

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].

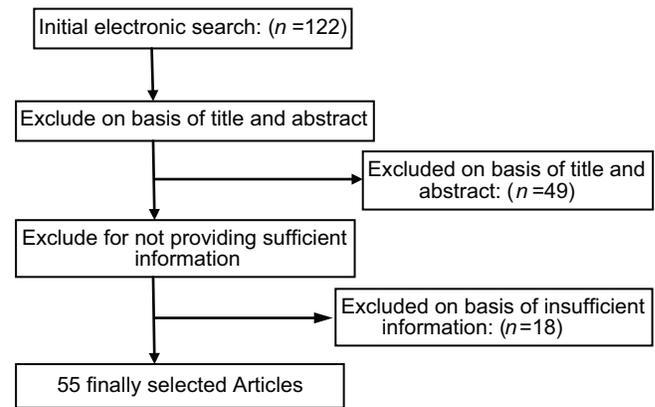


Figure 1: Flow chart for selection criteria.

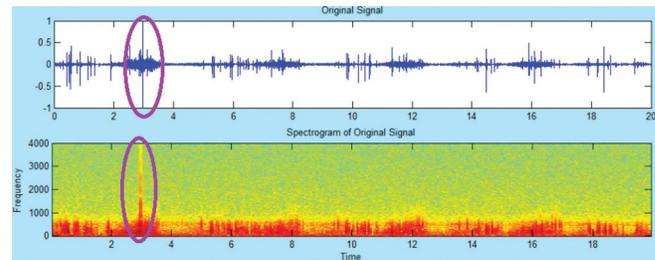


Figure 2: Visual analysis.

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 <i>k</i> -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.

- (a) *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.
- (b) *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.
- (c) *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].
- (d) 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.
- (e) 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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