

# Computer-based Respiratory Sound Analysis: A Systematic Review

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## Abstract

Over the years, lung auscultation has been used as an effective clinical tool to monitor the state of the respiratory system. Lung auscultation provides valuable information regarding the patient's respiratory function. Recent technical advances have led to the development of computer-based respiratory sound analysis which serves as a powerful tool to diagnose abnormalities and disorders in the lung. This paper provides a comprehensive review on computer-based respiratory sound analysis techniques employed by various researchers in the past. The search for articles related to computer-based respiratory sound analysis was carried out on electronic resources such as IEEE, Springer, Elsevier, Pub Med, and ACM digital library databases. Around 55 articles were identified and were subjected to a systematic review. In this review, we examine lung sound/lung disorder, sensor used, sensor locations, number of subjects, signal processing methods, classification methods, and statistical methods employed for the analysis of lung sounds by previous researchers. A brief discussion is undertaken on the overview from the previous works. Finally, the review is concluded by discussing the possibilities and recommendations for further improvements.

## Keywords

*Lung disorder, Machine learning, Respiratory sound, Review, Statistical.*

## 1. Introduction

Respiratory sound heard over the chest wall region gives vital information regarding the present condition of the lung. Auscultation is the art or skill of listening to the sounds in the body by using a stethoscope to diagnose abnormalities. Lung sound auscultation provides useful information for diagnosing abnormalities and disorders in the respiratory system [1]. One drawback of the lung sound auscultation technique is that it has a high possibility of false diagnosis. It requires a professionally well-trained physician to recognize the abnormalities exactly [2]. Lung auscultation is a subjective method, which depends on the experience, ability, and auditory perception of the physician. To overcome this drawback, researchers started to develop computer-based lung sound analysis systems. The only reliable and quantitative method for the assessment of lung sound is using digital recording and its subsequent analysis. Research on computer-based lung sound analysis started to appear in the literature in the early 1980s. The recent advancement in the field of signal processing is yet to be applied to determine the abnormalities and disorder using computer-based lung sound auscultation [3].

This paper discusses the use of computer-based lung sound analysis and the lung sound classification followed by discussion on the related works carried out

in the past on computer-based lung sound analysis. In the past, many research studies have been carried out on computer-based lung sound analysis, but there are no reports summarizing the previous research works in this area. Previous works on computer-based lung sound analysis strongly suggest that this method serves as an effective tool for lung disorder diagnosis [4].

## 2. Lung Sound Types and Characteristics

Respiratory sound signals acquired over the chest wall during inspiration and expiration gives useful information about the condition of the respiratory system. Lung sounds give non-stationary and non-linear signals, implying that frequency component changes over time [4-7]. The respiratory sounds are subdivided into the following three categories: normal respiratory sounds, abnormal respiratory sounds, and adventitious respiratory sounds [8]. An analysis of adventitious respiratory sounds provides useful information regarding the lung disorders. The adventitious respiratory sounds are classified into the following two categories: continuous respiratory sound and discontinuous respiratory sound. The continuous respiratory sound is further classified as wheeze and rhonchi. The discontinuous respiratory sound is divided into fine and course crackles. The characteristics of the normal, continuous, and discontinuous respiratory sounds are listed in Table 1.

### 3. Methodology

Literature search for articles related to computer-based respiratory sound analysis was conducted on electronic resources such as IEEE, Springer, Elsevier, PubMed, and ACM digital library databases and 122 articles were initially identified. The papers were selected for this review from those identified. The following criteria were used to select studies for inclusion in this review: (i) the studies published in English language; (ii) articles related to respiratory sounds or lung disorders; (iii) the studies which used microphones/stethoscope for collecting the respiratory sounds; (iv) the studies related to respiratory sound statistical analysis; and (v) the studies related to computer-based respiratory sound classification. Totally 55 articles that satisfied the criteria were selected finally. Figure 1 shows the detailed article selection procedure for this review. Of the initial 122 articles, 49 papers were excluded in the initial stage after going through their title and the abstract. These articles presented a medical perspective, describing the anatomy of the lungs and various procedures carried out in hospitals for diagnosis of lung disorder such as pulmonary function tests. In the second stage filtering of articles, 18 articles were excluded on the basis of insufficient information. The next section gives a brief overview on the 55 articles that have satisfied the selection criteria. Of these 55 articles, two articles used image processing techniques for classifying respiratory sounds [9,10].

### 4. Overview of the Literature Search

More than 120 articles were identified by the initial search process. After going through the abstract and methodology of the articles, 55 articles were found to discuss computer-based lung sound analysis. All the 55 articles satisfied the selection criteria. Based on the detailed review on these articles, an overview of analyzed sounds, sensor used, number of subjects used, position of the sensor, and methodology were tabulated. In general, the research on lung sounds analysis can be classified into three types. In the following subsections, the three categories are explained briefly.

#### 4.1 Visual Analysis

Using visual analysis, the respiratory sound signals were plotted and visually the physicians diagnose the respi-

ratory sound abnormalities from the respiratory sound waveform. The frequency waveforms of the respiratory signals are monitored to detect disorders. The disorder is identified by the frequency intensity of the signals. This type of system mainly depends on the expertise of the physicians. Visual analysis requires well-trained professionals to diagnose abnormalities in the respiratory sounds. As visual analysis is purely based on the expertise of the physician, it has a high possibility of human error. In this category, 7 articles were identified and the overview of these articles is presented in Table 2. The visual analysis is depicted in Figure 2. The circled area in Figure 2 shows the intensity changes which indicate the abnormalities in the respiratory system.

#### 4.2 Statistical Analysis

The second category is the use of statistical analysis methods to classify the respiratory sounds. Statistical analysis is used to process data sets to determine how usual an event occurs based on its historical data [17].

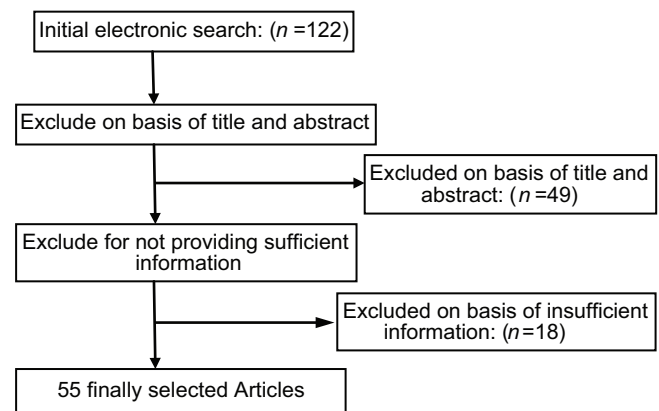


Figure 1: Flow chart for selection criteria.

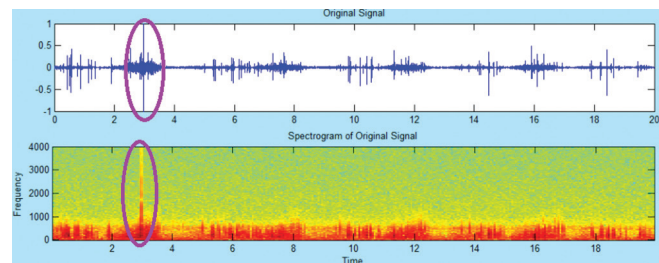


Figure 2: Visual analysis.

Table 1: Characteristics of lung sound [4-7]

Respiratory sound type	Dominant frequency range	Pitch	Duration	Disorders
Normal	150-1000 Hz	High/Low	N/a	N/a
Wheeze	>200 Hz	High	>250 ms	Asthma, pneumonia
Rhonchi	<200 Hz	Low	>250 ms	Chronic obstructive pulmonary disease (COPD), acute (or) severe bronchitis
Coarse crackles	200-2000 Hz	Low	<30 ms	Pneumonia, pulmonary fibrosis, congestive heart failure (CHF), idiopathic pulmonary fibrosis (IPF)
Fine crackles	200-2000 Hz	High	<10 ms	

N/a – Not applicable

**Table 2: Visual analysis in computer-based lung sound analysis systems**

Reference	Analyzed: Sound/Disorder	Sensor type	Dataset	Sensor: Position/Location	Method
[11]	Crackles	Air-coupled dynamic-type microphone	4 tuberculosis and 2 chronic bronchitis	Chest wall	Fast fourier transform
[12]	Normal, asbestosis and pulmonary edema	Electret microphone	15 subjects with lungs disorder and 5 normal subjects	Posterior basal segments of the lobes	Karhunen-loeve transformation
[5]	Normal and wheeze	Contact microphone (piezoelectric transducers)	20- Patients and 5- normal	Chest wall	Fast fourier transform
[13]	Lung sounds	Microphone	Not mentioned	Trachea	Fast fourier transform
[14]	Lung sounds	Piezo-electric transducers/microphone	493 sounds	Trachea, chest right, base right, base left	Fast fourier transform
[15]	Normal and pathological	4 Electret microphone	24 healthy and 17 pathological	Chest wall	Fast fourier transform
[16]	Lung sounds	Electret microphone	Not mentioned	Chest wall	Fast fourier transform

There are many researchers who have concentrated on respiratory sound analysis using statistical analysis. The methods used in this category are higher order crossing discrimination analysis, analysis of variance (ANOVA), Fisher discriminant analysis, lacunarity-based analysis, and linear discriminant analysis. In this category, 15 articles were identified and the overview of these articles is presented in Table 3.

### 4.3 Machine Learning

The third category is the use of machine learning techniques to recognize the respiratory sounds. This method does not require expertise of the physicians. The use of machine learning in almost every field of science has improved a lot in the past decade [32]. Machine learning techniques such as artificial neural network (ANN), Gaussian mixture model (GMM), hidden Markov model (HMM), *k*-nearest neighbor (*k*-nn), and fuzzy analysis were extensively used in computer-based respiratory sound analysis by previous researchers. Machine learning is a branch of artificial intelligence that deals with the development of intelligent algorithms for different applications. In this category, 33 articles were identified and the overview of these articles is presented in Table 4. Of these articles, only the work of Güler [33] shows effectiveness of hybrid machine learning algorithm. Most of the researchers have used *k*-nn and ANN for classifying respiratory sounds. The simplest method with less computational time is *k*-nn [34].

Some of the signal processing techniques used by earlier researchers are fast Fourier transform (FFT), autoregressive model (AR), fractal-dimension (FD) analysis, mel frequency cepstrum coefficients (MFCC), and wavelet analysis. Most of the signal processing methods used are time or frequency domain and very few researchers have opted to analysis the signals in time-frequency domain.

## 5. Discussion

This review provides an insight on the various methods applied in computer-based respiratory sound research

so far. This systematic review analyzed 55 articles on various computer-based respiratory sound analysis systems. These articles were categorized into three groups and a brief overview was tabulated. The research on respiratory sound analysis has gained attention of the researcher in the past few years. The works carried out in the past have concentrated more in developing respiratory sound analysis system rather than developing a lung disorder diagnosis tool. Few researchers were successful in developing a lung disorder diagnosis tool. Yamashita and Matsunaga presented a pulmonary emphysema diagnostic tool [62]. Li and Liu developed a lung disorder diagnostic tool for pneumonia and asthma [60]. Zolnoori and Zarandi developed a tool for diagnosis of asthma [58]. These methods were tested using artificial intelligence techniques such as *k*-nn, HMM, and fuzzy logic. These systems were found to be successful in an offline mode. This makes way for future research in developing real-time systems as lung disorder diagnostic tools. The methods for diagnosing pulmonary disorders such as chest X-ray, computer-based tomography (CT) scan, and pulmonary function test are very expensive and also time-consuming. X-rays and CT scans cause serious side effects on human body when exposed for a longer duration [4]. The pulmonary function test does not cause any serious effects but it is time-consuming and the patients need to put extra effort in some tests such as spirometry. The advantage of chest X-ray and CT scan is that they are used in other applications such as radiation dose unit and three-dimensional reconstruction [64,65]. Pulmonary function test is the complete examination of the respiratory system [66].

The major gap in research on computer-based respiratory sound analysis is to associate the respiratory sounds to its corresponding disorders accurately which has not been carried out by many researchers in the past. Each respiratory sound has different properties and technology has made it simple now to improve the classification of lung disorders. As each disorder has one or more respiratory sounds associated with it, it is difficult for the physician to recognize the disorder. The lung disorders have their

**Table 3: Statistical analysis in computer-based lung sound analysis systems**

Reference	Analyzed: Sound/ Disorder	Sensor type	Dataset	Sensor: Position/ Location	Method
[18]	Fine crackles, coarse crackles, and squawks	Electret microphone	6-Fine crackles, 5-Coarse crackles and 5- Squawks	Over the lungs	Wavelet-based de-noising and higher order crossing-discrimination analysis.
[19]	Respiratory sounds	EMT25C, Siemens Accelerometer	7 –trachea and 10-lungs	Trachea and lungs	ANOVA
[20]	Detecting explosive lung sound	Electrets Microphone	Patients with pulmonary pathology	Over the lungs	FD analysis
[21]	Wheeze, Rattles, and Crackles	Acoustic analysis –sensor (Siemens EMT 25C)	102 subjects	The right upper zone (anterior chest)	Validity and reliability using k-statistics.
[22]	Wheeze and crackle	14 channel Sony ECM-44BPT electrets microphones	Not mentioned	Posterior chest wall	Wavelet decomposition and kurtosis.
[23]	Crackles	Electret microphones	5 fine crackles, 5 coarse crackles, 4 normal and 4 wheezing.	Over the lungs	Wavelet packet transform for de-noise. FD analysis
[24]	Wheeze	5 Electret microphones (ECM-77B, Sony)	13 patients	Trachea, right and left axillae, and right and left posterior bases	Time-frequency analysis of wheeze sound.
[25]	Normal and wheeze	Electret microphone (ECM-77B, Sony)	7 healthy and 7 asthmatic cases	Over the lungs	Time-frequency distribution, histogram, sample entropy features, discrimination analysis.
[26]	Normal, Fine, and coarse crackles	Electret microphones	Normal and simulated data	Over the lungs	Time-variant Autoregressive (TVAR) model.
[27]	Crackles	25 channel Electret microphone	Patients with pneumonia	posterior surface of the thorax	Hilbert-Huang spectrum
[28]	Normal, crackles, and Wheezes	Contact accelerometer (EMT25C, Siemens) and Electret microphone (ECM140, Sony)	Not mentioned	Chest wall, neck and mouth	Wavelet transform and Lipschitz regularity analysis
[29]	Wheeze and non-wheeze from patients with asthma and COPD	14 channel Sony ECM-44BPT Electrets microphones chest piece	246 wheeze and non-wheeze	Posterior chest wall	Kurtosis, Renyi entropy, f50/ f90 ratio and mean- crossing irregularity and Fisher Discriminant Analysis (FDA)
[30]	Fine crackles, coarse crackles, and squawks	DBS database	Not mentioned	Over the lungs	Lacunarity-based discrimination analysis.
[31]	Crackles	14 channel Sony ECM-44BPT Electrets microphones	Patients with Cystic bronchitis	Lower left lung	Kurtosis, Percentile Frequency f90, Kullback-Liebler Distance and linear discriminant analysis
[10]	Respiratory sounds	18 piezoelectric sensors	82 patients	Posterior to the patient’s back	Wilcoxon’s signed-ranks test and Mann-Whitney U test

Squawks is a lower intensity wheeze

corresponding respiratory sounds and corresponding dominant frequency range, using which the disorder can be identified employing signal processing techniques. Advanced signal processing techniques can be applied to the respiratory sound signals and artificial intelligence can be used further to classify the lung disorders more accurately. Developing a computer-based respiratory sound analysis system that can diagnose the lung disorders in real time is another area of concern since there are a very few real-time systems developed in the past. At present, it is difficult to compare various methods reported in the literature because of the difference in data acquisition methods or methodology. Factors that influence the results include position of the sensor. To

position the sensor, it requires professionally trained physicians. Another important issue is that very few systems have used experimental data from hospitals and many systems have used data from lung sound CDs used for training the doctors and nurses. The data from lung sound CDs used by the previous researchers are not suitable for machine learning because of insufficient data. Supervised learning requires a larger data set for training the model. Developing a commercially available computer-based lung disorder diagnosing tool is a possible future focus area. The main advantage of computer-based respiratory sound analysis is that it is non-invasive and less expensive compared to other methods [4,16].

**Table 4: Machine learning in computer-based lung sound analysis systems**

Reference	Analyzed: Sound/ Disorder	Sensor type	Dataset	Sensor: Position/ Location	Method
[35]	lung sounds	Electret microphone	28 COPD, 23 restrictive lung disease patients and 18 normal	Two locations on the chest, left and right basilar	AR model, <i>k</i> -nn classifier and quadratic classifier
[36]	Wheeze and normal	Eight microphones	Not mentioned	Anterior upper chest	Fourier transform spectrum features and ANN
[37]	Normal and pathology	Electret microphone	28 COPD, 23 restrictive lung disease and 18 Normal	Two locations on the chest, left and right basilar	AR model and <i>k</i> -nn
[6]	Normal, rhonchi, wheezes, and crackles	Electrets microphone	Not mentioned	Over the lungs	An entropy based recognition system was developed
[38]	Normal, wheeze, and crackles	Electret microphone	50 school children with asthma and 10 control	Trachea	Fourier power spectrum features and neural network
[39]	Airways obstruction in asthmatic patients	Air-coupled electret microphone	10 Asthmatic	Trachea	The Welch method of spectral estimation features and <i>k</i> -nn
[40]	Normal and pathological	2 microphones (LS-60)	6 women and 11 men	Bronchial regions of the chest	Averaged power spectral density and ANN
[41]	Normal and pathological	Microphone	Not mentioned	Chest wall	AR model and <i>k</i> -nn
[42]	Wheeze or non-wheeze	Electret microphone	12 normal and 12 wheeze	Over the lungs	MFCC features and vector quantification
[43]	Normal and pathological	Electret microphone	9 normal and 11 abnormal	Left basilar and right basilar	Signal coherence and the PCA and nearest mean classifier
[44]	Normal and wheeze	Electret microphone	12 wheeze and 12 normal	Over the lungs	Wavelet transform and GMM
[4]	Normal, wheeze, crackle, squawk, stridor, rhonchus	Electret microphone	Not mentioned	Over the lungs	Discrete wavelet transform and ANN
[45]	Lung sounds	Acoustic analysis sensor Siemens EMT 25C	8 children	Over the lungs	Statistical features and <i>k</i> -nn
[46]	Normal and wheeze	ECM, KEC-2738 Electret microphones	12 Non-smoking asthmatic wheeze and 4 normal	Thorax	Spectrogram
[33]	Normal, wheeze, and crackles	Electret microphone (EK-3024 Knowles)	129 Subjects	Chest wall	Power spectral density and ANN and GA based ANN
[47]	Normal and abnormal lung sounds	Microphone array of 5x5	19 subjects	Various positions over the lungs	Multivariate AR model features, PCA and FFNN
[9]	Normal and wheeze	ECM, KEC-2738 Electret microphones	90- wheeze and 99-normal	Thorax	Spectrogram and peak detection algorithm
[48]	Fine and coarse crackles	Electret microphone	Not mentioned	Over the lungs	Wavelet packet filter, Fractal dimension and GMM
[49]	Lung sounds	Lung sound auscultation training via CD	Not mentioned	Over the lungs	Power spectral density and <i>k</i> -means clustering algorithm
[50]	Normal and abnormal lung sounds	Electret microphone (ECM140, Sony)	21 normal and 21 abnormal	Chest wall/lower lung lobes	AR model, <i>k</i> -nn and minimum distance classifier
[51]	Normal respiratory and abnormal respiratory sounds	Piezoelectric microphone and condenser microphone	109 patients with emphysema pulmonoma and 53 normal	Chest wall and posterior chest wall	Maximum likelihood approach and HMM
[52]	Adventitious lung sounds	Electronic stethoscope	Not mentioned	Chest wall	Power spectrum features and ANN
[53]	Wheeze	R.A.L.E database	Not mentioned	Over the lungs	Processed spectrogram image features and ANN
[54]	Normal and adventitious lung sounds	R.A.L.E database	Not mentioned	Over the lungs	Discrete wavelet and Radial basis function ANN
[55]	Normal, wheeze, and crackles	Electret microphone	12- normal, 13- wheeze and 11 crackles	Over the lungs	MFCC and AR model
[56]	Normal, crackles, and wheeze	Electret microphone	Over 50 lung sounds	Over the lungs	MFCC and GMM
[57]	Normal, wheeze, and crackles	Electret microphone	279 sounds	Over the lungs	Fast Fourier transform, Power spectrum density and ANN
[58]	Asthma severity	Lab data's	28 asthmatic patients	Over the lungs	Features were extracted and fuzzy rules

(Contd...)

Table 4: Contd...

Reference	Analyzed: Sound/ Disorder	Sensor type	Dataset	Sensor: Position/ Location	Method
[59]	Snore and non-Snore	2 ECM-77B microphone	20 patients	Treachea and the other hung in air over the head	Sub- band energy feature, principal component analysis and K-means clustering algorithm
[60]	Normal, pneumonia, and asthma	E-ScopeII sensor	Not mentioned	Over the lungs	AR model bispectrum estimation
[61]	Normal and abnormal lung sound	25 Electrets microphones	Normal (6 women and 2 men) and pathological (13 women and 6 men)	Posterior thoracic surface	Univariate autoregressive, multivariate autoregressive models and FFNN
[62]	Normal and pulmonary emphysema	Piezoelectric microphone	129 with pulmonary emphysema and 39 normal	Second Intercostals space	Acoustical spectral features, HMM and bigram model
[63]	Healthy and pathological	Electret microphone	7 Normal and 14 Pathological, From different Lung sound CD	Over the lungs	Time- frequency analysis and $k$ -nn

## 6. Recommendation

Some of the recommendations observed during our literature review are discussed in this section. The recommendations while developing a computer-based respiratory sound analysis system are as follows.

- Type of sensor:* There are a few types of sensors used in computer-based respiratory sound analysis and a comparison was done by Kraman in 2006 [67] on the various sensors used. In most cases, Electret microphones or contact microphone mounted on a stethoscope was used. The most important consideration in choosing the type of sensor is based on its ability to acquire a wide frequency range (150 to 2,000 Hz) for respiratory sound analysis.
- Position of the sensor:* There are certain standards such as CORSA (computerized respiratory sound analysis) [7] and RALE (respiratory acoustics laboratory environment) [68] followed by previous researcher to position the sensor. The data collection procedures are also given by CORSA and RALE.
- Filtering the heart sound and other artifacts:* The heart sound dominant frequency range is less than 150 Hz, whereas the respiratory sounds dominant frequency range are above 150 Hz and below 2,000 Hz [69]. Designing a band pass filter would be sufficient for removing the heart sound from the respiratory sound. An in-depth idea on filtering other artifacts from the respiratory sounds has been presented in the work of Sankar [70].
- Advanced signal processing techniques are yet to be applied in the research on computer-based respiratory sound analysis. The previous works have concentrated more on time and frequency domain analysis. There are very few works concentrating on time-frequency domain analysis.
- Artificial Intelligence techniques such as ANN, GMM, HMM,  $k$ -nn, and fuzzy logic have been

used by previous researchers. Artificial intelligence techniques such as support vector machine (SVM), genetic algorithm (GA), and optimization technique such as particle swarm optimization (PSO) have not been used in computer-based respiratory sound analysis till date. The use of hybrid models would also improve the classification. These Artificial Intelligence techniques may give improved results compared to previous methods and it is recommended to apply such algorithms in future researches.

## 7. Conclusion

The literature review found 55 articles that met the requirements for this review process. A brief overview on the previous research on computer-based respiratory sound analysis was provided. The overview provides up-to-date information regarding computer-based respiratory sound analysis and the various methods used in computer-based respiratory sound analysis. The research on respiratory sound analysis was divided into three categories and briefly explained. The recommendations for developing a computer-based respiratory sound analysis system were presented. This review provides enough evidence for computer-based respiratory sound analysis and its potential to improve the diagnostic values of respiratory disorders in both clinical and research settings. The research on computer-based respiratory sound analysis has come a long way, but the interest in commercialization is very low. Even though the research on computer-based respiratory sound analysis has been carried out for the past three decades, there is still a need for improvement in the existing systems. The future research should be focused on developing such systems with advanced signal processing and artificial intelligence techniques in real time and also to commercialize it.

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