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Audio-visual Recognition of Auscultatory Breathing Sounds using Fourier and Wavelet Analyses

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ABSTRACT— ***The era of computer management of clinical data demands the establishment of new techniques to analyze auscultatory sounds that can be better understood by both physicians and patients. This paper describes visual-based recognition techniques of breath sounds using two spectrograms created using short term FFT and wavelet analyses. Changes of frequency, intensity, and tone with time of breath sounds (21 samples) were shown using spectrograms of two kinds. Consequently, abnormal breath sounds were simply detected by differences of those patterns at first sight. They assist the recognition of the associated condition of disease. We expect to become a diagnostic support system in the near future.***

Keywords— Breath sound, Visualization, Image analysis, STFFT, Wavelet

1. INTRODUCTION

The invention of the stethoscope by René Laennec supported auscultation, a practical new method of bedside examination [1]. Auscultation is performed to examine the circulatory, respiratory, and gastrointestinal systems. However, this subjective method depends on long clinical experience, good listening skills, and auditory perception to differentiate sound patterns.

As shown in Table 1, breathing sounds are divisible into two categories according to their acoustic characteristics: normal and abnormal (adventitious). Abnormal sounds are either continuous or discontinuous sounds depending on their duration. Continuous sounds are further subdivided into wheezes and rhonchus. Discontinuous sounds are similarly divided into fine crackle and coarse crackle. In other words, abnormal breathing sounds are additional sounds that are heard over normal breathing sounds. Consequently, the main task is recognition of those abnormal sounds.

The shared bands between audible sounds and auscultatory sounds are extremely narrow, with low pressure with negative decibels, as presented in Fig. 1 (the tracheal and vesicular sounds shown are, respectively, those of Fig. 3 and Fig. 8). Therefore, some difficulties exist in relation to appreciate abnormal breathing sounds even with the stethoscope because the sensitivity of the human ear in detecting lower frequency and pressure of sound is poor. Therefore, special attention must be devoted to changes in frequency and sound pressure over time. One solution is to make sound visible as a pattern image. Many newer imaging techniques have been tried for the evaluation of breathing sounds. Kandaswamy et al. reported [2] the classification of breathing sounds using an artificial neural network with wavelet transform into six categories: normal, wheeze, crackle, squawk, stridor, or rhonchus and Göğüş et al. [3] classified to diagnose asthma using both discrete wavelet transform (DWT) and wavelet packet transform (WPT). Styliani et al. reported [4, 5] on the nonlinear analysis method of wheezes using wavelet bicoherence, and described the nonlinearities of wheezes with time. Gurung et al. [6] performed a systematic review on computerized lung sound analysis (CLSA) to aid in the detection of abnormal lung sounds for specific respiratory disorders. Many reports describe pattern recognition of the wheeze class [7], an integrated automated system for crackles recognition [8], signal analysis using FFT [9], and wavelets [10].

However most are reports about mathematical procedures and away from viewpoint of image recognition. Consequently, it is necessary to prepare visual-based evidence of auscultatory sound from practical viewpoint. Therefore, we have proposed [11] a visual based recognition technique for heart sounds using both short term fast FFT and wavelet analyses. Moreover, we have validated the procedures. This report describes a visual-based recognition technique of breathing sounds using spectrograms of two kinds created using short-term FFT and wavelet analyses. To confirm that the technique has clinical applicability for spectrograms of various abnormal breathing sounds, a feasibility assessment was performed using 21 breath sounds from a textbook with a CD [12]. Results show that abnormal breath sounds can be recognized by image pattern recognition.

Table 1: Classification of breath sounds and its acoustic characteristics

Normal sounds :	
i) tracheal breath sounds	iii) bronchovesicular breath sounds
ii) bronchial breath sounds	iv) vesicular breath sounds
Abnormal (adventitious) sounds :	
· continuous sound (longer than 0.25s)	
· wheeze (over 400 Hz, with a musical tone, low or high-pitched)	high / low frequency
· rhonchus (less 200 Hz)	low: dry whistlelike noise , resemble snoring
· discontinuous sound (less than 0.25s)	
· crackle	
fine crackle (≈1000 Hz)	high frequency : crepitation
coarse crackle (<500 Hz)	low frequency : bubbling rale
· other (miscellaneous sound)	
pleural friction rub	low : sound like walking on fresh snow

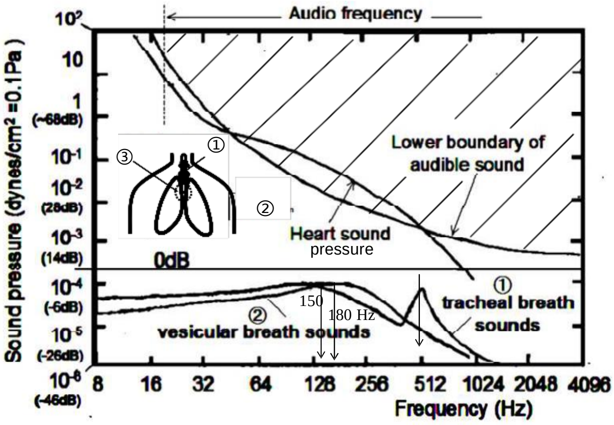

Figure 1: Graph showing frequency bands of audible and breath sounds: very low sound pressure with negative decibels. Curves (1 and 2) were plotted based on an earlier report [10].

2. METHOD AND SPECIMENS

Organs of the respiratory system include the airway (nose, pharynx, larynx, trachea, and bronchial tube) and the lungs. During breathing, air flows in and out of the respiratory tree, thereby producing complicated variations of air velocity that induce laminar and/or turbulent flows and vibrations in the airway walls by location. Furthermore, diseased respiratory tissue, mucus, or pus can produce abnormal sounds such as rales (rhonchus) and a whistling sound (wheezing). Changes in frequency, intensity (soft, loud), and continuous (wheeze) or discontinuous (crackle) sounds appear.

For this study, two techniques were used for spectrography: short-term Fast Fourier transform with a Gaussian window and continuous wavelet transform (CWT) with a complex Morlet function. Those are powerful tools to analyze time-frequency characteristics at a glance, which is the same method applied to heart sounds [11].

2.1 Visualization of breathing sounds by application of short-time Fourier transform and wavelet analyses

Short-Term Fast Fourier Transform (STFFT) Analysis

The Fourier transform is computed as a fixed-length window sliding along the time axis, resulting in a two-dimensional representation of the signal. Consequently, it has a fixed resolution. The width of the windowing function relates to how long the signal is represented by spectrum. A wide window gives good frequency resolution but poor time resolution, although a narrow window gives good time resolution but poor frequency resolution. To analyze overall trends with the time of oscillation phenomenon, this is the better technique. The conditions for analysis of breath sounds are shown in Table 2, where the heart sound [11] is also shown.

Continuous Wavelet Transform (CWT) Analysis

To analyze the specific frequency of breath sounds in detail, we applied CWT analysis. In general, wavelet transformation can clarify the spectral and temporal information within the signal simultaneously [13]. This method overcomes the basic shortcoming of Fourier analysis, which is that the Fourier spectrum includes only globally averaged information, which engenders location-specific features in the signal being lost. It gives the same analysis window width for all frequencies if the scale parameter of the mother wavelet function is constant. To analyze breath sounds, a small window width is necessary for wide bands. Then, the complex Morlet function [13, 14] and a scaling parameter are applied. The relation between the frequency (F) and the center frequency (F_c) is given as

$$F = F_c / a_n, \quad \text{--- (1)}$$

where is the sampling frequency, F_c is the center frequency, and the scaling parameter a_n is given by a numerical sequence,

$$a_n = a_1 + kn(n - 1), \quad \text{--- (2)}$$

where k is an arbitrary constant and n is the time of scaling. The value supports detailed analysis at higher frequency bands than for integer values of a_n.

Figure 2 shows the relation between frequency and the scale a_n (a_1 =5, k= 0.0014 and n=100) for the breath sounds.

Table 2: Calculation conditions of STFFT and wavelet analyses for breath sounds

	Breath sound	Heart sound [11]
Mother wavelet	Complex Morlet wavelets	Complex Morlet wavelets
Sampling frequency, Hz	10000	5000
Time of scaling,, a_n : :a_1=5	5-44 (n=1 - 100)	5-150 (n=1 - 121)
Arbitrary constant, k	0.014	0.01
Analyzed frequency, Hz	70-2000	33-1000

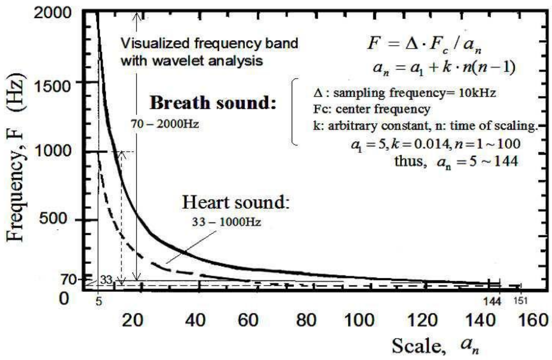

Figure 2: Relation between frequency (F) and scale a_n in Eq. 1: a =5, k = 0.014 and n_1=100.

2.2 Specimens

Normal breathing sounds are classified as tracheal, bronchial, bronchovesicular, or vesicular depending on the location of auscultation. Many types of respiratory system diseases exist such as pneumonia, pulmonary edema (PE), pleuritis sicca, bronchial asthma (BA), and so on. Therefore, breathing sounds induced by disease are complicated. To demonstrate the audio-visual based recognition technique proposed here, 21 specimens were quoted from the compact disc (CD) of the textbook [12]. As Tables 3 and 4 show, the diagnosed result and its comment were partly quoted in the discussion. In the report, two categories were divided as shown below.

A: tracheal and bronchoalveolar breath sounds, five specimens ① **and** ③

① tracheal breath sounds
② vesicular breath sounds
③ bronchoalveolar breath sounds

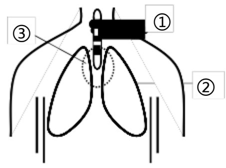

Table 3: Tracheal and bronchoalveolar breath sounds quoted from the CD [12]

No	Associated conditions	Remarks
1	Normal tracheal breath sounds	Fig. 3
2	Normal bronchovesicular breath sounds	Fig. 4
3	Bronchial stenosis, low-frequency continuous sounds	Fig. 5
4	Bronchial asthma, low-frequency continuous sounds	Fig. 6
5	Bronchial asthma, low-frequency continuous sounds (sputum retention)	Fig. 7

B: vesicular breath sounds, 16 specimens: ② **vesicular breath sounds**

Table 4: Vesicular breath sounds quoted from the CD [12]

No	**Associated conditions**	**Remarks**
1	Normal vesicular breath sounds	Fig. 8
2	Mild pulmonary fibrosis, fine discontinuous sounds	Fig. 9
3	Pulmonary fibrosis, fine discontinuous sounds	Fig. 10
4	Hypersensitivity pneumonitis, fine discontinuous sounds (recorded during slow breathing)	Fig. 11
5	Chronic articular rheumatism, fine discontinuous sounds	Fig. 12
6	Early stage heart failure (recorded during deep breathing), fine discontinuous sounds	Fig. 13
7	Bronchiectasis (secretions in the airway), coarse discontinuous sounds	Fig. 14
8	Bronchiectasis, coarse discontinuous sounds	Fig. 15
9	Mild pneumonia, coarse discontinuous sounds	Fig. 16
10	Lobar pneumonia, coarse discontinuous sounds	Fig. 17
11	Acute pulmonary edema, coarse discontinuous sounds	Fig. 18
12	Bronchial asthma, high tone continuous sounds	Fig. 19
13	Bronchial stenosis, high tone continuous sounds, wheezes monophonic	Fig. 20
14	Sinobronchial (SB) syndrome, discontinuous and continuous sounds	Fig. 21
15	Bronchiectasis (BE) with squawk	Fig. 22
16	Pleuritis sicca and dry pleurisy, pleural rub sounds (snowball crepitation)	Fig. 23

3. RESULTS AND DISCUSSION

A: tracheal and bronchoalveolar breath sounds

1) Normal tracheal breath sounds

Figure 3 shows normal breath sounds of a healthy person: a) waveform of sound, b) spectrogram by STFFT, and c) spectrogram by wavelet transform. In the present report, the STFFT image shows the whole frequency-time spectrogram. The wavelet shows the spectrogram of 70–250 Hz as a visible pattern on the nonlinear scale.

At first glance, it might seem to represent an abnormal breath sound. However, the result indicates the existence of carotid pulse (70-150 Hz with an interval of ≈0.9 s) because the stethoscope was put at the trachea near the cervical artery. Repeated images of the carotid pulse were formed of a slim and vertically long shape, as shown in Fig. 3(c). The carotid pulse is denoted by symbol "CP" and an arrow in the figure. Therefore, by ignoring the carotid pulse wave, the normal tracheal breath sounds can be understood as clear and soft sounds like air blown through a pipe.

In brief, a strong wavelet analysis tool for STFFT could be useful for identifying unrecognized sound(s).

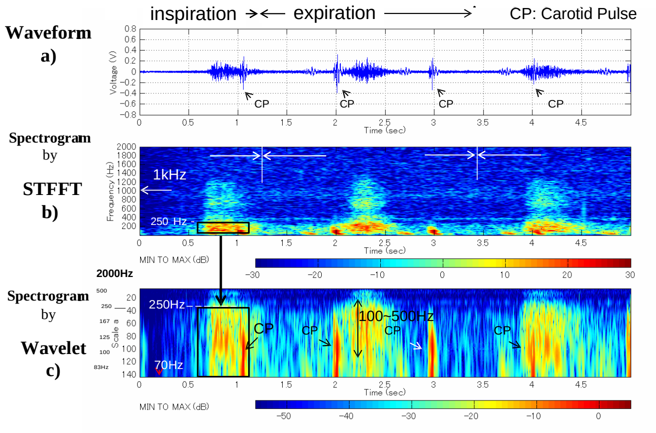

Figure 3: Normal tracheal breath sounds.

2) Normal bronchovesicular breath sounds

Figure 4 shows normal breath sounds at the posterior chest between the scapulae and in the center part of the anterior chest. The times between that during inspiration and expiration are nearly equal. Furthermore, it has middle intensity and low frequency of about 200 Hz. Next we examine the long, thin spectrogram in Fig. 4(c), where the heart sound (HS) can be found; symbol "HS" and arrows are portrayed in Fig. 4(a). By applying both STFFT and wavelet methods, one can have a short path for recognition of a plurality of sound sources.

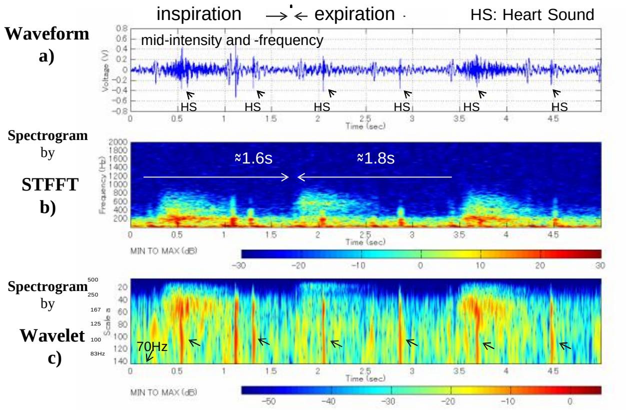

Figure 4: Normal bronchovesicular breath sounds.

3) Bronchial stenosis, low-frequency continuous stenos

Figure 5 shows the sound made by a bronchial stenosis patient. Stenosis is a disease that causes various failures in the chest cavity: some bronchial passages become narrower than usual. The sounds are continuous monophonic rhonchus [12]. Therefore, the wavelet image shows a unique shape and long expiration time with frequency of about 200 Hz, as presented in Fig. 5 c).

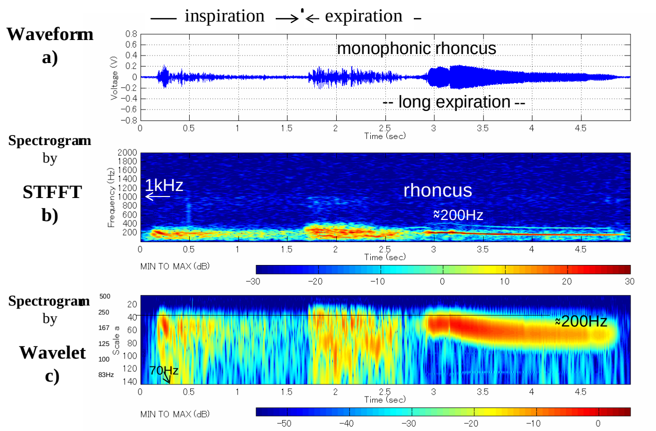

Figure 5: Bronchial stenosis, low-frequency continuous sounds.

4) Bronchial asthma, low-frequency continuous sound

Figure 6 shows sounds of a bronchial asthma patient. A symptom of the disease is that the bronchi become narrower, engendering shortness of breath and a wheezy sound from the small bronchial tubes when breathing. Results show moderate polyphonic rhonchus during the phase of inspiration and low intensity rhonchus during the phase of expiration. Furthermore, the wavelet image shows typical rhonchus by a distribution map of the disease. The difference between STFFT and wavelet images is readily apparent. Consequently, the importance of using both figures is clear.

5) Bronchial asthma, low-frequency continuous (sputum retention)

Figure 7 shows the sound of a bronchial asthma with a sputum retention patient. The result of the sound shows polyphonic and intense rhonchus of 70–200 Hz. The wavelet image shows clear variations of frequency during the phases of inspiration and expiration. It is easier to understand than the STFFT image.

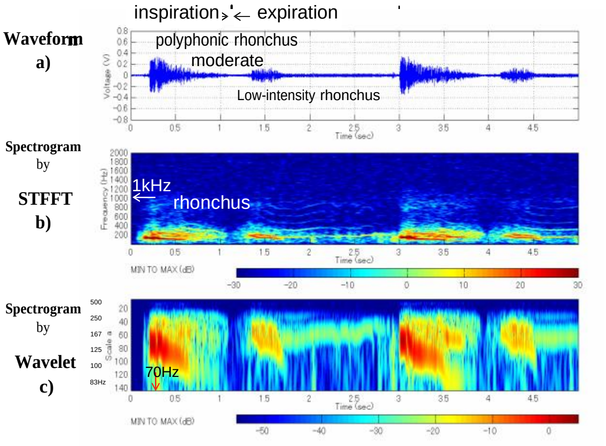

Figure 6: Bronchial asthma, low-frequency continuous sounds.

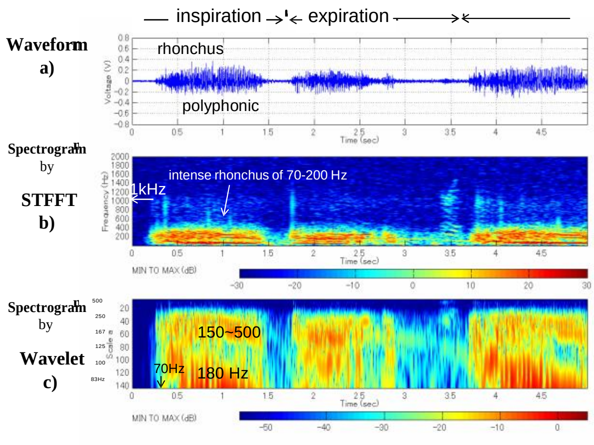

Figure 7: Bronchial asthma, low-frequency continuous sounds (sputum retention).

B: vesicular breath sounds

1) Normal vesicular breath sounds

Figure 8 shows normal breath sounds. The sound shows low-pitched quality with high intensity of about 180 Hz during the phase of inspiration and shows softer sound during the phase of expiration. In Fig. 1, the frequency differences between this vesicular breath sound and the bronchial sound (Fig. 3) are shown. The respective peak frequencies of the two sounds are about 180 Hz (monophonic sound) and 100–500 Hz (fluctuating sound). The normal vesicular breath is more of a softer whispering sound than the others.

2) Mild pulmonary fibrosis, fine discontinuous sounds

Figure 9 shows sounds obtained from a mild pulmonary fibrosis patient. The sign and symptom of the disease are rapid respiration (tachypnea) with a respiratory cycle of about 1.6 s and discontinuous sounds. Intense fine crackles are observed during the latter half of the inspiration, followed by coarse crackles during the phase of expiration. The characteristic shape of crackle sounds is a slim and vertically long shape with a frequency range of about 1000 Hz and moderate 600–1800 Hz, as shown in the STFFT and wavelet images. The color distribution shows the sound intensity. Consequently, it will be easy to differentiate fine crackle or other sounds from the viewpoint of the frequency range and its repeat variation.

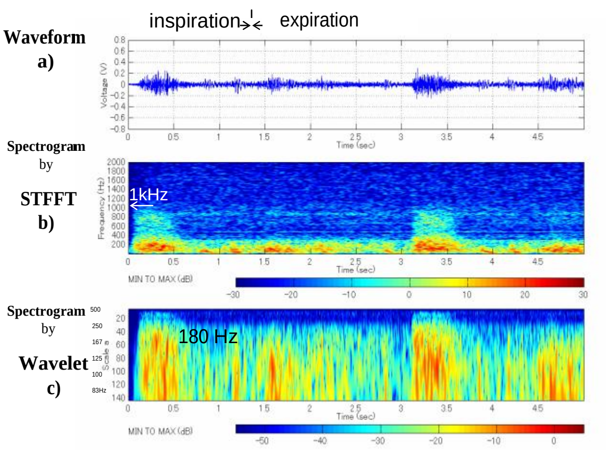

Figure 8: Normal vesicular breath sounds.

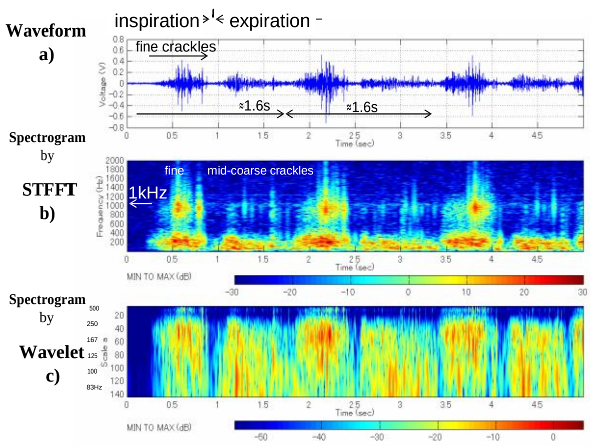

Figure 9: Mild pulmonary fibrosis, fine discontinuous sounds.

3) Pulmonary fibrosis, fine discontinuous sounds

Figure 10 shows the sound of a pulmonary fibrosis patient. The sign is rapid respiration caused by breathing difficulty; respiratory cycle of about 1.7 s. Intense fine crackle with about 1 kHz is observed during the phase of inspiration, with no crackle during the phase of expiration.

4) Hypersensitivity pneumonitis, fine discontinuous sounds (sound recorded during slow breath)

Figure 11 shows the sound recorded during slow breathing of a hypersensitivity pneumonitis patient. The disease is known to occur most often in people who work or live in places with high levels of dust. Many fine crackles (crepitant rale) with moderate intensity occurring during the phase of inspiration and discontinuous soft sounds during the phase of expiration are clearly apparent in the STFFT and wavelet images.

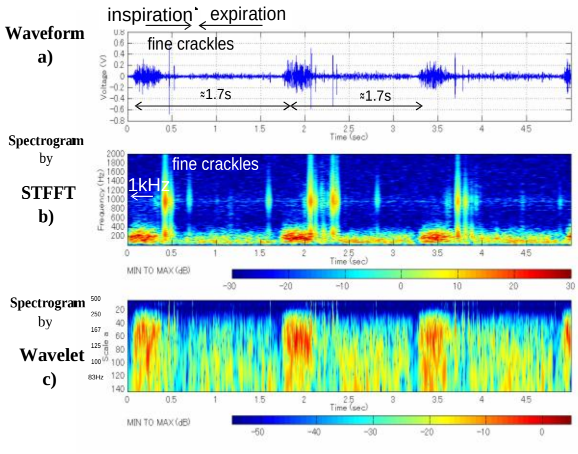

Figure 10: Pulmonary fibrosis, fine discontinuous sounds.

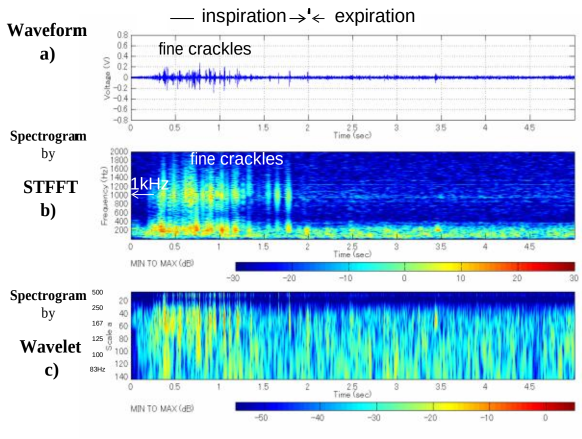

Figure 11: Hypersensitivity pneumonitis, fine discontinuous sounds (recorded during slow breathing).

5) Chronic articular rheumatism, fine discontinuous sounds

Figure 12 shows sounds of a chronic articular rheumatism patient. Very intense fine crackles during the phase of inspiration and discontinuous soft sounds during the phase of expiration are clearly apparent in the figure.

6) Early stage heart failure (recorded during deep breathing), fine discontinuous sounds

Figure 13 shows the sound of early stage heart failure (repeated deep breaths). The sounds include fine crackle also with low-frequency during the phase of inspiration. In case of fine crackle induced by elevated legs, the possibility exists of position-induced sound that suggests disease of potential heart failure and pulmonary congestion [15].

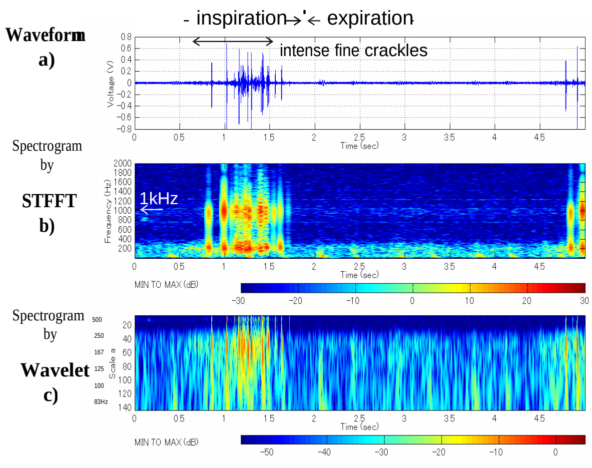

Figure 12: Chronic articular rheumatism, fine discontinuous sounds.

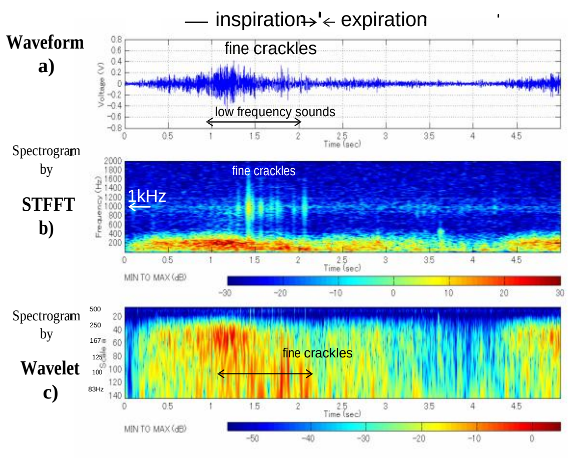

Figure 13: Early stage heart failure (recorded during deep breathing), fine discontinuous sounds.

7) Bronchiectasis (secretions in the airway), coarse discontinuous sounds

Figure 14 shows sound of a bronchiectasis (secretions in the airway) patient. Many coarse crackles are visible, followed by fewer crackles attributable to secretions remaining in the airway. The coarse crackle frequency is about 250 Hz.

8) Bronchiectasis, coarse discontinuous sounds

Figure 15 shows sounds of a bronchiectasis patient. It is apparent that many coarse crackles and then fewer crackles occur, respectively, during the phase of inspiration and the phase of expiration. Coarse crackles are a bubbling sound caused by bronchiectasis [10]. It is apparent in the figures as a discontinuous bubbling sound (coarse crackles) attributable to bronchiectasis.

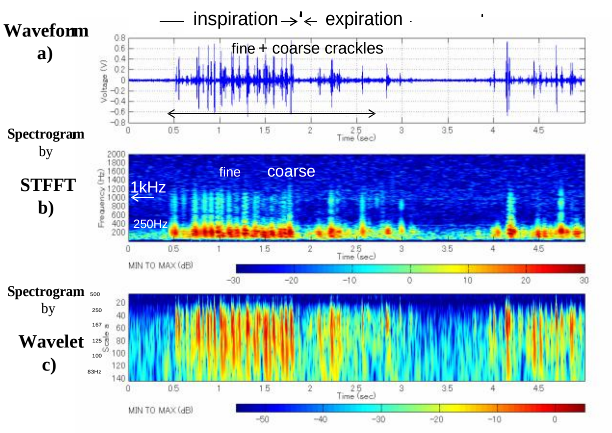

Figure 14: Bronchiectasis (secretions in the airway), coarse discontinuous sounds.

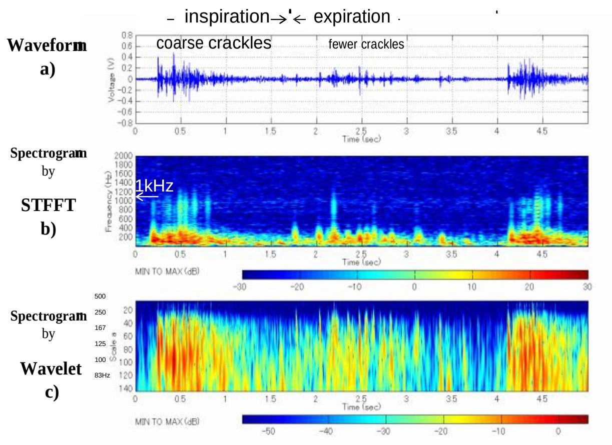

Figure 15: Bronchiectasis, coarse discontinuous sounds.

9) Mild pneumonia, coarse discontinuous sounds

Figure 16 shows sounds of a mild pneumonia patient. Some single crackle with mostly low and partly high frequencies is apparent because of mild pneumonia. There is no feature in the distribution of low-frequency sound as shown in the wavelet image.

10) Lobar pneumonia, coarse discontinuous sounds

Figure 17 shows sounds of a lobar pneumonia patient. Both intense fine and coarse crackles are apparent during the phases of inspiration and expiration. As shown in the figure, the visual-based recognition technique is useful in cases of complicated sounds.

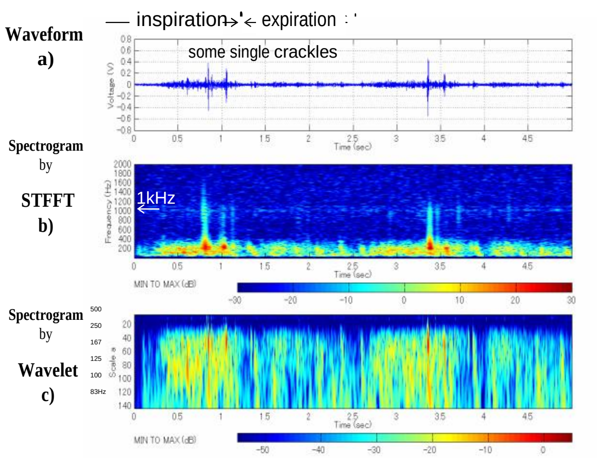

Figure 16: Mild pneumonia, coarse discontinuous sounds.

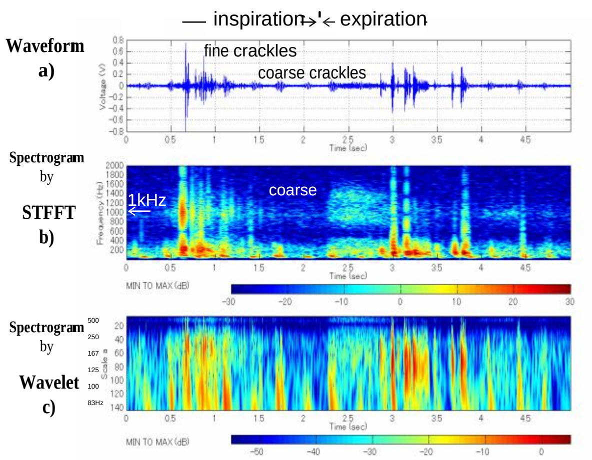

Figure 17: Lobar pneumonia, coarse discontinuous sounds.

11) Acute pulmonary edema, coarse discontinuous sounds

Figure 18 shows the sound of an acute pulmonary edema patient. Typical intense coarse crackles are apparent during the phases of inspiration and expiration. The frequency distribution of coarse crackles is apparent in the wavelet image.

12) Bronchial asthma, high tone continuous sounds

Figure 19 shows the sound of a bronchial asthma patient. High-pitched tone continuous and intensive sounds during the last half of the phase of expiration are apparent. The frequency is about 380 Hz, nearly a wheezing sound.

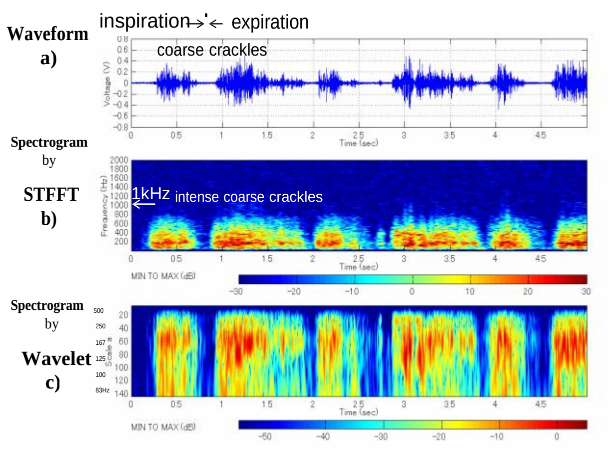

Figure 18: Acute pulmonary edema, coarse discontinuous

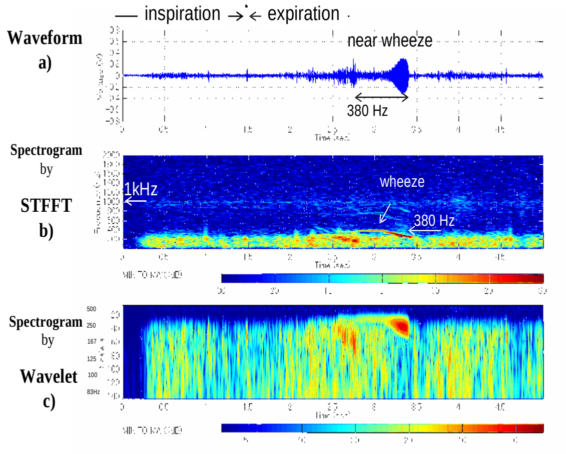

Figure 19: Bronchial asthma, high tone. continuous sounds.

13) Bronchial stenosis, high tone continuous sounds, wheezes monophonic

Figure 20 shows sounds of a bronchial stenosis patient including monophonic wheezes. It appears that crackles and long-time monophonic continuous sounds (wheeze) of about 800 Hz is apparent during the phase of expiration, as shown in the STFFT image.

14) Sinobronchial (SB) syndrome, discontinuous and continuous sounds

Figure 21 shows the sound of a sinobronchitis syndrome patient. It appears as intense fine crackles and wheeze during the phase of inspiration, and fine, coarse crackles and polyphonic continuous during the phase of expiration. A spectrogram of wheezing is shown as a typical stripe image in the STFFT and wavelet results.

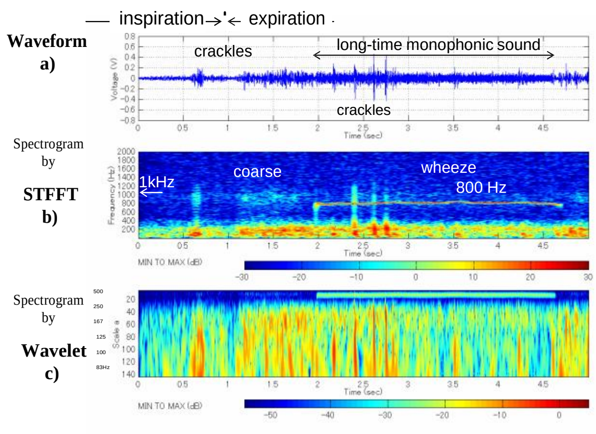

Figure 20: Bronchial stenosis, high tone continuous sounds, wheezes monophonic.

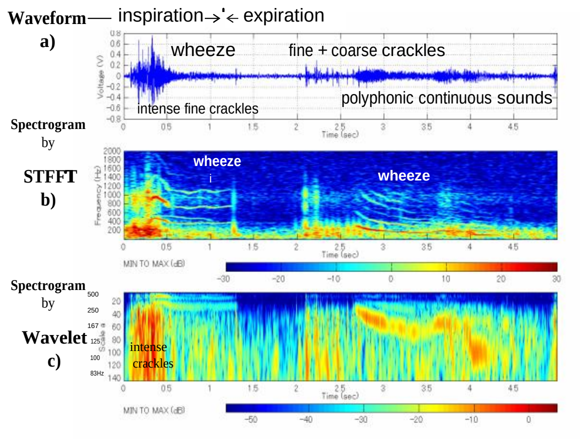

Figure 21: Sinobronchial (SB) syndrome, discontinuous and continuous sounds.

15) Bronchiectasis (BE) with squawk

Figure 22 shows the sound of a bronchiectasis patient. It appears monophonic or polyphonic squawk (wheeze) with both low-frequency and high-frequency sounds after discontinuous coarse crackles [10]. The STFFT image allows clear recognition of these sorts of sounds.

16) Pleuritis sicca and dry pleurisy, pleural rub sound (snowball crepitation)

Figure 23 shows sounds of pleuritis sicca and a dry pleurisy patient. It shows typical sounds occurring by rubbing of the parietal pleura, intense crepitation (low and high frequencies) during inspiration and discontinuous sounds (about 250 Hz) during expiration. Associated conditions are pleuritis, pneumonia, and pulmonary embolism.

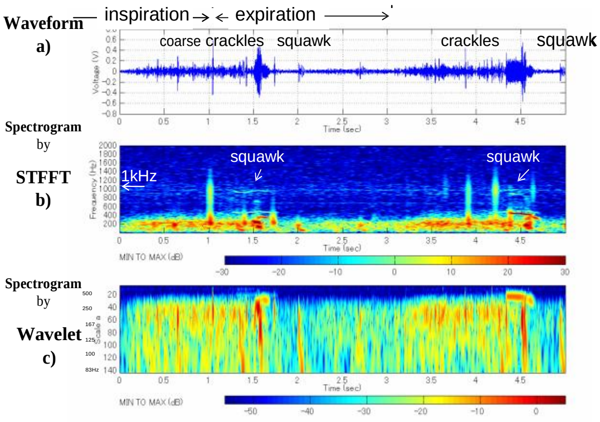

Figure 22: Bronchiectasis (BE) with squawk.

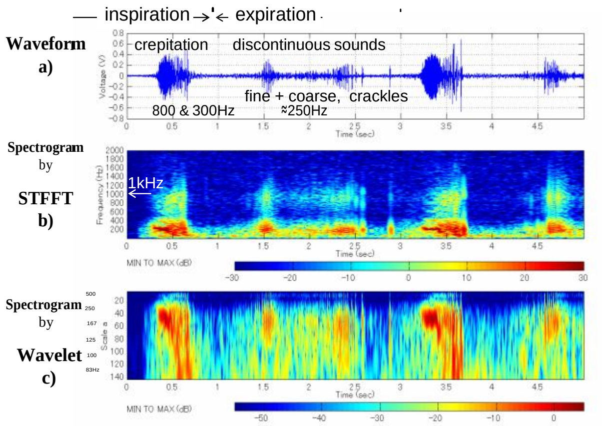

Figure 23: Pleuritis sicca and dry pleurisy, pleural rub sounds (snowball crepitation).

C: A characteristic classification of breath sounds

As the figures presented above show, auscultatory breath sounds are extremely complicated. Figure 24 shows the typical characteristic of abnormal sounds classified according to image pattern. It was selected from the viewpoint of acoustic properties shown in Table 1. These image patterns are expected to become useful evidence for both physicians and patients. Therefore, we are able to classify different kinds of lung diseases by referring to these patterns.

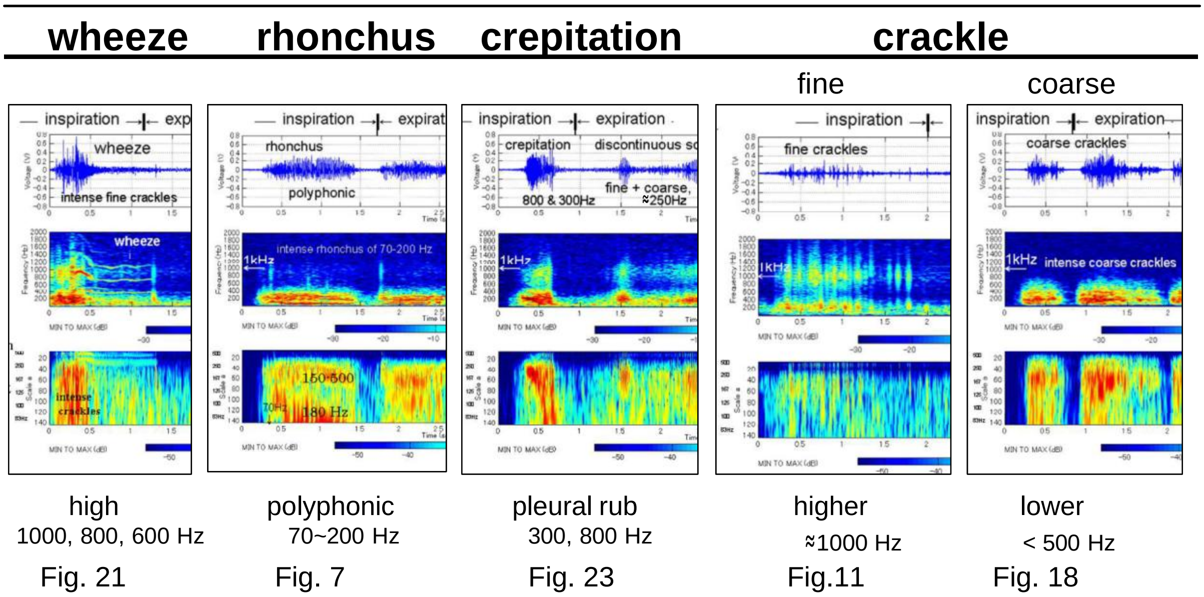

Figure 24: Typical characteristic classification of abnormal sounds as image pattern recognition

4. CONCLUDING REMARKS

Because various difficulties are associated with auscultation, we proposed an audio-visual based recognition method to assist in the evaluation of breath sounds. For this study, we used a compact disc with recorded clear breathing sounds for educational medical training to confirm that the technique has clinical applicability showing spectrograms for various abnormal breath sounds. The feasibility assessment was performed using 21 breath sounds of the textbook [10].

1) Images of both types created by Fourier and wavelet analyses provided useful tools to recognize causes of abnormal sounds. The STFFT images in this study showed a global frequency band. The wavelet image showed specific frequency of the sounds between 70–2000 Hz on a nonlinear scale. In the visible image of the distribution, frequencies of 70–250 Hz are readily apparent: it was focused on the low-frequency band depending upon the coefficients of Table 2.

2) The created image patterns are expected to be helpful to detect differences and classification of abnormal breathing sounds such as wheeze, rhonchus, crepitation, and crackles. It might be possible to develop a detection system to assist in the diagnosis of associated conditions of the diseases.

In clinical applications, it is also necessary to examine the accuracy, sensitivity, specificity, precision, time process and other performance parameters of this technique using many other subjects because actual breathing sounds include various noises and individual differences.

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