

Preliminary Study on Production of Coarse and Fine Crackles in Respiration Using a Model of Communication Theory

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Abstract— This study described an original one-cycle sine wave passing the chest wall to be a coarse crackle or a fine crackle for the examination of the reason of the crackle formation. The results explain the differences between the definitions of crackle which were proposed by Sovijarvi et al. and Reichert et al. Lung sounds with crackles were synthesized by computer simulation. The results show that higher frequency (more than 100 Hz) carriers of bursts penetrate the equipollent bandpass filter of the chest wall directly while the coarse crackles occurred. Consequently, this communication system model supports the formation of normal lung sounds, wheezes, and crackles by the modulation theory and filter from the macro perspective.

Keywords—crackle, computer simulation, lung sound, respiration, amplitude modulation, frequency modulation.

I. INTRODUCTION

A crackle is an adventitious, discontinuous, explosive sound occurring usually during inspiration [1]. Furthermore, Melbye et al. indicated that some crackles can also be found during expiration [2]. Their study revealed that the number of crackles occurring during inspiration was greater than that occurring during expiration.

Murphy et al. [3] and Hoevers [4] investigated the measurement of crackles. Sovijarvi et al. [1] 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.” Reversely, 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 the relative breath sound fields followed the definitions to judge coarse or fine crackles, because the

definitions were reported by the issue of “Standardization of computerized respiratory sound analysis (CORSAs)” [5] which offered many golden standards for studying the lung sounds. Furthermore, Reichert et al. described the crackles as [6, 7] that the duration of a crackle is lower than 20 ms and the frequency range is between 100 and 200 Hz.

This study included five sections. Introduction section presented the motivation and literature study of this article. Method section introduced the communication model. Results section presented the experimental data. Discussion section showed the comparison of previous studies. Finally, we have a conclusion in the last section.

II. METHODS

A crackle sound was coded by MatLab (R2016a, MathWork, USA). The steps were 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; and 5) the output in wave, audio signal and spectrogram.

A. The simulation respiration signal using the approaching saw tooth wave

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

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

where x_s denoted the pressure signal of expiration and inspiration; k was the order of x_s harmonics; f_{br} was the fundamental frequency of the saw tooth wave, which was the

expiration and inspiration pressure signal; and t denoted time. In this study, the signal was synthesized using a sampling frequency of 44,100 Hz.

B. Sound source of breath with crackle 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,

$$x_{cs}(t) = A_1 x_s(t) + A_2 p(t) + A_3 n_{cs}(t) \quad (2)$$

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 ($n_{cs}(t)$).

C. Modulation

The movement of air particles in the airway follows the wave equation of fluid dynamics. Grotberg et al. developed a theoretical model for wheezes [8]. 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 [9]. The model was developed by a combination of amplitude modulation (AM) and frequency modulation (FM).

D. 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,

$$y_m = \sigma_{am} y_{am} + \sigma_{fm} y_{fm} \quad (3)$$

where σ_{am} and σ_{fm} are the coefficients of the intensity of AM and FM, respectively.

E. Noise and burst

The noises cause from the environment, electronic devices, collisions in the airway, inter-fraction of tissues near the air way, and so on. The summation of noises was denoted as $n_s(t)$. Therefore,

$$y_n(t) = y(t) + n_s(t) + 10p(t) \quad (4)$$

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

F. Filter

Bertram [10] found that low frequency oscillations produced a sound of a 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. [11] i.e. 100 to 600 Hz. In this study, a fourth-order Butterworth bandpass filter was employed. Its range was 100 to 600 Hz to match the model which was proposed by Wodicka et al. For an analog filter, the transfer function is expressed in terms of $B(s)$ and $A(s)$ as,

$$H(s) = \frac{B(s)}{A(s)} = \frac{\sum_{r=0}^3 b_r s^3 - r}{\sum_{r=0}^3 a_r s^3 - r} \quad (5)$$

$$b_r = [1606 \ 0 \ -0.6425 \ 0 \ 0.9637 \ 0 \ -0.6425 \ 0 \ 0.1606] * 10^{-5} \quad (6)$$

$$a_r = [1.0 \ -7.80 \ 26.63 \ -51.99 \ 63.45 \ -49.58 \ 24.22 \ -6.76 \ 0.82] \quad (7)$$

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

G. Output

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

$$Y(s) = Y_n(s)H(s) \quad (8)$$

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,

$$y(t) = \frac{1}{2\pi} F^{-1}\{Y(s)\} \quad (9)$$

H. Criteria for the recognition of crackles

The criteria for the recognition of crackles to verify the simulation results of the synthesized signals were based on the definition which Sovijarvi et al. [1] defined. That is a coarse crackle defines 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.” Furthermore, a fine crackle defines as “A crackle that has a high pitch, low amplitude and short duration. Its total duration (2CD) is <10 ms.”

III. RESULTS

The normalized frequency response of the fourth-order Butterworth bandpass filter is shown in Fig. 1. The passband is in the range from 150 to 660 Hz. The lung sounds synthesized with crackles when the frequency of the square wave carrier was 50 Hz are presented in Fig. 2. The burst of a 1-cycle pure sine wave is shown in Fig. 2 (a); the lung sound with crackles is presented in Fig. 2 (b) and its spectrogram is shown in Fig. 2 (c). The synthesized sound, crackle2019Apr1073752563897.wav, can be heard through the website given in the appendix.

IV. DISCUSSION

In this study, a 4-th order Butterworth bandpass filter was employed. The passband was 150 to 660 Hz. However, the passband whose lower cutoff frequency is in the range from

80 to 250 and higher cutoff frequency is round 400 to 800. Therefore, it can be used to explain the tone differences in the patients. Lu et al. reported that the wheezes were disclosed by the second order of the Butterworth filter, and the normal breath was synthesized in the fourth order of Butterworth filter. In this article, we employed the fourth order of Butterworth filter to avoid the occurrence of wheezing to simplify the synthesized results for the clear-cut observations. In the near future, we will discuss lung sounds with both of crackles and wheezes.

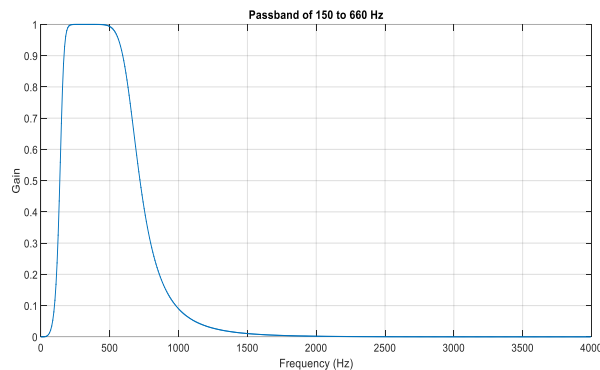


Fig. 1 Normalized frequency response of the fourth-order Butterworth bandpass filter

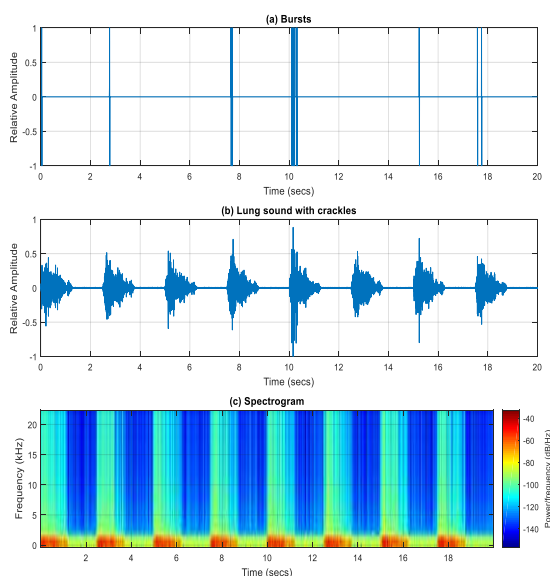


Fig. 2 Synthesized lung sound with crackles (Frequency of square wave carrier = 50 Hz)

Wodicka et al. [11] 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. Furthermore, Reichert et al. [6] pointed out that the frequency of lung sounds ranged between 50 to 2500 Hz, and that tracheal sounds could reach up to 4000 Hz. Sovijarvi et al. [12] pointed out that abnormal breathing such as in individuals suffering from asthma and chronic bronchitis has frequency components up to 600–1,000 Hz. 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 [11] and the deviation of passband will be discussed in the future studies.

V. CONCLUSION

Wadicka's model is based on the circuitry, but the model we purposed is based on the signal and system. Wodicka et al. [11] proposed that the chest wall had a bandwidth of 100- 600 Hz which was verified by both experimental and theoretical analysis based on the transmission line model. However, this study focused on the transmission of the chest wall. We tested the bandwidth by auscultation. Remarkably, the passband matched with that of Wodicka's model.

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