Respiratory sound analysis as a diagnosis tool for breathing disorders

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Respiratory Sound
Analysis as a Diagnosis Tool for Breathing Disorders

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Abstract. This paper provides an overview of respiratory sound analysis (RSA) and its functionality as a diagnostic tool for breathing disorders.

A number of respiratory conditions and the techniques used to diagnose them, including sleep apnoea, lung sound analysis (LSA), wheeze detection and phase estimation are discussed. The technologies used, from multi-channel bespoke recording systems to using a smart phone application are explained.

A new study that focusses on developing a non-invasive tool for the detection and characterisation of inducible laryngeal obstruction (ILO) is presented.

ILO is a debilitating condition, caused by malfunctioning structures of the upper airway, commonly triggered by exertion, leaving children feeling out of breath and unable to exercise normally. In rare cases it can lead to critical laryngeal obstruction and admission to intensive care for endotracheal intubation. The current definitive method of diagnosis is by inserting a camera through the nose while the person is exercising. This approach is invasive, uncomfortable (in particular for young children) subjective and relies on the consultant's expertise. There are only a handful of consultants with the appropriate level of expertise in the UK to diagnose this condition.

Keywords: Respiratory sound analysis· Inducible laryngeal obstruction · Respiratory diseases · Paradoxical vocal cord dysfunction · eILO

1   Introduction

This paper discusses the history of respiratory sound analysis (RSA) and how it is currently used in the medical environment to diagnose and characterise respiratory conditions. It will discuss the evolution of RSA and how it has been used in studies across a range of areas and respiratory disorders.

Following this, it will detail some of the short comings of existing studies and diagnosis tools and how they may be improved using digital technology and digital signal processing (DSP) techniques for effective diagnosis and monitoring of breathing disorders

After this, it will introduce our study, and present the method for combining digital technologies with related software for a practical clinical applicability. This study will be primarily focused on the identification and characterisation of the respiratory condition, inducible laryngeal obstruction (ILO), previously referred to as paradoxical vocal cord dysfunction (pVCD).

2 Background

2.1 The Stethoscope

Rene-Theophile-Hyacinthe Laennec invented the stethoscope in the early 1800's, since then the stethoscope has become common place in every medical setting and almost synonymous with the profession itself [1]. Laennec demonstrated his original prototype in 1816, a tube of tightly rolled paper; which then evolved to a thick paste board cylinder and then to a wooden tube, following extensive investigations [2].

Following the invention, stethoscopes evolved over time. In 1855 doctor George Cammann introduced the first binaural stethoscope; this was similar in its basic design to modern stethoscopes, by having two tubes from the earpieces extend to join a single bell-shaped chest piece [3].

Kahya [4] and Alsmadi [5] discuss the use of traditional stethoscopes which amplify frequencies lower than 112 Hz and attenuate frequencies above it. They state that they have low diagnostic value due to the attenuation of higher frequencies which contain valuable diagnostic information regarding respiratory sounds.

Stethoscopes are also subjective to the medical staff's experience and knowledge, this can lead to a high inter-observer variability, also the varying quality of stethoscopes and the lack of standardised nomenclature of respiratory sounds can affect the reliability of diagnosis [5-8].

2.2 Respiratory Sound Analysis

RSA seeks to address the issues of the stethoscope by allowing physicians to record, store and visualise the sounds produced by the respiratory system. In its infancy, the sounds were electronically recorded onto cassette tapes [9], which allowed doctors to replay and share what they could hear from a patient. Advances in technology have enabled the design of digital recording and analysis equipment specifically for the use of recording respiratory sounds.

RSA has numerous potential diagnostic applications for breathing disorders. For example, when diagnosing nocturnal asthma in children; currently the diagnosis is lung function testing, which is performed using spirometry, meaning the patient must be periodically woken up to perform the test, resulting in periodic results throughout the night. However, when RSA is used the patient could be continuously monitored during the night with a small sensor attached to their chest [10].

RSA could potentially provide diagnosis information for conditions that present themselves similarly to others, such as pVCD and asthma, where asthma presents with an expiratory wheeze and pVCD presents inspiratory stridor [11].

3 Previous RSA Studies

There have been many studies into using electronic audio recording devices in clinical environments, many of them explored diagnosis of respiratory conditions using lung sound analysis (LSA); however, there are also studies that investigated using RSA to diagnose conditions such as sleep apnoea and asthma; these are possible as RSA covers the whole respiratory tract including upper airway sounds as well as lung sounds.

This section aims to review related studies;

3.1 Lung Sound Analysis (LSA)

Pulmonary sounds are believed to be produced by turbulence in the lungs, although the exact cause is still unknown; as the lungs and chest wall effectively act as a lowpass filter, the sounds transmitted to the skin are a filtered version of the original [5].

Computerised LSA involves recording the patient's lung sounds via an electronic device, followed by computer analysis and classification of lung sounds based on specific signal characteristics [12].

Animoto et al [13] used LSA to describe the acoustic features of wheezing in a patient with vocal cord dysfunction (VCD) and bronchial asthma, using seven microphones with a bespoke recording device. They placed multiple microphones on patients, one on the neck, two on the anterior chest and four on the upper back. They showed that the respiratory sounds related to VCD originated in the throat. They concluded their study by stating that they believed that LSA is a valid method of determining the source of respiratory sounds and could be used to differentiate between asthma and VCD [14].

3.2 Sleep Apnoea

Obstructive sleep apnoea is a sleep disorder in which the airways close, causing intermittent interruptions in breathing during sleep [15]. RSA has been used in several sleep apnoea studies, such as Nakano et al [16] who used a tracheal microphone to record patients sleeping and then analysed the data to highlight respiratory events such as snoring, hypopnea, obstructive apnoea and central apnoea. However, due to the nature of the condition, the recordings all took place in a quiet space with minimal body movement as they are asleep. This minimised distortions eliminating the need to remove background sounds during post analysis.

3.3 Wheeze Detection

If cough sounds are excluded from the acoustic signs related to respiratory disease, wheezing becomes the most common adventitious lung sound [17]. Pasterkamp [17] indicated that it is surprising that detection and characterisation of wheezing has remained almost entirely in the domain of a few research laboratories.

However, there are a few centres that are using RSA to diagnose conditions that present with a wheeze. Prodhan et al. [18] compared the effectiveness of a recording device, with the software to identify and count wheeze events, to intensive care medical staff in their ability to detect the presence of a wheeze. They concluded that the device and staff were similar in the ability to detect the absence of a wheeze, but the device was better than the staff at detecting wheeze.

Bokov et al[19] highlighted a requirement for an outpatient objective tool for wheeze recognition, this was due to parents hearing wheeze symptoms from their child, but the symptoms were no longer present during the medical consultation. Cane & McKenzie [20] conducted a study where they showed video clips of children with audible wheezing to 190 parents. The parents were asked to identify the clips in which wheezing occurred and 59% were correctly labelled.

Elphick et al[21-22] conducted a similar study investigating the terminology used by parents to describe their children's breath sounds. This involved interviewing the parents of 92 infants with noisy breathing, starting with an open question for them to describe the sounds and then directing them towards a detailed description. Following this the parents were shown videos demonstrating each breath sound and then were asked again to describe their children's breathing sounds; 59% of the parents initially described the breath sounds as wheeze but following the videos only 36% were still using this term at the end of the interview.

These studies highlight a need for a device that could automatically identify a wheeze and properly diagnose the condition. Bokov et al. [19] used a smartphone to record the respiratory sounds. They used the phone's built in microphone placed in front of the patients mouth to provide a non-contact recording solution. The recordings were saved and then exported to a personal computer (PC) for further analysis where mathematical analysis and machine learning algorithms were applied. They suggested that the parents could record any abnormal breath sounds and then present the recordings to health workers to obtain diagnosis. This not only provided the health workers with a portfolio of the patient's conditions but allowed them to share the recordings with more experienced respiratory consultants.

3.4 Phase Estimation

Many conditions present respiratory sounds such as wheezes, coughs and crackles, however some conditions can be diagnosed from when these sounds occur during respiration. This led to a number of RSA devices designed to work alongside a flow monitoring systems or chest movement sensors to determine the respiratory phase, inspiration or expiration.

Huq and Moussavi [23] developed a tracheal recording system to determine the respiratory phase from an audio recording alone, they used a smartphone as the recording device with a condenser microphone alongside a flow meter to verify the findings. They compared the audio recording with the flow meter results and then applied signal analysis and machine learning to determine the phase. This is an advance on other methods as most required multiple microphones (chest and tracheal) and some studies recorded the initial breathing phase and then assumed it was alternating from that point onwards. This work has potential to be implemented in an RSA system which only records the tracheal sounds, but using the algorithms provided, more data can be collected from the patient without additional sensors.

3.5 Summary of Previous Studies

Following the analysis of previous studies, it was found that very few studies are focused on recording respiratory sounds related to diagnosis of ILO. Many studies used LSA for diagnosis of asthma and Chronic Obstructive Pulmonary Disease (COPD) and determining the location of origin of respiratory sounds.

There were studies that used RSA to acquire statistical information such as the wheeze rate and breathing phase, also devices designed to record sleep apnoea events such as hypopnea.

4 Development of a Diagnosis Tool for ILO

We are currently developing a tool for diagnosing and characterising ILO, especially exercise induced laryngeal obstruction (eILO), which is a form of ILO where the patient suffers from symptoms during exercise [24].

The current diagnostic methods for this condition involve the patient exercising on a treadmill and then a consultant performing laryngoscopy to visualize their larynx. This procedure is very invasive and uncomfortable for the patient, especially for a paediatric patient.

This study aims to develop a non-invasive solution using RSA to improve the diagnosis with aims to enable more clinics to offer the diagnosis as currently the number of centres that can offer it are very few and therefore oversubscribed.

4.1 Inducible Laryngeal Obstruction

Inducible laryngeal obstruction (ILO) is a well-recognised condition in both children and adults, it is characterised as the paradoxical closure of the vocal cords during inspiration, which results in complaints of throat tightness, wheezing and dyspnoea [25-27,29,30]. The condition has been known previously as vocal cord dysfunction (VCD) and paradoxical vocal cord dysfunction (pVCD) but a nomenclature that stated ILO would be used to describe the condition was agreed at a conference in 2013 [26].

ILO presents itself during an attack with symptoms of air-hunger, choking sensation, chest tightness, chest pain, difficulty swallowing, globus sensation and intermittent aphonia or dysphonia [27]. These symptoms then can be worsened by the sensations causing fear, panic and anxiety due to breathlessness and choking [27].

It is hard to quantify the prevalence of ILO in the general population due to the difficulties in diagnosis as ILO can be misdiagnosed as exercise-induced asthma [27,28]. Misdiagnosis may lead to unnecessary health care utilisation and inappropriate medication use and possible hospitalisation [28].

Although, there is no standardised treatment for ILO, many clinics use techniques such as reassurance and hyperventilation into a breathing bag [29]. ILO attacks also have little or no response to medical treatment such as inhalers and bronchodilators [30]. The 'gold standard' for diagnosing ILO is the direct visualisation of the vocal cords, whilst the patient is having symptoms [31]. However, this is subjective to the consultant's expertise and currently continuous laryngoscopy is rarely performed during diagnosis [32], more commonly an attack happens and then the visualisation takes place.

Previous studies have shown the effectiveness of audio recording in the diagnosis of ILO and other respiratory conditions [4,6,7,9,12,13,16,17,23,33,34].

4.2 Challenges

Many studies already mentioned were carried out in controlled environments with minimal background sounds, also with the patient seated or in a sleeping position; this is different to the diagnosis of ILO where exercise tests are often used as stimulus, this means that the patient is moving in a potentially very noisy environment.

These key differences raise new design challenges for both the hardware and software development during the study. They also present new signal processing and

interpretation requirements; The factors that will present the challenges to this study can be summarised as follows:

- Respiratory sounds being masked by much louder sounds, such as external noise from the clinical environment and treadmill.
- Patient being attached to multiple monitoring equipment whilst attempting to exercise.
- Availability of sessions due to complexity and cost of current diagnosis.

4.3   Potential Solutions

Using Signal Processing to Remove Unwanted Noise. This study aims to improve the post diagnosis processing and analysis of the recorded sounds, which could help with the identification and classification of breathing events such as wheezes and rattles.

To achieve this, signal processing techniques will be used to analyse and interpret the recorded respiratory sounds. Initially these tools will be used to visualise and analyse the components of the recordings, such as the Fourier transform which provides frequency information about signals. Following this, tools such as the short-time Fourier transform, wavelet transforms, and independent component analysis will be used for further signal classification and signal source separation and de-noising.

As the sounds will be recorded during exercise, the environment will be very noisy; each microphone will pick up background noise alongside the wanted respiratory sounds. To analyse the upper airway sounds, it is necessary to separate them from the background and heart sounds, one method of this is to use independent component analysis (ICA).

'Unchaining' the Patient from Monitoring Equipment. The current diagnosis procedure involves exercising on a treadmill with the patient's cardiac activity monitored using an ECG and, in some cases, with a breathing mask to attain breathing phase; these interventions may increase stress in an already uncomfortable situation.

An initial respiratory sound study at the start of this study highlighted that there is potential for recording multiple variables using a single type of sensor. It was seen that not only breath sounds were available at the trachea, but also the heart rate in the form of a pulse sound [33] and potential for identifying breathing phase, i.e. inspiration or expiration [23,34].

This study has developed a wireless tool which aims to increase the comfort of the patient during the diagnosis session by allowing them to move freely without restraint.

Making the Diagnosis more Accessible for Non-specialised Centres. Currently the diagnosis takes place within a specialist clinical laboratory and requires specialist staff to carry out key parts of the diagnostic process. These requirements mean that sessions are restricted due to hospital staff time and cost restraints and therefore the number of patients seen are very few.

However, if the screening service was implemented at a general practitioner's level before the patient is referred, then many more patients could be sent home to perform diagnosis in their own time and then return a full dataset back to a specialist for analysis.

This could be performed manually or with the aid of machine learning and artificial intelligence algorithms to identify key breathing events.

4.4 Possible Impact of Device

This device is placed externally on the patient, and can be attached by a non-specialist, such as a parent, and provides a non-invasive recording solution which is capable of constantly recording the patient's respiratory sounds. This solution allows the use of the device outside of specialist diagnostic laboratories which, if adopted, will allow the hospitals to send the device home with patients to perform their own data collection and then to send the recorded data back for analysis, reducing the time required for the clinicians to spend with each patient and allowing a much higher throughput.

Enabling the patient to carry out the recording session in their own environment allows them to be more natural and comfortable, as some paediatric patients may feel stressed in a hospital laboratory environment and this could affect the results received; this could also allow the patients to perform the activity that has previously provoked their symptoms and not be constrained to the treadmill.

This device aims to provide similar diagnostic value to that achieved in the hospital, in which the patient has their heart activity and breathing monitored during the session with specialised equipment, normally involving many sensors to be placed on the patient, such as a twelve-lead ECG.

This device aims to achieve similar results using only a single sensing system based in a low-profile recording system. Using the sound recorded at the neck, it aims to be able to isolate breathing sounds such as wheezes and crackles alongside heart rate from the pulse sounds available at the neck and then determine breathing phase in further analysis. This allows the device to identify and classify respiratory sounds automatically following each recording and thus saving consultant's time by allowing them to focus on the key parts. By recording and storing each session, it allows the sharing of information between specialists to enable a second opinion and reduces the reliance on consultant experience and expertise as currently, the visualisation of the larynx is not recorded, and the consultant must make the diagnosis from what they can see at the time.

5 Conclusion

RSA has been studied for diagnosing and monitoring a variety of respiratory conditions in both adults and children; studies have also shown that in some cases computer analysis can detect symptoms, such as wheezes, when medical staff cannot.

This paper highlighted how RSA has been used by previous studies and how new and novel techniques are evolving to provide more comfort for the patient whilst reducing cost to the healthcare service by removing expensive equipment, such as studies involving existing everyday technology such as smartphones.

The development study introduced in this paper has highlighted the clinical need for a non-invasive respiratory tool to assist with the diagnosis of ILO. This tool aims to improve on the current equipment available by using state-of-the-art processing techniques and the latest technology to achieve this.

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