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Research Paper

Transmission Perspective on the Mechanism of Coarse and Fine Crackle Sounds

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The possibility of a normal distribution indicates that few particles are in the same phase during a breath and their reflections can be observed on the chest wall, then a few explosive waves with relatively large power occurr occasionally. Therefore, the one-cycle sine wave which is simulated as a single burst of the explosive effect phenomenon penetrates through the chest wall and was analysed to explore the reason of the crackle sounds. The results explain the differences between the definitions of crackle proposed by Sovijärvi *et al.* (2000a). The crackles in the lungs were synthesised by a computer simulation. When the coarse crackles occur, the results indicate that higher burst frequency carriers (greater than 100 Hz) directly penetrate the bandpass filter to simulate the chest wall. The simulated coarse crackle sounds were low pitched, with a high amplitude and long duration. The total duration was greater than 10 ms. However, for a lower frequency carrier (approximately 50 Hz), the fundamental frequency component was filtered out. Therefore, the second harmonic component of the lower frequency carrier, i.e., the fine crackle, penetrated the chest wall. Consequently, it is very possible that the normal lung sounds may contain many crackle-shaped waves with very small amplitudes because of the filtering effects of the chest wall, environment noises, electric devices, stethoscopes, and human ears, the small crackles disappear in the auscultations. In addition, our study pointed out that some unknown crackles of the very low frequency under the bandwidth of the human ears cannot penetrate the airways and be detected by medical doctors. Therefore, it might be necessary to focus advanced electronic instrumentation on them in order to analyse their possible characteristics for diagnosis and treatment of the respiration system.

Keywords: crackles; computer simulation; lung sound; respiration; amplitude modulation; frequency modulation.

1. Introduction

Proper auscultation by medical doctors is crucial for diagnosing the of respiration system diseases such as pneumonia and fibrosis which contain the sounds of coarse and fine crackles. Moreover, wheezes and crackles in auscultation may indicate asthma or heart failure. Experienced medical doctors often detect the sounds of crackles to evaluate the profile of the airway. A crackle is an adventitious, discontinuous, explosive sound generally occurring during inspiration (Sovijärvi *et al.*, 2000a). Melbye *et al.* (2016) revealed that the number of crackles occurring during inspiration was greater than that occurring during expiration. However, they indicated that some crackles can also be found during expiration (Vyshedskiy *et al.*, 2009). Murphy *et al.* (1977) and Hoevers and Loudon (1990) investigated the measurement of crackles. Sovijärvi *et al.* (2000a) defined a coarse crackle as "A crackle that is low pitched and with a high amplitude and long duration. Its total duration (two-cycle duration (2CD)) is > 10 ms". They defined a fine crackle as "A crackle that has a high pitch, low amplitude and short duration. Its total duration (2CD) is < 10 ms". Most studies on relative breath sounds followed these definitions to determine if the crackles were coarse or fine because these definitions were reported by the issue of "Standardization of computerized respiratory sound analysis (CORSA)" (Sovijärvi *et al.*, 2000b), which offers many golden standards for studying the lung sounds. However, the higher pitched lung sounds frequently occur at the narrowing of the airway with conditions such as benign tracheal stenosis and cracles. Therefore, the detection of the higher frequency components is noteable in most of the auscultations by medical doctors. Cheetham *et al.* (2000) indicated that some acoustic signals beyond 4 kHz and even beyond 10 kHz such as crackle, cough, snore and speech-like sounds certainly contain significant energy.

Murphy *et al.* (1989) attempted to count the number of crackles using a computer. Thereafter, several studies investigated the automatic recognition of crackles. For example, Charbonneau *et al.* (2000) employed a temporal analysis to detect crackles. Cohen and Landsberg (1984) used the fast Fourier transform (FFT) and a linear prediction of coefficients to analyse crackles and designed a fuzzy non-stationary filter for their enhancement. Güler *et al.* (2005) developed genetic algorithms for application in neural networks to detect crackles. Hadjileontiadis and Rekanos (2003) and Du *et al.* (1997) used the wavelet analysis to recognise crackles.

The aforementioned methods provide significant data and lung sound characteristics. A previous study (Lu *et al.*, 2011) presented the computer synthesis of lung sounds using inverting analysis processes. The crackles that were synthesised based on communication theory included the following components:

1) a flow source as a transmitter,
2) frequency and amplitude-modulated (FM–AM) sounds,
3) accompanying noise as a modulator,
4) an airway wall medium, and
5) a microphone as a receiver.

The main contribution is to demonstrate that the wheeze is contained in the domain frequency at 400 Hz. However, some of the studies have suggested that this range is between 80–1600 Hz and 350–950 Hz. Therefore, we modified the model to simulate the sounds of crackles.

The lung sound has been analysed by physiologic and engineering observations. The turbulence is the main mechanism of breath sound production. However, the generation of crackles has been explored by many research groups. Munakata *et al.* (1986) investigated on the normal canine lungs and focused on the crackle generated by the opening of the small airways. Ploysongsang and Schonfeld (1982) examined 5 normal volunteers for the generation of crackles. The effects of shallow breathing of air (LVB-air) and oxygen (LVB-O2) at low lung volumes (below closing capacity) and tidal breathing at FRC (FRC-air, FRC-O2) have been investigated, and the results reinforced that generation of the crackles was caused by the inflation of atelectasis lung. The results of these studies supplied the valuable information of the original crackle sound in the airway in the computer simulation of the lung sounds.

Nowadays, artificial intelligence (AI) is applied to research in various fields such as signal processing (Hidaka *et al.*, 2019; Kido *et al.*, 2019; Eren *et al.*, 2019) and image processing (Heslinga *et al.*, 2019; Mukherjee *et al.*, 2019; Liu *et al.*, 2019). Jácome *et al.* (2019) investigated the detection of respiration phases by a convolutional network (CNN). Zhang *et al.* (2015) used the morphological features of crackles in spectrograms using a wavelet analysis to detect the crackles automatically. Certain criteria based on the morphology have been determined to identify crackles. Dubey and Bodade (2019) reviewed classification techniques based on neural networks for pulmonary obstructive diseases and indicated that the CNN technique is commonly applied to classify respiratory sounds in recent times. Chen *et al.* (2019) combined the S-transform and deep learning (DL) techniques to classify lung sounds. Rizal *et al.* (2006; 2017a; 2017b) and Rizal and Suryani (2008) published several papers related to lung sounds. Their methods are used as modern solutions for classifications. CNN and DL techniques require big data for training parameters of neuron network functions. However, clinical practices which collect lung sounds for classification are difficult and complex. The auscultation processes are complex and reviewing the clinical trial documents is time consuming. However, if the communication model proposed in this paper can be enhanced in future studies, the computer synthesised lung sounds will be a valuable resource.

This article is organised as follows: the definitions of crackle and a review of important previous studies are presented in Sec. 1; the synthesis process and the equipment used are described in Sec. 2; the waveforms and spectrograms of the synthesised crackles are presented in Sec. 3; the dominant carrier frequencies causing coarse or fine crackles are explained in Sec. 4; the findings of the study are summarised in Sec. 5; and a website where the readers can review the crackles synthesised in this study is presented in the Appendix.

2. Methods

The crackle sounds were generated using Matlab (R2016a, MathWorks, USA). The following steps were followed:

1) simulation of a respiration signal using an approaching saw tooth wave;
2) AM-FM modulation;
3) addition of noises and pulses of crackle sources;
4) Butterworth filter;
5) the output in wave, audio signal, and spectrogram.

Melbye *et al.* (2016) indicated that some crackles can also be found during expiration. Their study revealed that the number of crackle occurrences during inspiration was greater than those during expiration. Therefore, the possibility settings of the crackle occurrences are quite different between the duration of inspiration and expiration in this study. A block diagram of the simulated communication model for crackles is presented in Fig. 1.

Fig. 1. Flow chart of the simulation processes for the communication model of crackles.

2.1. Simulation of respiration signal using the approaching saw tooth wave

2.1.1. Saw tooth wave approach

The respiration model employed the fifth-order harmonics to approach a saw tooth wave, the mathematical expression of which was given as

$$x_s(t) = \frac{1}{\pi}\sum_{k=1}^{5}\frac{1}{k}\sin\left(2\pi k f_{br} t\right), \tag{1}$$

where x_s denotes the pressure signal of expiration and inspiration; k is the order of x_s harmonics; f_{br} is the fundamental frequency of the saw tooth wave based on the expiration and inspiration pressure signal; and t denotes the time. In this study, the signal was synthesised using a sampling frequency of 44 100 Hz.

2.1.2. Burst

The possibility of the normal distribution indicated that few particles are in the same phase and their reflections can be observed on the chest wall. Therefore, a few explosive waves with relatively large power occurred occasionally. The pressure spikes and the avalanche dynamic model of Alencar *et al.* study (2001) were simulated as the 1-cycle sine wave burst train in the communication system model in our study.

The bursts were generated by random numbers denoted as $r_p(t)$ whose range is between 0 and 1. A single cycle sine wave burst occurs under the following conditions:

In expiration, $p(t) = 0$. If $r_p(t_p) > th_1$, then

$$p(t) = A_p \sin(2\pi f_c(t - t_p)) \qquad t_p \le t \le t_p + T_c. \tag{2}$$

In inspiration, $p(t) = 0$. If $r_p(t_p) > th_2$, then

$$p(t) = A_p \sin(2\pi f_c(t - t_p)) \qquad t_p \le t \le t_p + T_c, \tag{3}$$

where $p(t)$ was the 1-cycle sine wave burst train for crackles. $T_C = 1/f_c$ was the period of the 1-cycle sine wave. The burst was a 1-cycle sine wave whose frequency was the same as the fundamental frequency of the carrier of the modulation in the wall and tissues of the airway. A_p represented the amplitude of the burst whose value was 1.2. The threshold in the period of expiration, th_1, was 0.65 while that in the period of inspiration, th_2, was 0.95.

2.2. Sound source of breathing with crackling and noise

Based on the theory of signals and systems, the original sound source of a breath with crackles and noises in the airway can be linearly added as

$$x_{cs}(t) = A_1 x_s(t) + A_2 p(t) + A_3 n_{cs}(t), \tag{4}$$

where $x_{cs}(t)$ denoted the sound source of the breath with crackle and noise and A_1 was the amplitude of $x_s(t)$. A_2 was the amplitude of $p(t)$, i.e., the pulse train. A_3 was the amplitude of the noises in the airway ($n_{cs}(t)$).

2.3. Modulation

The movement of air particles in the airway follows the wave equation of fluid dynamics. Grotberg and Gavriely (1989) developed a theoretical model for wheezes. However, lung sounds are mainly produced by the collisions, i.e. the air particles impacted on the chest wall, but not the collisions of the air flow in the airway. Therefore, the synthesis of lung sounds should focus on the collision sounds in the airway. A communication model revealed the importance of the macro perspective of sound propagations when determining the characteristics of wheezes (Lu *et al.*, 2011). The model was developed by a combination of amplitude modulation (AM) and frequency modulation (FM).

2.3.1. Amplitude modulation

In AM, the voltage level of the signal to be transmitted changes the amplitude of the carrier proportionately. The baseband signal $x(t)$ is modulated on a square wave whose fundamental frequency is f_c (Lu *et al.*, 2011). Therefore,

$$y_{am}(t) = \sum_{k=1,3,5,\ldots}^{11} Ac_k\left\{1 + x(t)\right\}\cos\left(2\pi k f c t\right), \tag{5}$$

where Ac_k are the amplitudes of harmonics in the square wave carrier. Based on Fourier series, we have

$$Ac_k = \frac{8(-1)^{\frac{k-1}{2}}}{\pi^2 k^2}, \tag{6}$$

where $k = 1, 3, 5, \ldots, 11$.

2.3.2. Frequency modulation

FM uses the instantaneous frequency of a modulating signal (voice, music, data, etc.) to directly vary the frequency of a carrier signal. The modulation index, β, is used to describe the ratio of maximum frequency deviation of the carrier to that of the modulating signal (Lu *et al.*, 2011). According to the FM theory, we have

$$y_{fm} = Bc_k \cos\left(2\pi k f_c t + \beta \sin(2\pi f_m t)\right), \tag{7}$$

where $Bc_k = Ac_k$, which are the amplitudes of harmonics in a square wave carrier. In this study, $\beta = 0.1$.

2.3.3. Mixed AM and FM

The normal respiration sounds present that the sound is louder, the tone is higher. Therefore, the pressure signal of inspiration and expiration was modulated by AM and FM as follows:

$$y_m = \sigma_{am} y_{am} + \sigma_{fm} y_{fm}, \tag{8}$$

where σ_{am} and σ_{fm} are the coefficients of the intensity of AM and FM, respectively. In this study, $\sigma_{am} = 3$ and $\sigma_{fm} = 0.15$.

2.4. Noise and burst

Noise is produced by the environment, electronic devices, collisions in the airway, inter-fraction of tissues near the airway, and so on. The summation of noises was denoted as $n_s(t)$. Therefore,

$$y_n(t) = y(t) + n_s(t) + 10p(t), \tag{9}$$

where $y_n(t)$ was the modulated signal with noises.

2.5. Filter

Bertram (2008) found that low frequency oscillations produced a sound of the range of 50–350 Hz in a long downstream pipe. This frequency range was similar to the transfer function of model acceleration at the tracheal that was proposed by Wodicka *et al.* (1989), i.e. 100 to 600 Hz. In this study, a fourth-order Butterworth bandpass filter was employed. Its range was 100 to 660 Hz to match the model which was proposed by Wodicka *et al.* (1989) and Korenbaum *et al.* (2016). For an analogue filter, the transfer function is expressed in terms of $B(s)$ and $A(s)$ as

$$H(s) = \frac{B(s)}{A(s)} = \frac{\sum_{r=0}^{8} b_r s^{8-r}}{\sum_{r=0}^{8} a_r s^{8-r}}, \tag{10}$$

$$b_r = [0.1606 \quad 0 \quad -0.6425 \quad 0 \quad 0.9637 \quad 0 \quad -0.6425 \quad 0 \quad 0.1606] \cdot 10^{-5}, \tag{11}$$

$$a_r = [1.0000 \quad -7.8017 \quad 26.6388 \quad -51.9950 \quad 63.4524 \quad -49.5764 \quad 24.2182 \quad -6.7629 \quad 0.8265], \tag{12}$$

where r is the index of the coefficients of a_r and b_r.

2.6. Output

In the frequency domain, the output of the filtering was described as

$$Y(s) = Y_n(s) H(s), \tag{13}$$

where $Y_n(s)$ was the Fourier transform of $y_n(t)$. Furthermore, $Y(s)$ was the output of the simulation in the frequency domain.

An inverse Fourier transform was employed to obtain $Y(s)$ in the time domain. Therefore,

$$y(t) = \frac{1}{2\pi} F^{-1}\{Y(s)\}. \tag{14}$$

2.7. Criteria for the recognition of crackles

The criteria for the recognition of crackles to verify the simulation results of the synthesised signals were based on the definition by Sovijärvi *et al.* (2000a). A coarse crackle is defined as "A crackle that is low pitched and with a high amplitude and long duration. Its total duration (two-cycle duration (2CD)) is > 10 ms". A fine crackle is defined as "A crackle that has a high pitch, low amplitude and short duration. Its total duration (2CD) is < 10 ms".

2.8. Equipment

The simulation was compiled in MATLAB R2016a (MathWorks, USA) development environment. A laptop PC (ACER Aspire V Nitro, Taiwan, ROC) with Intel CPU Core i7-4720HQ, NVIDIA GPU GeForce GTX 960M (4 GB GDDR5) with a 16 GB DDR4 memory, was used. The operating system was Microsoft Windows 8.1.

2.9. Tests

A test for a square wave carrier of variable frequency was designed to verify and explain the physical phenomena. Carrier frequencies of 50, 100, and 150 Hz have been employed for computer simulation.

3. Results

The normalised frequency response of the fourth-order Butterworth bandpass filter is shown in Fig. 2. The passband is in the range from 150 to 660 Hz.

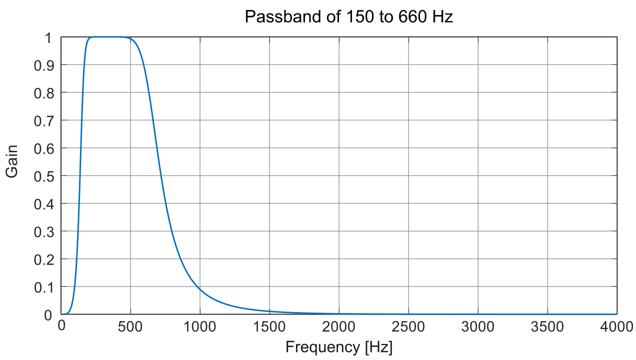

Fig. 2. Normalised frequency response of the fourth-order Butterworth bandpass filter.

To investigate the instant response of crackles whose frequency of square wave carrier = 50 Hz, we focused on the lung sounds between 10 to 10.2 s in Fig. 3. There were two bursts in Fig. 3a. These bursts induced two crackles which were shown in Fig. 3b. The first crackle whose IDW = 1 ms and 2CD = 4 ms, occurred at 10.101 s. The second crackle whose IDW = 1 ms, and 2CD = 3 ms, occurred at

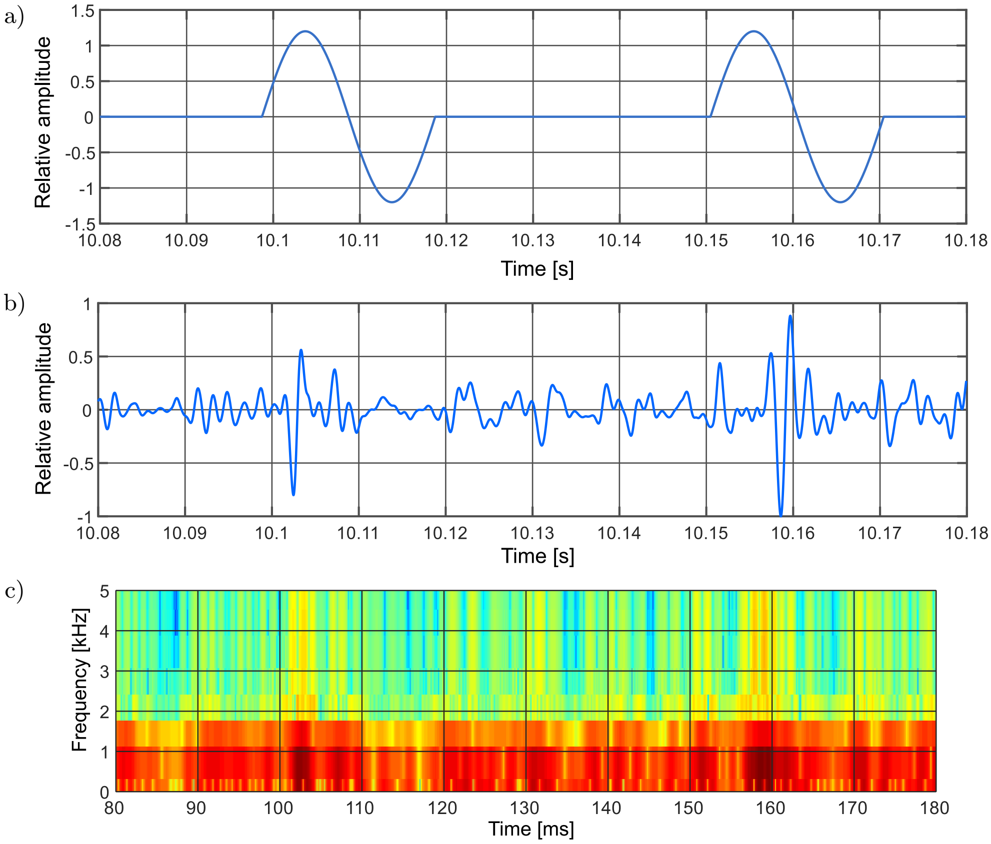

Fig. 3. Synthesised lung sound with crackles (frequency of square wave carrier = 50 Hz).

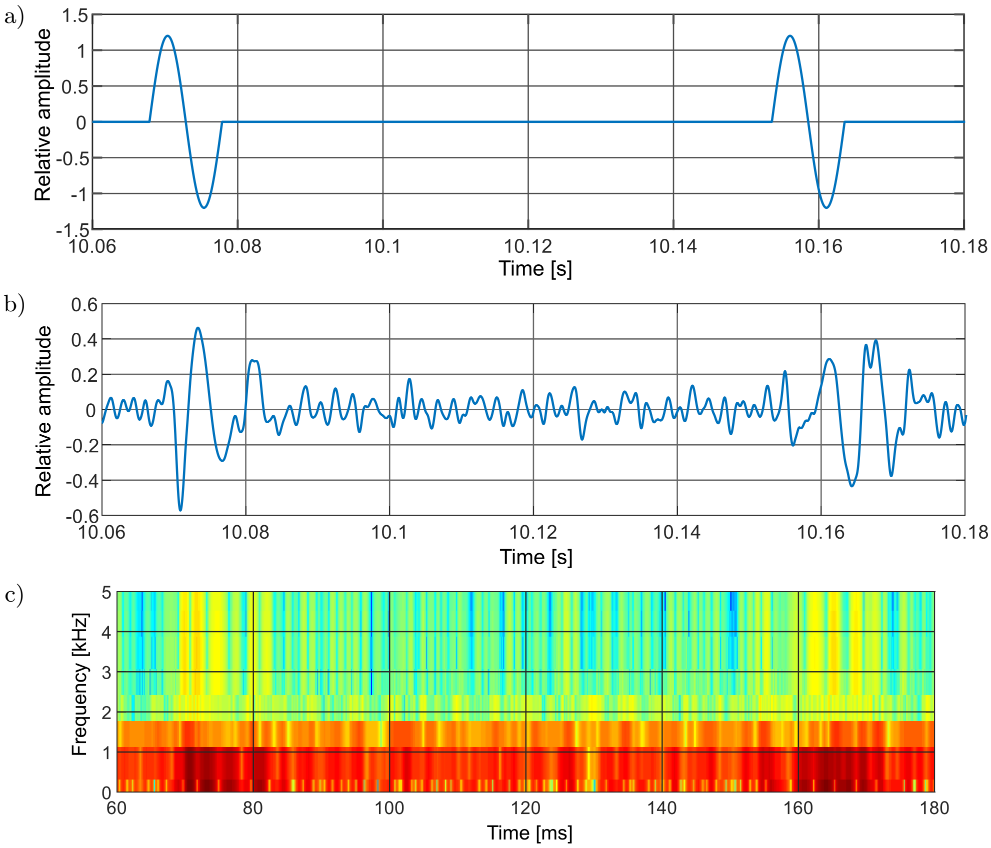

Fig. 4. Synthesised lung sound with crackles (frequency of square wave carrier = 100 Hz).

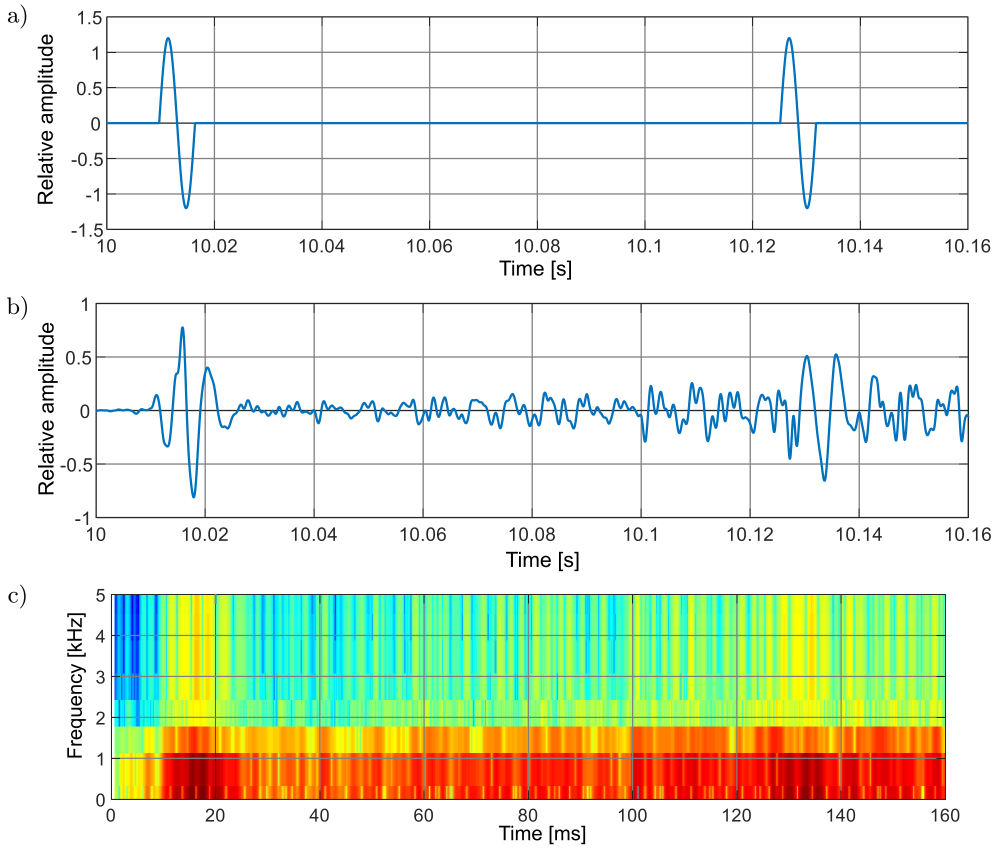

Fig. 5. Synthesised lung sound with crackles (frequency of square wave carrier = 150 Hz).

10.157 s. The frequencies of the two crackles, which differed from the fundamental frequency of the carrier (50 Hz), were 250 Hz and 333 Hz from the reciprocal of the 2CDs, respectively. The synthesised sound, crackle2019Apr1073752563897.wav, can be played at the website in the Appendix. In Fig. 3c, the crackles cab be observed to present a higher pitched and strong magnitude signals in the spectrogram.

The sound crackle2019Apr1073752565465.wav, synthesized by the square wave carrier of 100 Hz frequency, can be played at the website in the Appendix. The magnification of the region of interest which was focused on the duration of 10.06 to 10.18 s is shown in Fig. 4. There were two bursts in Fig. 4a. These bursts induced two crackles in Fig. 4b. The first crackle with IDW = 3 ms and 2CD = 10 ms occurred at 10.068 s. The second crackle with IDW = 1 ms and 2CD = 10 ms occurred at 10.157 s. The frequencies of the two crackles were the same as the fundamental frequency of the carrier, i.e., 100 Hz. It has been observed that the crackles present a higher pitched and strong magnitude signals in the spectrogram of Fig. 4c.

The sound crackle2019Apr1073752567217.wav synthesised by the square wave carrier of 150 Hz frequency can be played at the website in the Appendix. The the magnification of ROI in the duration of 10.00 to 10.16 s is shown in Fig. 5. There were two bursts in Fig. 5a. These bursts induced two crackles in Fig. 5b. The first crackle with IDW = 2 ms and 2CD = 7 ms occurred at 10.01 s. The second crackle with IDW = 3 ms and 2CD = 6.6 ms occurred at 10.13 s. The frequencies of the two crackles were close to the fundamental frequency of the carrier. It can been observed that the crackles present a higher pitched and strong magnitude signals in the spectrogram of Fig. 5c.

4. Discussion

4.1. Mechanism of a crackle

Vyshedskiy *et al.* designed a systematic experiment to find the relationship between inspiratory and expiratory crackle characteristics for exploring the mechanism of crackle generation which was described as a sudden airway closing during expiration and sudden airway reopening during inspiration in the study (Vyshedskiy *et al.*, 2009). The observations quantitatively supported the hypothesis of stress-relaxation quadrupole. Olson and Hammersley (1985) reviewed the mechanisms of the crackles which were based on the points of clinical, physiologic, and theoretical view. They suggested that the opening of small airways may be the initiating event which is very similar to the concept that Vyshedskiy *et al.*

(2009) indicated. The mechanism proposed by Olson and Hammersley (1985) can be illustrated by creating the sound heard when a cork is popped from a pressurized bottle. Forgacs (1978) termed the phenomena of "explosive equalisation" that means the pressure difference upstream and downstream from a collapsed airway rapidly equalises with airway opening, creating a short duration noise. However, we employed the summation of the single burst of 1-cycle sine wave to simulate the source of crackle sounds that the aforementioned hypotheses pointed out. Because the airway is changed dynamically, the single burst occurs randomly in the specific duration while the crackle frequently occurs in the computer simulation.

4.2. Fine and coarse crackles

The processes involved in the formation of coarse or fine crackle sounds in the communication system model are presented in Fig. 6. Alencar *et al.* (2001) developed an avalanche model to support a mean-field solution of the model that provides information about lung inflation. A magnified segment with consecutive spikes was found in the experimental data obtained from a dog lung. The pressure was measured in this study to verify the avalanche dynamic model. Based on the model, several air particle collisions occurred between the particles and the chest wall in the avalanche duration. The possibility of the normal distribution indicated that few of the particles are in the same phase and their reflections can be observed on the chest wall. Therefore, a few explosive waves with relatively large power occurred occasionally. The pressure spikes and the avalanche dynamic model of Alencar *et al.* (2001) study were simulated as the 1-cycle sine wave burst train in the communication system model in our study. These processes were summarised in Steps 1, 2, and 3 in Fig. 6.

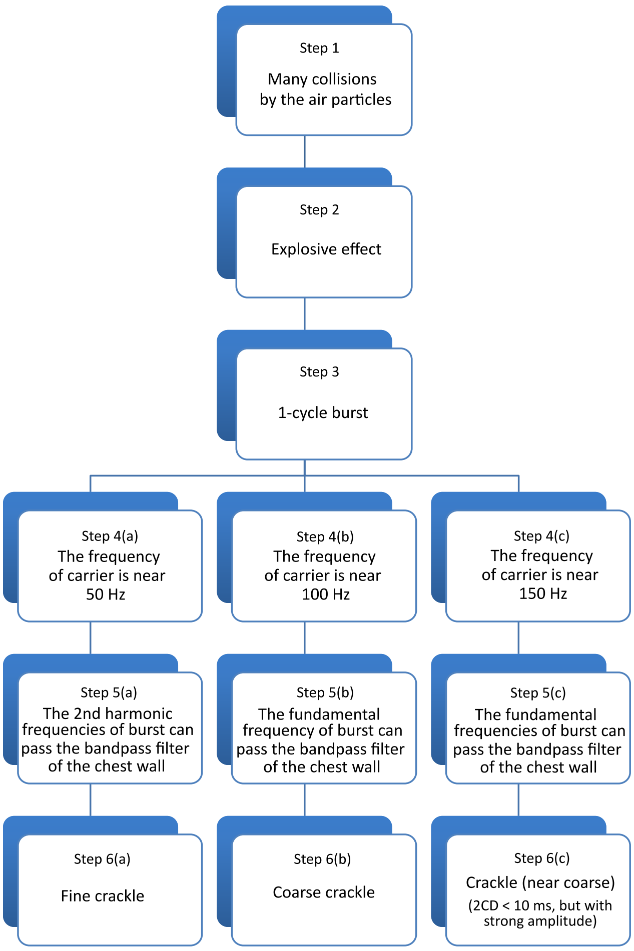

Fig. 6. Mechanism analysis of the crackle sounds in the communication system model.

The computer simulation presented the synthesised lung sounds with the square wave carriers whose frequencies were 50, 100, and 150 Hz. In Fig. 3, the bursts induced 2 crackles in (b). The first crackle with IDW = 1 ms and 2CD = 4 ms occurred at 10.101 s. The second crackle with IDW = 1 ms and 2CD = 3 ms occurred at 10.157 s. In short, the fine crackles were synthesised successfully. The frequencies of the two crackles that differed from the fundamental frequency of the carrier (50 Hz) were 250 Hz and 333 Hz from the reciprocal of the 2CDs, respectively. The frequencies are different because the component of the fundamental frequency was suppressed and the components of the 5th and 7th harmonics penetrated the bandpass filter of the chest wall. In fact, the fine crackle is more difficult to detect in auscultations. Because the intensity of higher order harmonics is intuitively weaker than that of the fundamental frequency in the square wave carrier, the intensity of the fine crackle becomes smaller.

In Figs 4 and 5, the frequencies of the crackles were individually the same as the fundamental frequency of the carrier, i.e., 100 and 150 Hz. In Fig. 4, the first crackle with IDW = 3 ms and 2CD = 10 ms occurred at 10.068 s. The second crackle with IDW = 1 ms and 2CD = 10 ms occurred at 10.157 s. Therefore, coarse crackles have been successfully synthesised using a 100 Hz carrier frequency in Figs 5 and 6. However, in Fig. 5, the first crackle with IDW = 2 ms and 2CD = 7 ms occurred at 10.01 s. The second crackle with IDW = 3 ms and 2CD = 6.6 ms occurred at 10.13 s. Although both the 2CDs of the two crackles were less than 10 ms, their amplitudes were large. Therefore, the two crackles cannot be considered coarse or fine under the aforementioned definitions. Experienced doctors recognise high pitch and low intensity crackles as fine crackles, but low pitch and high intensity crackles as coarse crackles. The results show that higher frequency (more than 100 Hz) carriers of bursts penetrate the bandpass filter of the chest wall directly. However, for a lower frequency (around 50 Hz) carrier, the component of the fundamental frequency was filtered and reduced so that the 2nd harmonic component of the lower frequency carrier could penetrate the wall. These processes are illustrated in Steps 4, 5, and 6 in Fig. 6.

4.3. Bandpass filter effect of the chest wall

In this study, the 4th order Butterworth bandpass filter was employed. The passband was 150–660 Hz. The passband filter whose lower cutoff frequency is in the range of 80–250 Hz and higher cutoff frequency in 400–800 Hz can be used to explain the tone differences in the patients. Lu *et al.* (2011) reported that the wheezes were disclosed by the second order of the Butterworth filter, and the normal breath was synthesised in the fourth order of Butterworth filter. In this article, we employed the 4th order of Butterworth filter to avoid the occurrence of wheezing to simplify the synthesised results for the clear-cut observations. In the near future, we will discuss lung sounds with both crackles and wheezes.

Wodicka *et al.* (1989) proposed that the wall of the chest had a bandwidth of 100 to 600 Hz, which was verified by experiment and theoretical analysis based on the model of transmission line. Korenbaum *et al.* (2016) experimented with the distances to sources of wheezing sounds in the frequency range of 100–500 Hz. Furthermore, Reichert *et al.* (2008) pointed out that the frequency of lung sounds ranged between 50 to 2500 Hz, and that tracheal sounds could reach up to 4000 Hz. Sovijärvi (2000) pointed out that abnormal breathing such as in individuals suffering from asthma and chronic bronchitis has frequency components up to 600–1000 Hz. Parkhi and Pawar (2011) indicated that crackles had a wide frequency range from 100 Hz to 2 KHz. Therefore, the researchers do not have the same view about the frequency range. However, this study focused on the transmission of the chest wall. We have tried the bandwidth by auscultation and the passband matched with Wodicka's model (Wodicka *et al.*, 1989) and the deviation of passband will be discussed in the future studies.

In the simulation processes of this communication system model, the differences of the crackle definitions were analysed by the penetration of the chest wall which was simulated by a 4th order bandpass filter. Because the passband of the filter depends on the amplifier, stethoscope, and electronic filter, the original sounds of crackles are prone to distortion. This study displayed an original 1-cycle sine wave passing the chest wall to be a coarse crackle or a fine crackle.

Murphy *et al.* (1989) developed an automatic crackle counter, its criteria were:

1) the amplitude of the largest peak was greater than twice the amplitude of the background noise,
2) the beginning of the event had a sharp deflection in either a negative or a positive direction, and
3) crossings of the baseline after the initial deflection were progressively wider.

Charbonneau *et al.* (2000) investigated the time parameters of the crackles such as two-cycle duration (2CD), initial deflection width (IDW), and largest deflection width (LDW). Parkhi and Pawar (2011) indicated that the duration of a crackle is less than 20 ms and the frequency range is typically wide, from 100 to 2000 Hz or even higher. Zhang *et al.* (2015) conducted further studies that focused on the spectrogram of a crackle which had a rough shape of a circle. However, through the examination of the synthesised crackles in this study, we suggest the definition proposed by Sovijärvi *et al.* (2000a) because it is precise and simple. Our model proves the possibility of coarse crackles and the fine crackle is a distortion of a 1-cycle sine wave in the sound transmission. The frequency of the carrier wave dominates the type of crackles, i.e., coarse (near 100 Hz) or fine crackles (near 50 Hz). All results agree with the definition proposed by Sovijärvi *et al.* (2000a).

4.4. Frequency of the square wave carrier

Based on the communication system, normal lung sounds are usually in the lower frequency region of the square wave carrier. In the attached file, the fine crackles are more difficult to verify. Furthermore, Forgacs (1978) speculated about the phenomena of "explosive equalisation" which means the tiny time noise that was generated by the pressure difference upstream and downstream from a collapsed airway rapidly equalises with the airway opening. Therefore, it is very possible that the normal lung sounds may contain many crackle-shaped waves with very small amplitudes because of the filtering effects of the chest wall, environment noises, electric devices, stethoscopes, and human ears, the small crackles disappear in the auscultations. In addition, our study pointed out that some unknown crackles of the very low frequency under the bandwidth of the human ears cannot penetrate the airways and be detected by medical doctors. Therefore, it might be necessary to focus advanced electronic instrumentation on them in order to analyse their possible characteristics for diagnosis and treatment of the respiration system. ROI of the spectrogram Cheetham *et al.* (2000) indicated that some acoustic signals beyond 4 kHz and even beyond 10 kHz such as crackle, cough, snore, and speech-like sounds certainly contain significant energy. Therefore, ROI of the spectrogram focus on the frequency range between 0 to 5 KHz in our study. These specified the necessary information to show the components of the crackles for a better presentation which referred to the frequencies of the 4 and the 10 KHz that Cheetham *et al.* (2000) mentioned. Surprisingly, many ROI of the spectrograms in our study shows significant energies whose frequency ranges are over 2 KHz. Consequently, the synthesised results of our communication model agree with Cheetham *et al.* (2000) decriptions in Sovijärvi *et al.* (2000b) Standardization of Computerized Respiratory Sound Analysis (CORSA) which is one of the golden standards of the respiration research. Intuitively, our study presented the computer synthesised lung sounds without speech-like sounds, i.e. a pure lung sounds for researchers.

5. Conclusion

Acoustically, Wodicka's model is based on the circuitry, but the model we proposed is manipulated by the theory of signals and systems. Wodicka *et al.* (1989) proposed that the chest wall had a bandwidth of 100–600 Hz which was verified by both experimental and theoretical analysis is based on the transmission line model. However, we focused on the frequency response of transmissiom by the chest wall. Remarkably, the passband much matched with that of Wodicka's model.

This study disclosed the possible reason of crackles in the communication system model. Lung sounds with crackles were synthesised. These results show that higher frequency (more than 100 Hz) carriers of bursts penetrate the equivalent bandpass filter of the chest wall directly while the coarse crackles occurred. The simulated coarse crackles meet the definition "*A crackle that is low pitched and with a high amplitude and long duration. Its total duration (two-cycle duration (2CD)) is >10 ms*". However, for a lower frequency (around 50 Hz) carrier, the component of the fundamental frequency was filtered and cancelled out, therefore the 2nd harmonic component of the lower frequency carrier can penetrate the chest wall, i.e. the fine crackle, which agrees with the definition. The further studies are expected to verify the possible reason.

In the simulation processes of this communication system model, the differences of the crackle definitions are caused by the filtering deviation. The filter passband may be changed by amplifier, stethoscope, and electronic filter, and the filtering effects in human ears so the sounds of crackles are distorted not only by instrumentation but also by differences of the individual ears. This study displayed an original 1-cycle sine wave passing the chest wall to be a coarse crackle or a fine crackle.

It is very possible that the normal lung sounds may contain many crackle-shaped waves with very small amplitudes because of the filtering effects of the chest wall, environment noises, electric devices, stethoscopes, and human ears, the small crackles disappear in the auscultations. In addition, our study pointed out that some unknown crackles of a very low frequency under the bandwidth of the human ear cannot penetrate the airways and be detected by medical doctors. Therefore, it might be necessary to focus advanced electronic instrumentation on them in order to analyse their possible characteristics for diagnosis and treatment of the respiration system.

Appendix

The crackling sounds synthesised for this study may be found at the following website:
https://docs.google.com/forms/d/e/1FAIpQLScs-igL3sc7kgV7FivKS4mZQgkHh7wMhUSBJQQ2lEbBge5rZA/viewform?vc=0&c=0&w=1.

Conflict of interest

All authors declare no conflict of interest as well as support of funds.

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