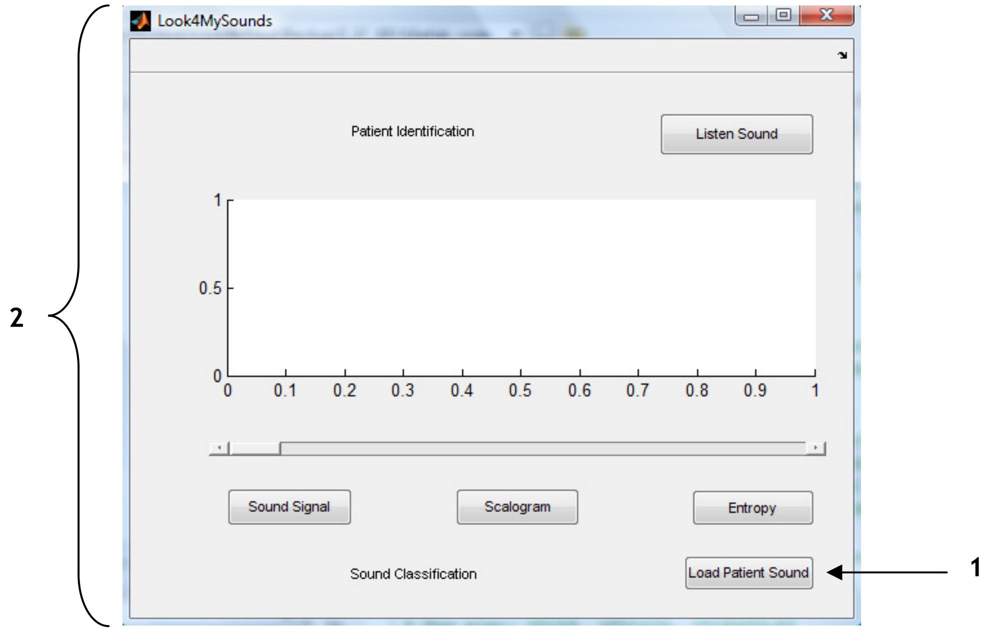
Table III - Experimental tests to define the threshold of the second criterion of the crackles classification stage.

Sounds	Entropy's Mean
Obvious crackles	
Maria	0.0974
Maria	0.0992
Conceição	0.0994
Normal	
Miguel	0.1021
Ilda	0.1075
Emílio	0.1162
Margarida	0.1237

Table IV – Algorithm final tests.

	Sounds tested	Wheezes	Crackles	Normal	Notes	Correct Classifications	
Healthy People							Normal
Catarina	18	0	0	18			18
Daniel	18	0	1	17	1 normal misclassified		17
Margarida	18	0	0	18			18
Ilda	19	0	3	16	3 normal misclassified		16
Miguel	19	0	0	19			19
Emílio	20	0	0	20			20
Patients						Pathologics	
Mário	18	1	13	4	2 crackles misclassified/1 crackle gives wheeze	12	4
Maria	20	0	18	2	3 crackles misclassified	15	2
António	17	0	9	8	3 crackles misclassified	6	8
Carminda	19	0	18	1	1 crackle misclassified	17	1
Conceição	18	0	11	7	1 crackle misclassified/1 crackle gives wheeze	10	7
Lucília	17	1	6	10	3 crackles misclassified	4	10
Moltina	20	8	7	5	1 crackle misclassified/1 wheeze gives crackle	14	5
José	20	0	11	9	6 crackles misclassified	5	9
Júlia	9	0	3	6		3	6
Manuel	16	0	2	14	1 normal misclassified	2	13
Vitória	17	1	5	11	1 normal misclassified	6	10
Joaquim	14	0	7	7	2 crackles misclassified	5	7
Fernando	18	0	5	13	2 crackles misclassified	3	13
Luís	12	6	5	1	2 wheezes misclassified/1 wheeze gives crackle	9	1
Isaías	15	0	4	11	1 crackle misclassified	3	11
Bernardes	16	3	4	9	1 wheeze gives crackle	7	9
TOTAL	378	20	128	230		121	224

11.4 GUI Functionalities



Legend: 1- Load patient to sound analysis; 2 – Menu.

Figure 1 – Main window of the GUI.

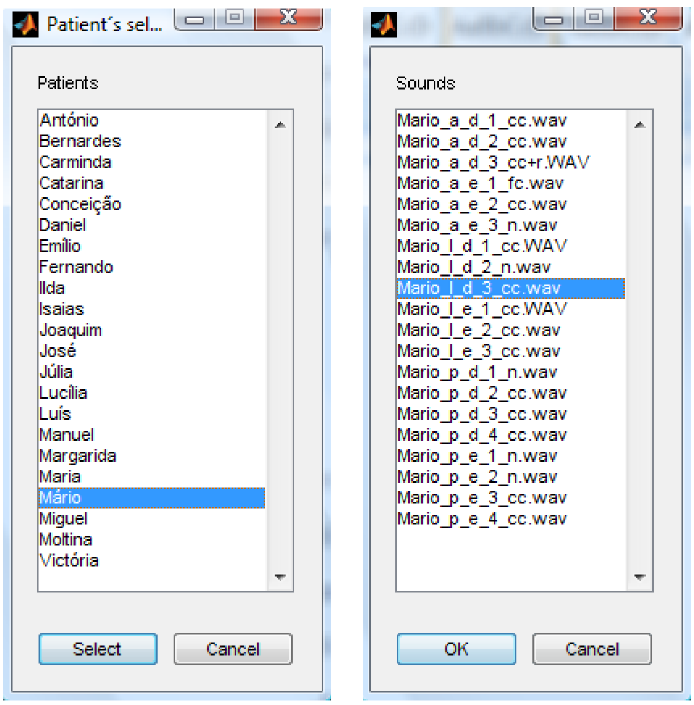
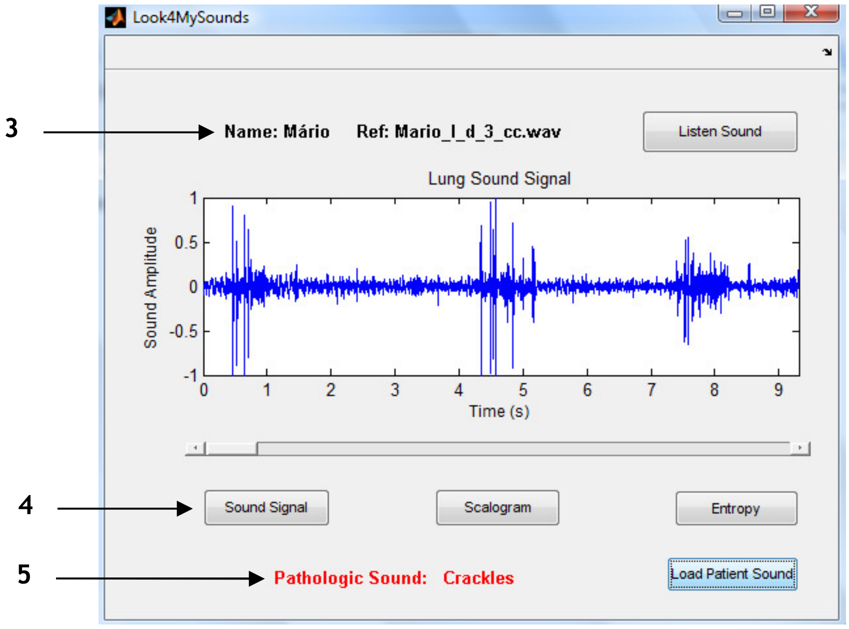


Figure 2 – Patient’s and sound’s selection.



Legend: 3- Patient sound details; 4- Graphic of the signal; 5- Sound classification.

Figure 3 – Visualization of all the sound information.

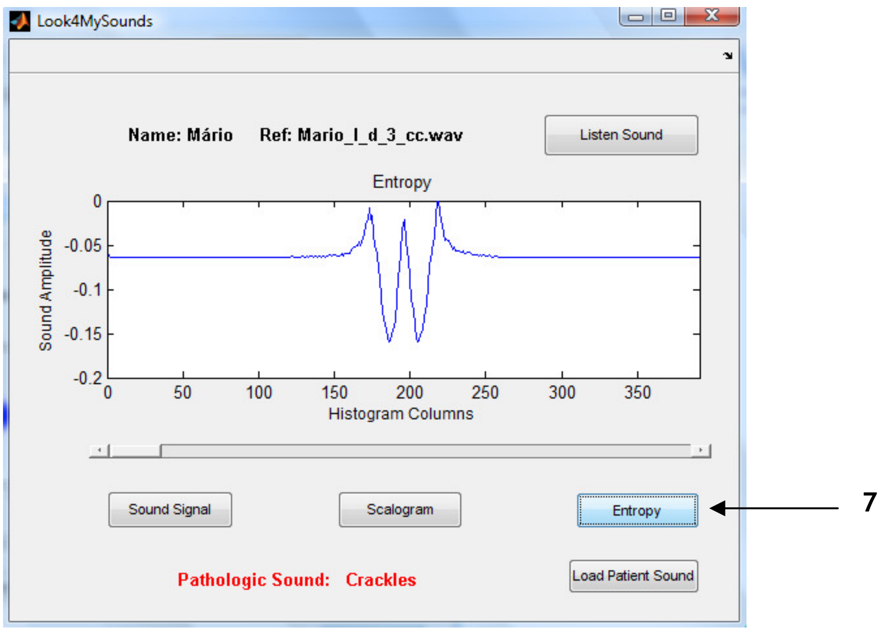
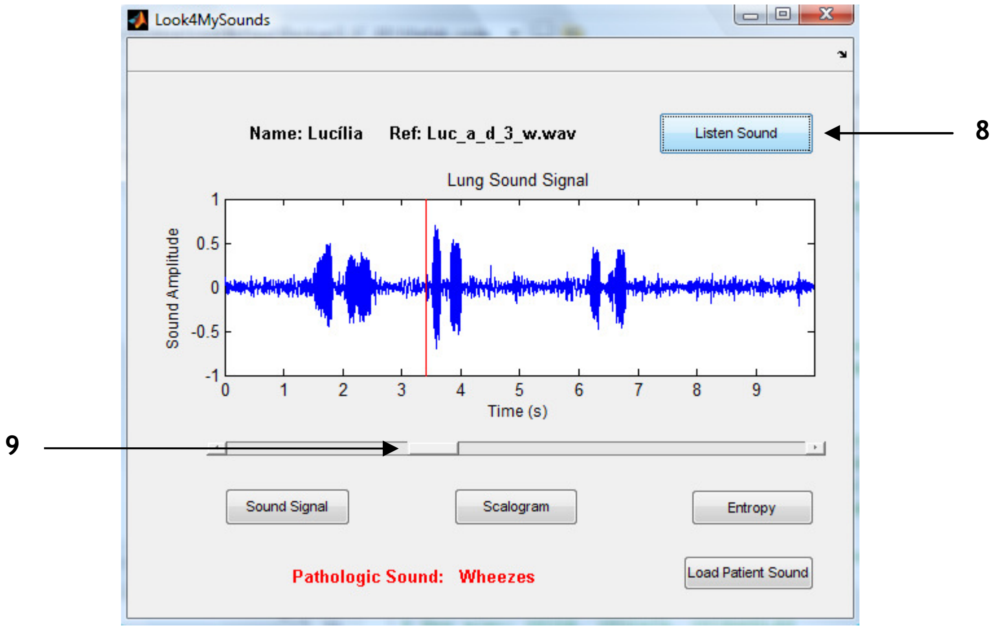


Figure 4 - Histogram's entropy visualization of a sound with crackes (button 7).



Legend: 8 – Button to listen the sound; 9 – Slider to listen segments of the sound.

Figure 5 – Listen sound functionality.

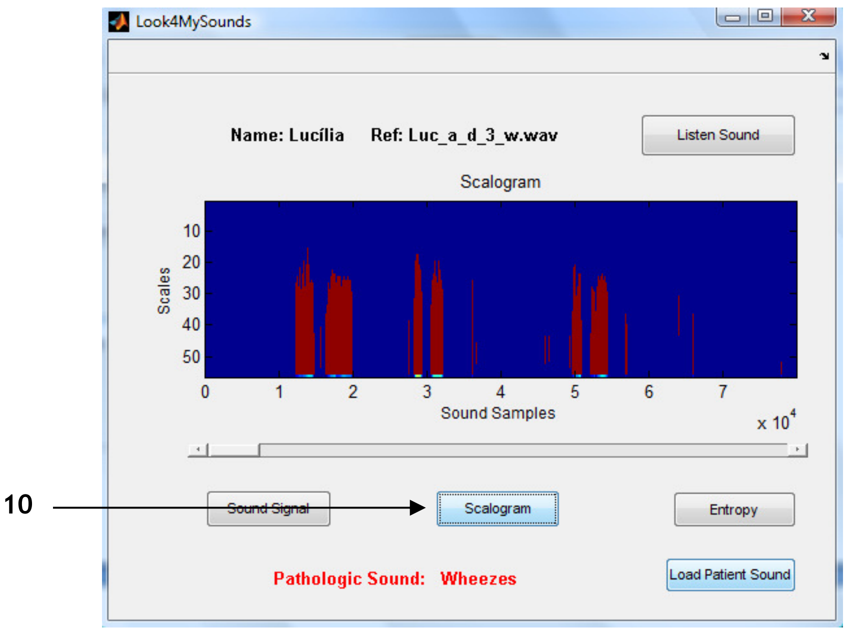


Figure 6 – Scalogram visualization of a sound with wheezes (button 10).