



25th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

Non-invasive devices for respiratory sound monitoring.

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Abstract

Respiratory diseases are leading causes of death and disability in the world. The recent COVID-19 pandemic is also affecting the respiratory system. Detecting and diagnosing respiratory diseases requires both medical professionals and the clinical environment. Most of the techniques used up to date were also invasive or expensive.

Some research groups are developing hardware devices and techniques to make possible a non-invasive or even remote respiratory sound acquisition. These sounds are then processed and analysed for clinical, scientific, or educational purposes.

We present the literature review of non-invasive sound acquisition devices and techniques.

The results are about a huge number of digital tools, like microphones, wearables, or Internet of Thing devices, that can be used in this scope.

Some interesting applications have been found. Some devices make easier the sound acquisition in a clinic environment, but others make possible daily monitoring outside that ambient. We aim to use some of these devices and include the non-invasive recorded respiratory sounds in a Digital Twin system for personalized health.

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Peer-review under responsibility of the scientific committee of KES International.

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Keywords: respiratory sounds; non-invasive; acquisition; stethoscope; Internet of Things; smartphone; wearable.

1. Introduction

Respiratory diseases, like Chronic Obstructive Pulmonary Disease (COPD) or asthma, are leading causes of death and disability in the world, above all in developed countries [1]. Asthma is the most common respiratory illness. According to the WHO, 235 million people suffer from it, which is very common among children. About 65 million people suffer from COPD, and 3 million die from it each year. There are other diseases as chronic bronchitis, lung cancer, or pneumonia that also affect people. More children under five years are dying because of acute lower respiratory infections (ALRI) than from malaria, VHI, and tuberculosis [2]. COVID-19 infection is also a disease that is causing a vast range of problems with the respiratory system.

The detection and diagnosis of respiratory disorders first step is to hear the breathing sounds using a stethoscope. This is a simple, non-invasive tool that physicians use to make auscultation. It allows them to listen better the lung sounds. However, the auscultation process depends on the doctor's subjectivity [3, 4] and can be contaminated by environmental noise [5, 6]. There are also problems when the sound level is not loud enough. Other techniques as CT scan or spirometry are used to diagnose respiratory illnesses in clinical environments. They are very expensive and invasive.

Respiratory sounds are vibrations generated by the movement of air through the respiratory system. They are the first way of detecting illnesses in the respiratory system. As it was said, they can be identified by a trained physician using a stethoscope. The frequency of these sounds is usually from 100 to 1000 Hz [7]. There are different ways of classifying these sounds. The most common pathological ones are wheezes (100-150 Hz) and crackles (about 650 Hz). These are kind of continuous adventitious sounds (CAS), which refer to sounds that are also heard with the expected breath sound [8]. Obstructive sleep apnea is worthy of note. It is a common sleep disorder in which patients suffer pauses in breathing during sleep. Each pause can last for seconds to minutes. To detect and treat that disease, patients should sleep in a hospital scene, connected to different machines controlling heart rate, cerebral signals, and breathing [9].

In general, the detection of respiratory illnesses requires invasive techniques and needs a physician or other health specialists. This could be a tricky issue in some ways: for people living in remote locations, with patients that cannot move from their house, with children or other patients in which it is delicate to perform the test or in isolation situations as the world has suffered because of the COVID-19 pandemic.

The application of new technologies could represent a new approach to detect and diagnose respiratory disorders. Electronic stethoscopes record lung sounds and transform them into digital signals that can be processed using a laptop. Smartphones or digital microphones could register acoustic signals from breathing. There are also devices for reducing noise, pre-processing, and cleaning the audio records. The aim is to make sound acquisition easier for both patients and physicians. The process can be automatized too, and later make electronic tools for supporting the health system.

Databases with respiratory sound are being created to be used for engineering or educational purposes [10]. There is a research study [11] in which fake respiratory sounds are simulated using authentic sounds. The aim is a better train for doctors with real sounds but not in a real stressful situation and using it as a dataset for train Machine Learning models for respiratory diseases classification.

Internet of Things (IoT) devices are technical gadgets that can make our lives easier. It ranges from an intelligent fridge to a bread toaster. They can be used to improve and personalize health (eHealth). The concept eHealth is about healthcare services provided via Internet. They can record and take real-time data for people with chronic diseases in their homes. The information is sent to the clinical professionals, and the system can detect critical situations. Regarding the respiratory ambient, these sounds can also be monitored outside the hospital environment. This information could later be used for the early detection of diseases.

In this review, the current state of the art using non-invasive technical devices for respiratory sound detection is explored. This is a new research field but indicates a promising future. The paper is organized as follows. Section 2 summarized the objectives of the paper, and the obtained results are detailed. We have classified the devices into four categories: electronic stethoscopes (section 2.1), sound devices (section 2.2), wearables and IoT (section 2.3), and smartphones (section 2.4). Then we present different systems regarding the clinic scope of application, the specific

hardware used, and the system's functionality.

2. Non-invasive respiratory sounds acquisition

This paper presents existing solutions for non-invasive respiratory sounds acquisition, starting with the more general and clinic ones and finally with the innovative ones concerning smartphones, IoT, and wearable devices. Our aim here is to apply this technology in Digital Twins (DT) and sleep phase monitoring research.

Digital Twins are virtual representations of physical entities. They have been used in the industrial field to create simulations to improve and predict the behaviour of a system. In recent years, they are being used in other ambits as health. These kinds of models are going to make proper personalized health for everyone. Personal data is used to build the model, and treatments and clinic procedures can be tested in a virtual environment. The optimal solution is the only one that is applied to the patient. We will be able to introduce information from non-invasive sensors in our database. This will allow us to create more specific DT models with real-time information.

2.1. Electronic stethoscopes

Specific clinic technical devices are designed and built with the objective of record respiratory sounds. One of these devices is the electronic stethoscope. These devices can amplify and record respiratory and heart sounds. These acoustic signals are converted into electrical signals and saved as digital files. This allows for better processing and transmission of the data. Most of them have extra functionality as noise-cancelling or signal processing elements [12].

Such digital stethoscope could be used as the traditional one. The physician makes the patient's auscultation with the stethoscope as usual, but sounds detected have also been recording. The sound must be heard in both conditions breathing and talking, and in different parts of the chest and back [13].

Some research groups use an electronic stethoscope to generate input data for further analysis or classification using Machine Learning algorithms like convolutional neural networks (CNN) or support vector machines (SVM). They aim to detect and support the diagnosis of respiratory disorders [14-16]. Most of the electronic stethoscopes used in the research experiments are commercial solutions.

R. Liu, S. *et al.* [8], and Emmanouilidou, D. *et al.* [6] used digital stethoscopes in their experiment of creating a model for the detection of respiratory sounds in children. This is usually a complex process because children are sometimes crying or moving, and parents were talking. Their respiratory sounds are also weaker than adults. Furthermore, R. Liu, S. *et al.* [8] try to detect adventitious respiratory sounds. They use the recorded data to train and test a CNN model to classify the sounds between wheeze and crackle to make more accessible the diagnose of asthma in children. They record paediatric respiratory sounds from several hospitals in Shenyang and Shanghai. The recorded data was divided into two second-length audio files. The electronic stethoscope used is Smartho-D2.

Bandyopadhyaya, I. *et al.* [3] carried out a recording environment using an electronic stethoscope in a four-channel lung sound signal (LSS) data acquisition system (DAS). Microphones are used to amplify the signal that is detected by stethoscopes. They record acoustic signals in four sites in the patients' bodies, sitting, and in a quiet environment. The signals were amplified to 2000 Hz because evidence exists that the essential information of respiratory sounds is limited to this frequency. The data were digitalized using external sound cards and saved in 'wav' format.

On the other hand, Aykanat, M. *et al.* [4] built their electronic stethoscope using a small and directional microphone. It had noise problems when meets dry skin and hair. They solve that problem by lubricating the area of contact. The stethoscope can connect with a laptop. It is used for data acquisition in three different hospitals. They monitor 1630 patients, each one with 11 different positions of the stethoscope. The vast amount of data recorded is involved in a feature extraction process using machine learning techniques.

Research exists in quiet and noisy frames for children and adults and a great set of respiratory disorders. In conclusion, there are different examples of applications of electronic stethoscopes. One key issue is that real clinic environments are usually not quiet, so it is a significant objective to record useful sounds in these situations.

2.2. Sound acquisition devices

Sound recording devices have been used in the music industry for many years. They can be used as a non-invasive way of obtaining respiratory sounds. These devices are usually able to minimize ambient noise and improve sound quality. They also have specific software and applications to manipulate the audio recorded. They are significantly related to the operation of a digital stethoscope. Microphones are used to amplify their signal. They are used in literature to record both respiratory and ambient sounds.

They are applied in the research from van Gilst, M.M. *et al.* [10]. Here they create a non-invasive environment for sleep monitoring. Metrics as respiratory effort, airflow, or oxygen saturation are recorded with different machines. Graef Trachel Microphone (Compumedics, Australia) is used for the acquisition of snoring sounds. M23 microphones (Eatworks, USA) and ECM8000 microphones (Behringer, Germany) are used for acoustic environment signal registration. These microphones are placed at different heights (60-120 cm) around the bed where the patient sleeps. For respiration, the signal is processed with a low-pass 15 Hz filter to reduce the effect of hearth sounds. For snoring, the records are limited between 30 and 450 Hz. This technique seems to have an excellent potential for the non-invasive monitoring of sleep disorders.

They are also used in mentioned research from Emmanouilidou, D. *et al.* [6]. They use a commercial stethoscope to perform digital paediatric auscultation in eight body locations. They also used a microphone to record the ambient sound to evaluate the quality of the audio scripts. They classify the data in interpretable (high quality) and non-interpretable sounds (missing records, noise, etc.) using the information recorded.

2.3. Wearables and IoT

Wearables are mobile devices that many people use in their daily lives nowadays. They are small, light, and usually have a wireless connection. IoT is about every "thing" connected to the Internet. With recent technology advances, everyday things as a fridge or a vacuum cleaner will be "intelligent". This will make it possible to create a network of AI devices and sensors to control and monitor a vast amount of data. These devices can be used for monitoring respiratory suffers in their homes. The future remote and personalized health systems will be based on them [17].

In general, IoT systems combining fixed data acquisition devices and wireless connections to store the information. For example, Velvizhi, R. *et al.* [18] proposed an IoT-based architecture for cough detection. The system would have acoustic sensors placed in different rooms at the patient's house and an Internet connection for sharing data with physicians or emergency services.

More common wearable systems for respiratory sound acquisition are usually about a wireless acoustic sensor that the patient wears, connected to a smartphone for data storage [19, 20]. Some of them are based on electronic stethoscopes. These devices have an acoustic sensor similar to the stethoscope and other parts as a microprocessor or an amplifier circuit; they can amplify and process the recorded signals. The patient is wearing the sensor using a chest or shoulder elastic band to be close to the thoracic region. They must be light and easy to wear in daily life. For instance, Li, S.-H. *et al.* [21] develop a wearable device that can record breath sounds and transfer them wirelessly to a host system using Bluetooth technology. It allows real-time monitoring of the patient outside the hospital. Some devices record not only respiratory sounds but chest movements [22-24]. For example, the system developed by Ghahjaverestan, M. *et al.* [23] is a tiny wearable that combines a microphone and an accelerometer. They also collect data with other machines as electroencephalograms (EEG) or polysomnography (PLS). This information is used for automatic respiratory phase identification in patients with sleep apnea. The device designed by Gupta, P. *et al.* [24] also has an acoustic sensor and an accelerometer in order to acquire cardiopulmonary physiological data as heart sounds or respiratory rate. Oletic, D. and Bilas, V. [19, 20] make research about creating more efficient and less power consumption wearables sensor for monitoring asthma patients. They evaluate aspects as the low-power battery, the circuit for Bluetooth communication, and the circuit for signal acquisition.

Cotur, Y. *et al.* [25] point out that the sensor must contact bare skin. In some cases, it is difficult when motorizing people or animals. The sensor's material needs to be elastic and comfortable too. The purpose of a stretchable wearable consisted of a silicone membrane with a microelectronic sensor inside. The acoustic waves are propagated by a few

water or hydrogel inside the silicone capsule. The sensor can be worn over clothes or hairy skin. It was reported good results with heart monitoring but only preliminary ones with respiratory sounds.

Some research groups designed multimodal wearable systems to record breath sounds and heart rate, ECG, or oxygen saturation [26-29]. For instance, Bor-Shing, L. *et al.* [27] designed a wearable device for the Six-Minute Walking test performing. This test is used for respiratory capacity measurement, and they proposed a multiparameter monitoring system to record data about breathing sounds, oxygen saturation, ECG, and walking at the same time. The system was combining different wearable sensors placed in the patient's chest and ankle. The devices are connected to a host system via Bluetooth.

Furthermore, Chen, X. *et al.* [28] fabricated an innovative e-skin based wearable with both monitoring and sound alarm function. It detects physiological signals as breath or heartbeat to be applied for cardiovascular diseases or sleep apnea monitoring. The alarm function is activated when abnormal signals are detected. Besides, Yin, S. *et al.* [29] uses an IoT system for monitoring athletes' respiratory measurements. Intelligent clothing is used for heart, respiratory, and movement data acquisition. A smartphone controls the process.

Muscles as intercostals and diaphragm are essential for breathing. Some wearable solutions can measure these muscles' movement or activity to evaluate the respiratory functions. Yilmaz, G. *et al.* [30] proposed a wearable "stethoscope" that is not using air as a propagation medium. It is a contact microphone in a silicone rubber which is in contact with the skin. It does not detect the respiratory sound but the diaphragm movement. In addition, Uduak, Z.G., *et al.* [31] designed and implemented their device using commercial EMG (Electromyography) patches. Electromyography is a medicine technique for evaluating the electrical activity of the muscles. Here it is used to monitoring intercostals and diaphragm. The sensor is tiny and light and has Bluetooth Low Energy (BLE) connection to transmit information to a smartphone or laptop.

2.4. Mobile phones

Some research articles are using a smartphone for recording respiratory sounds. The use of the built-in microphone of these devices is a low-cost, contact-free, trustable, and straightforward solution for breathing monitoring [32-36]. It can help monitor patients during the night for improving the treatment of some disorders, like sleep apnea [33, 34] or asthma [35]. Snoring is studied as a critical sound for these diseases. These systems have been tested with real subjects, but more studies and clinical validation are required [32-35]. Another example is the research of Bokov, P. *et al.* [36]. They use a smartphone for recording respiratory sounds in paediatric patients. The device was placed close to the mouth (5-10 cm) of children. Its microphone has a sensitivity of 94 dB, and recording software was installed. The data is used for wheeze recognition using an SVM classifier. Clinical professionals have validated the system. Both Apple [32,33] and Android [34, 35, 36] devices are used in this field.

Other research groups use smartphones to control the sound acquisition process [37, 38]. For example, Reyes, B. A. *et al.* [37] develop an automatic system to detect crackle sounds. They built an acoustic sensor with a commercial microphone and connect it to the 3.5 mm audio input of an Android smartphone. They also created an app, which is installed on the smartphone. It displays and processes the functionality of the system. The app takes 15 seconds to detect a crackling sound after receiving data using a machine learning model.

Furthermore, Reyes, B.A. *et al.* [39] used acoustic sensors connected to smartphones too. They compare Android and Apple devices for tracheal sound acquisition. Then they created an automatic respiratory sound monitoring and classification system with Android smartphones [40]. They used a spirometer to measure the airflow, one smartphone video camera for recording chest movement, and an acoustic sensor connected to other smartphone audio input for tracheal sounds. Video recordings are dropped to 25 fps and converted to RGB format. The recorded data is transfer to a computer for further processing and analysis.

On the other hand, there are some mobile applications related to sound acquisition related to respiratory diseases. For example, a recent study about COVID-19 [41] proposed an interactive app for self-diagnosis of respiratory diseases (including COVID-19) using the user breathing sound recorded by the smartphone microphone. However, the detection of COVID-19 with only respiratory sounds has not been studied yet. The first step, according to the article, is to create a coronavirus breathing sound database. Vallejo Valdezate, L. *et al.* [42] have created an engaging mobile app for using a smartphone as a stethoscope. Health professional with hearing impairments have severe

difficulties in recognizing body sounds as heartbeat or breathing. This article presents an app for recording these sounds (using the smartphone's microphone or a high-quality external one) and transmitting them to the doctor's headphones via Bluetooth. The data is processed and saved in .wav format and can be sent to a computer.

Table 1 summarized all the devices, their function, and the specific clinic scope in where they have been tested or designed.

Table 1. Device summary.

Kind of device	Hardware	Clinic scope	Function	References
ELECTRONIC STETHOSCOPE	Commercial stethoscope	Pediatrics	Sound acquisition	[6], [8]
	Stethoscope + microphone	Respiratory	Sound acquisition	[3]
	Own built stethoscope	Sleep disorders	Sound acquisition	[4]
SOUND ACQUISITION DEVICES	Commercial Microphone	Pediatrics	Ambiental sound	[6]
	Microphone + other devices	Sleep disorders	Sound acquisition	[10]
WEARABLES + IoT	Chest wearable	Respiratory	Sound acquisition	[19], [20], [21], [25]
			Chest movement acquisition	[30], [31]
	Chest wearable + Accelerometer	Respiratory	Resp. sounds + chest movement	[22] [23], [24]
	Wearable + other machines	Cardiorespiratory	Physiological metrics	[26], [27]
	Clothes	Sleep disorders	Physiological metrics	[28]
		Sport	Physiological metrics	[29]
	Fixed sensor at home	Respiratory	Sound acquisition	[18]
MOBILE PHONES	Built-in microphone	Asthma	Sound acquisition	[32], [35]
		Sleep disorders		[33], [34]
		Pediatric		[36]
	CPU	Respiratory	Control acquisition process	[37], [38]
	Camera	Respiratory	Chest movement	[39], [40]
	Apps	COVID-19	Diagnosis	[41]
		Hearing	Resp. sounds	[42]

3. Conclusions

The main objectives when using new technologies for respiratory sound acquisition are developing non-invasive methods and creating the possibility to monitoring patients out of the hospital. Both purposes are possible with these devices. We are going to apply them in further research to improve both sleep monitoring and personalized health care using Digital Twins [43,44].

Technological items as electronic stethoscopes and microphones are used nowadays to improve sound acquisition in clinical environments. In this case, most of them are related to sleep apnea and pediatric respiratory diseases. This is because data in these illnesses is difficult to record in a non-invasive way. The devices mentioned achieve good results and improve the traditional methods of hearing and then analyzing respiratory sounds. Some of them have been tested in a real clinic environment. However, when using electronic stethoscopes, we still need the patient in a clinical ambient. Recording data from patients at home is only possible when we use mobile devices as wearables, smartphones, and IoT items. Further studies need to be done in the field of integrating this data in health systems.

Smartphones are used to record hours of sounds to detect disorders and play apps related to illness diagnosis. They are a powerful and easy-access device. Wearable and IoT sensors are more related to a continuous monitorization of the patient. Different materials and detection technologies are used to record respiratory sounds or other measurements related to lung function, like chest movement. Wearable devices need to be comfortable, easy to wear and transmit the recorded data.

In conclusion, electronic devices improve sound acquisition, and mobile ones will revolutionize it, evolving to personalized health. These devices are going to make easier providing health care remotely, monitoring patients at home. This is called telemedicine or telehealth, in which information and telecommunication technologies are used to reduce hospital visits with less costs for both patients and health systems [45].

Acknowledgments

This research has been partially supported by the Evolving towards Digital Twins in Healthcare (EDITH) Research Project (PGC2018-102145-B-C21, C22 (AEI/FEDER, UE)), funded by the Spanish Ministry of Science, Innovation, and Universities.

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