Characterization of crackles from patients with fibrosis, heart failure and pneumonia

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1. Introduction

Crackles are adventitious lung sounds that often occur in cardiopulmonary diseases and are described as short, explosive and transient waves. They are associated to the recruitment of obstructed airways during breathing and are characterized by an initial fast pressure deflection followed by a short ringing duration [1–3]. Two mechanisms have been proposed to explain their genesis: (1) air bubbling through secretions; (2) sudden opening of collapsed airways as result of fast pressure equalization of lung compartments [4].

Lung auscultation, a non-invasive diagnostic tool widely used to assess the cardiopulmonary system, could be even more effective if quantitative indexes extracted from the crackles could be better related to the different diseases. To achieve this aim, researchers have been proposing methods to evaluate trends of parameters obtained from the crackles in the time and frequency domains.

Intervals of expanded crackle waveform were correlated to psychoacoustic characteristics as well as to diseases [5]. Fig. 1 shows some of the time intervals investigated in the literature in the attempt to characterize the crackles sounds [6]. Holford [7] suggested the classification of the crackles as fine (high-pitched) or coarse (low-pitched) sounds based on two time intervals: initial deflection width (IDW) and two cycle duration (2CD). Hoevers and Loudon [8] proposed the same classification above using the largest deflection width (LDW). The 2CD has also been investigated to identify the different diseases.

The time intervals are related to the frequency content of the crackles sounds being affected by the filters of the system utilized to record them. According to Kudoh et al. [9], frequency
content of the fibrosis crackles ranges from 2 to 5 kHz. Dalmaso et al. [10] reported fibrosis crackles with frequencies between 0.1 and 2 kHz, but they emphasized that most of the signal energy was concentrated below 1 kHz. Sovijärvi et al. [11] stated that crackles frequency content typically ranges from 0.1 to 2 kHz with a duration inferior to 20 ms. Piirilä et al. [12,13] reported that the maximum frequencies for fibrosis, heart failure and pneumonia crackles are $550 \pm 110$ Hz, $350 \pm 50$ Hz and $437 \pm 31$ Hz, respectively. The highest frequency found was below 1 kHz.

Although several methods have been proposed to classify the crackles, there are inconsistencies among indexes measured by different research groups. They may occur due to the different technical specifications of the systems used for the sound acquisition [14]. To circumvent that, the Computerized Respiratory Sound Analysis (CORSA) project of the European Respiratory Society (ERS) established guidelines for the investigation of the lung sounds [15]. It is expected that these guidelines may contribute to overcome some of the current obstacles towards the characterization of the respiratory sounds, allowing the researchers to exchange data obtained with similar systems. However, most of the currently available data on crackles was obtained from sounds acquired with systems developed before the publication of the CORSA guidelines. Besides, some parameters were measured using signal processing techniques which are not suitable for the analysis of non-stationary signals.

In addition to the problems described above, the frequency content of the crackles sounds has been related to the recruitment of collapsed regions of the lung [2]. If there is atelectasis, the partial collapse of a lung region, the recruitment occurs in avalanches and a large number of crackles is generated in both recruiting and non-recruiting volumes and may also overlap [1,16]. In this scenario, the breathing rate and the inspired volume may also affect the spectral content of the crackles.

Here, we analyze crackles acquired from patients using equipment developed according to the CORSA guidelines. The sounds were recorded from patients diagnosed with fibrosis, heart failure and pneumonia. To determine the spectral content of these signals, discrete pseudo Wigner–Ville distribution (DPWD) was used. Since the guidelines do not provide a specific value for the high-pass filter cutoff frequency, its effect on the measured parameters was investigated. Crackles recorded from patients with fibrosis were further investigated, focusing on the effect of the breathing rate and the tidal volume on the maximum frequency and on the 2CD index.

### 2. Materials and methods

This section describes the system, based on the CORSA guidelines, developed to acquire the crackles, as well as their recording and processing.

#### 2.1. Acquisition system

The sounds were acquired by an electret microphone (Knowles Acoustics, MD9745APA-1) housed into an acoustic coupler. This microphone model has a flat frequency response from 100 to 3000 Hz and sensitivity of 9 mV/Pa. Fig. 2a shows the dimensions of the used coupler manufactured according to the Kraman et al. [17] recommendations as the power spectral distribution of sound transmitted through the chest and acquired with the acoustic coupler model presented in Fig. 2b. As can be seen, the lower frequency components of the lung sounds are less attenuated by the thorax and thorax-microphone interface. Therefore, a low high-pass filter cutoff frequency demands a low gain to avoid the saturation of the analog to digital converter (A/D).

To assess the influence of the high-pass filter cutoff frequency and amplification on the calculated parameters, the low voltage output signal of the microphone (9 mV/Pa) is conditioned by three different circuits (Table 1) with different bandwidths (BW) and gains (G). The band-pass filters were built by the cascading of second-order Butterworth high-pass and second-order Butterworth low-pass filters.

<table>
<thead>
<tr>
<th>Channel</th>
<th>BW (Hz)</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60–2500</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>150–2500</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>200–2500</td>
<td>100</td>
</tr>
</tbody>
</table>

To identify the breathing phases (inspiration and expiration), the airflow waveform and lung sounds are simultaneously sampled. For that, the patient breathes through an acrylic duct containing...
a pneumotachograph. The pressure drop across the pneumotachograph is proportional to the flow velocity [18]. The transducer (DC030ND4C, Honeywell Inc.) measures the differential pressure through the obstacle within a range of ±76.2 cmH₂O. It has a sensitivity of 52.36 mV/cmH₂O, generating a voltage output of 2.25 ± 2.0 V. The output voltage signal of the pressure transducer is filtered by a second-order Butterworth low-pass filter with a cutoff frequency of 40 Hz. The signal amplitude is adjusted to the maximum input value of the A/D (0–2.5 V), considering the maximum expected flow range (−70 to +70 L/min). For that, it is amplified and summed to a DC offset to achieve positive values. The obtained resolution is 17.9 mV/L/min⁻¹.

The three audio signals and the flow waveform are simultaneously sampled at 10 kSPS by the IC SMP04 (Analog Devices). The microcontroller ADuC841 (Analog Devices) converts, one by one, the sampled voltage values to 12-bit words. It carries out each conversion in 8 μs with a resolution of 0.61 mV (1LSB = 2.5 V/4096). The digital samples are sent to the IC FT245BM (Future Technology Devices Intl.) which establishes USB communication with a laptop computer, transmitting data at the rate of 1 Mbit/s.

Software developed in C++ Builder running in the laptop establishes the communication with the acquisition hardware. The software de-multiplexes the received data and shows it on the screen in real time. Each sampled waveform is stored into the hard disk in individual wave files (16 bits pulse code modulation – PCM). More information on the developed system can be found elsewhere [19].

2.2. Crackles recordings

Crackles were acquired from 30 patients with heart failure, pulmonary fibrosis and pneumonia. For each disease, sounds were recorded from 10 patients to allow the comparison of the obtained results to the ones of previous studies [12,13]. The recordings were carried out at three different Hospitals (Medical School Hospital of the Federal University of Santa Catarina, Regional Hospital of São José and Cardiology Institute of Santa Catarina) after approval by their respective research ethics committees (Process numbers: 175/09, 041/10 and 086/10, respectively). Written informed consent was obtained from the patients. They were diagnosed by specialized physicians based on their clinical signs and symptoms, chest X-rays, lung capacity measurements (carried out by spirometry, mostly for fibrosis patients) and echocardiogram exams (for heart failure disease; heart ejection fraction below 80% and Killip scale ranging between levels II and III). Critically ill patients did not take part of this study, since they were not physically able to follow the proposed breathing protocol. The fibrosis patients whose crackles were recorded during monitoring exams have their disease originated by occupational exposure; they did not present other associated diseases. Table 2 summarizes their physical characteristics.

The patients were seated in a room without noise level control (infarnry). Before recording the sounds, an examiner auscultated the posterior chest wall to locate the spot with the loudest crackles. In that position, the nylon acoustic coupler containing the microphone was attached using double-sided tape. Patients were instructed to breathe through an acrylic duct containing the pneumotachograph at the rate of 12 breaths/min guided by a metronome. Patients with fibrosis were also asked to breathe at the rates of 10 and 15 breaths/min. Lung sounds and flow waveforms were recorded during at least 3 breathing cycles (3 inspirations and 3 expirations). Each sampled waveform was recorded into a separated file under the hospital patient registration number. The flow waveform allows for localization of the crackles in the respiratory cycle: inspiration or expiration.

2.3. Assessment of the high-pass filter cutoff frequency influence on the 2CD index

The CORSA guidelines [15] report that most researchers employ a high-pass filter cutoff frequency (HPFCF) within the range from 30 to 150 Hz, most commonly between 50 Hz and 60 Hz. To assess the HPFCF impact on the measured parameters, the sound that reached the microphone placed on the thorax was processed by three different conditioning circuits (Table 1) that were sampled and stored into files.

Within the range pointed out by the CORSA, this work investigated HPFCFs of 60 Hz and 150 Hz. The 60 Hz HPFC (one of the most used HPCF [15]) allows a good quality recording (gain: 35) while avoiding the amplifier saturation by the normal breathing sounds that have lower frequencies components and higher amplitudes.
The 150 Hz HPCF (the highest one suggested by the CORSA) is used to measure the maximum detected frequency using a higher amplifier gain (gain: 80); amplifier saturation does not occur since the lower frequency components are further attenuated by this filter.

A 200 Hz HPCF was also investigated in order to assess its suitability for the measurements of the 2CD and maximum frequency indexes, since the CORSA guidelines do not determine a maximum HPCF.

The files containing the simultaneous recordings by each of the three different channels can be opened together with commercial audio software. Thus, the same crackle can be identified in the three channels and also expanded to allow for the measurement of the 2CD interval. For the sampling period of 0.1 ms, a 2CD segment containing 52 samples corresponds to 5.2 ms (Fig. 3).

2.4. Signal processing

Biomedical signals are usually non-stationary and are commonly analyzed by the application of discrete Fourier transform (DFT) to consecutive short segments that have constant mean and variance (wide-sense stationarity). Nevertheless, there is no information on the period during which the crackles can be considered stationary for the different diseases. Therefore, the DFT may not provide a good estimation of the crackles spectra.

The discrete pseudo Wigner-Ville distribution (DPWD) has been used in the analysis of non-stationary signals [20]:

$$\text{DPWD}[n, k] = 2 \sum_{|m|<M/2} [h[m]]^2 z[n+m]z^*[n-m]e^{-j4\pi km/M}$$ (1)

where the term $z[n+m]z^*[n-m]$ of Eq. (1) is the instantaneous autocorrelation of the signal under analysis, $h[m]$ is the window that defines the interval of analysis and $M$ is the number of signal samples. The * denotes conjugate complex. In this work, a Hamming window was used.

The effect of the cross terms that occur in the Wigner-Ville distribution is reduced using DPWD [20]. However, the cross terms do not interfere with the detection of the maximum frequency, as they arise among frequency components of the signal and not above them.

To estimate the maximum frequency envelope of ultrasound Doppler sonograms without assuming an arbitrary threshold, objective methods were reported, such as the modified geometric method (MGM) [21]. Appendix A illustrates the feasibility of applying the MGM to detect the maximum frequency of the crackles.

Piirilä et al. [12,13] estimated the maximum frequency of the crackles applying an arbitrary threshold of −20 dB below the maximum detected power of the spectra computed by DFTs from sampled segments of 200 ms.

In this work, the DPWD was applied to four crackles belonging to the inspiration phase of each patient. These crackles were identified by the visual inspection of the sound recordings using the audio editor. This procedure was repeated for all patients (Table 2). The crackles were contained in segments of 6.4 ms (fibrosis) or 12.8 ms (heart failure and pneumonia). These intervals were defined based on the maximum duration of the crackles observed in each disease, considering the employed sampling rate (10 kSPS). This procedure avoids interference of noise on the maximum frequency estimation. From the obtained DPWD, the maximum frequency of each crackle was estimated applying the MGM. The Time-Frequency Toolbox was used to calculate the DPWD [22].

Each of these crackles was expanded and the 2CD was measured by means of manually controlled tools of the audio editor.

2.5. Assessment of the breathing rate effect on the crackles indexes

The same air volume crossing a high resistance section of the lung airways during different time intervals may generate crackles with different spectra, precluding the comparison of their characteristics among patients breathing at different rates.

The ideal way to investigate that would be to have different patients inhaling a constant air volume at different breathing rates, that is, at different inspiration intervals. However, this is not feasible since different patients have distinct physical characteristics as well as different degrees of lung impairment. Thus, the breathed airflow varied among individuals. Therefore, this work analyzes the intra-individual effect of the breathing rate and volume on the generated crackles. The volume effect was assessed in terms of relative inspired volume as explained below.
Crackles and flow waveforms were recorded from 10 fibrosis patients breathing at the rates of 10, 12 and 15 breaths/min. Fibrosis patients were chosen because the crackles are generated by a consolidated alveolar alteration associated to the current disease phase; that is, the spectra is not affected by the current fluid volume within the lungs as could occur in other diseases. During the lung sound acquisition, it was assured that the patients were breathing at the metronome pace.

For each patient who breathed at the rates of 10 and 15 breaths/min, two crackles were analyzed since some patients had difficulties to follow the metronome pace.

To better evaluate the achieved results, the relative volume at each breathing rate was calculated for each patient. As reference, the volume measured at the rate of 12 breaths/min was used. Therefore, the relative volume (RV) will be greater than 1 when the patient breathes a larger volume than the reference one; otherwise, RV will be equal to 1 (same volume) or less than 1 (smaller volume). This approach intends to reduce factors of variability for a better analysis.

From the acquired airflow waveform and Eq. (2) [23], the breathed volume can be calculated to investigate its influence on the spectral content of the crackles.

\[ V = \sum_{n=0}^{N-1} K F(n) \Delta T \]  

where \( \Delta T \) is the sampling period; \( F(n) \) is the discrete flow waveform that has an amplitude proportional to the differential pressure applied to the pneumotachograph; \( K \) is a constant related to the constructive aspects of the pneumotachograph (duct diameter and resistance) and fluid characteristics.

Curve A in Fig. 4 gives an example of the flow waveform during an inspiration that is used to calculate the volume, while curve B gives the volume as a function of time. The constant \( K \) will be cancelled when dividing the volumes calculated at the breathing rates of 10 and 15 breaths/min by the volume obtained at the rate of 12 breaths/min.

### 3. Results

The effect of the HPFCF on the measurements, the maximum frequencies and 2CDs measured from the crackles acquired with a

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Maximum frequency, 2CD and IDW measured from a same crackle recorded with different HPFCFs and different gains.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPFCF (Hz)</td>
<td>Gain</td>
</tr>
<tr>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td>150</td>
<td>80</td>
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<tr>
<td>200</td>
<td>100</td>
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CORSA based system and the measurements carried out for crackles acquired from fibrosis patients breathing at different rates are now reported.

#### 3.1. The influence of the high-pass filter cutoff frequency on crackles measurements

To illustrate the role of the HPFCF, a case study is presented. A same crackle was simultaneously acquired (Fig. 5) from a patient with pulmonary fibrosis by the three conditioning channels with different gains and different HPFCFs (Table 1). Higher HPFCF allows for the use of a higher gain since the lower frequency components of the lung sounds are attenuated, and therefore, the A/D does not saturate. Thus, components of higher frequencies and lower amplitudes can be recorded.

Table 3 presents the maximum frequency (measured by DPWD and MGM), 2CD and IDW obtained for each waveform shown in Fig. 3. When filtered with a HPFCF of 60 Hz, the baseline oscillations hamper the identification of the crackle in the recorded waveform. The IDW and 2CD intervals did not change significantly when the HPFCF was raised from 150 Hz to 200 Hz. The maximum frequency increased about 8.5%.

#### 3.2. Measurements of the maximum frequency and of the 2CD index

Table 4 shows the mean, standard deviation and 95% confidence interval of the maximum frequency values for the crackles acquired with a HPFCF of 150 Hz (the highest HPFCF suggested by the CORSA guidelines). It also shows the mean, standard deviation and 95% confidence interval of the 2CD index. For each disease, the presented data were calculated from 40 crackles. For that, 4
crackles of each patient for a same inspiratory phase were selected by visual inspection of the sound recordings using the audio editor. The crackles with the higher amplitudes were chosen since they have higher signal-to-noise ratio. For each disease, the procedure was repeated for 10 patients. The patients breathed at the rate of 12 breaths/min. The maximum frequency was estimated by applying DPWD and MGM. The obtained data sets have normal distribution according to the Shapiro–Wilk test.

The statistical analysis of the results showed that the mean value of the maximum frequency and 2CD are different between the fibrosis and pneumonia crackles, and also between fibrosis and heart failure crackles ($p < 0.05$ for both cases). There are no statistical significant differences between the mean values of the maximum frequency and of the 2CD index for pneumonia and heart failure. The data were processed using one-way ANOVA followed by Tukey test for comparison between groups.

### 3.3. Influence of the breathing rate and volume on the maximum frequency of the fibrosis crackles

Table 5 also shows the mean, standard deviation and 95% confidence interval values of the maximum frequency (obtained with DPWD and MGM) and of the 2CD index for fibrosis crackles recorded from patients breathing at three different rates: 10, 12 and 15 breaths/min. The distribution of these two indexes was ranked as normal by the Shapiro–Wilk test. The data were tested using one-way ANOVA for comparison among groups. The differences among the mean values of the maximum frequency ($p = 0.913$) and of the 2CD index ($p = 0.335$) for the three groups (10, 12 and 15 breaths/min) were not statistically significant.

These results suggest that the crackles are generated by the sudden opening of collapsed airways without a major atelectasis recruitment [2].

To assess the intra-individual breathing volume effect on the maximum frequency, one respiratory cycle was selected for each patient and for each breathing rate (10, 12 or 15 breaths/min). For the breathing rates of 10 and 15 breaths/min, two crackles of the same inspiratory phase were selected. The analyzed crackles were grouped according to the relative volume (RV) breathed below ($RV < 1$) and not below ($RV \geq 1$) the volume breathed at 12 breaths/min. The estimated maximum frequencies for the crackles associated to the RVs are presented in Table 6.

The maximum frequency distributions of all groups (A, B, C, D, E) were ranked as normal by the Shapiro–Wilk test. The differences among their mean values were not statistically significant ($p = 0.532$) according to the one-way ANOVA test.
Fig. 6. (a) Signals generated by the Eq. (A2) considering a sampling rate of 10kSPS, f = 900Hz and σ = 0.0008 (52 samples); (b) curve of the cumulative fractional energy squared (IEC (K)) calculated by Eq. (A1).

<table>
<thead>
<tr>
<th>Breathing rate (breath/min)</th>
<th>Maximum frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RV &lt; 1</td>
</tr>
<tr>
<td>10</td>
<td>817.77 ± 120.37</td>
</tr>
<tr>
<td></td>
<td>(681.56–953.98)</td>
</tr>
<tr>
<td>[3] Group A</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>907.81 ± 161.27</td>
</tr>
<tr>
<td></td>
<td>(807.85–1007.77)</td>
</tr>
<tr>
<td>[10] Group B</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>912.41 ± 254.85</td>
</tr>
<tr>
<td></td>
<td>(708.49–1116.33)</td>
</tr>
</tbody>
</table>

4. Discussion

As shown, the parameters measured from the crackles (IDW, 2CD and maximum frequency) were affected by the choice of the HPFCF. Most of the measurements presented here were obtained from crackles acquired with the HPFCF of 150 Hz, the highest one suggested by the CORSA guidelines. This choice aimed to sample crackles with higher frequencies components since the lower ones are highly contaminated by normal breathing sounds.

Researchers found that the IDW decreased and has lower sensitivity for higher HPFCF values [24,25]. As shown in Table 3, the IDW did not change when the HPFCF was raised from 150 Hz to 200 Hz. Therefore, the use of a 150 Hz HPFCF is enough to attenuate the low frequencies components that hamper the first zero crossing detection. The further attenuation of these components by using a 200 Hz HPFCF does not change the zero crossing point significantly.

Table 7 contains 2CD index measurements available in the literature and those obtained in this work. Unfortunately, it is not possible to compare the data since no information related to HPFCF is provided by the referred studies.

The HPFCF also affects the maximum frequency, since a higher HPFCF allows further amplification of the lung sounds during their acquisition. Therefore, components of higher frequencies and lower amplitudes can be recorded. That may explain the controversial findings of different research groups. The CORSA guidelines state that crackles have frequencies up to 2000 Hz. Piirilä et al. [12] did not measure frequencies above 660 Hz. The maximum frequency estimation is also affected by the discrete-time signal processing techniques.

Using a system with a HPFCF of 95 Hz, maximum frequency measurements were carried out by Piirilä et al. [12,13] with DFT and an arbitrary threshold (−20 dB). They reported that fibrosis crackles have higher frequency components than those observed in patients with heart failure and pneumonia. The lowest maximum frequencies were detected in heart failure crackles.

Processing the crackles with a 150 Hz HPFCF and analyzing them with DPWD and MGM (Table 4), it was found that the maximum frequency of fibrosis crackles was superior to the ones found in heart failure and pneumonia. However, the maximum frequency estimated in this work was almost twice that obtained by Piirilä et al. [12,13]. The heart failure crackles were also found to have the lowest maximum frequency. Table 8 shows the maximum frequency values obtained by different laboratories.

The role of other variables was studied to assess their influence on the maximum frequency. The results in Table 5 do not show

Table 6
Mean ± standard deviation and 95% confidence interval (upper and lower bounds between parenthesis) of the maximum frequency acquired from 10 fibrosis patients. Each patient breathed at 3 different rates (10, 12 and 15 breath/min). For the 10 and 15 breath/min rates, two crackles were analyzed from one inspiratory cycle and the RVs (RV < 1; RV ≥ 1) were calculated. The number of patients used to compute the data is presented between brackets under each result.

Table 7
2CD index measured by different research groups.

<table>
<thead>
<tr>
<th>Disease</th>
<th>Piirilä et al. [12,13] (HPFCF = 95 Hz)</th>
<th>Munakata et al. [26] (ms)*</th>
<th>Kawamura et al. [27] (ms)*</th>
<th>Our results (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibrosis</td>
<td>7.70</td>
<td>4.40</td>
<td>-</td>
<td>4.70</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>8.60</td>
<td>-</td>
<td>6.54</td>
<td>6.61</td>
</tr>
<tr>
<td>CHF</td>
<td>11.80</td>
<td>-</td>
<td>-</td>
<td>6.59</td>
</tr>
</tbody>
</table>

* HPFCF not informed.
significant differences for fibrosis patients breathing at different rates. However, the dispersion of values was increased. Table 6 does not show significant differences for fibrosis patients breathing at different volumes and rates. Therefore, to allow the exchange of more consistent data among research groups, we suggest that the breathing rate during which the crackles were acquired should be reported. The rate of 12 breaths/min proved to be a comfortable one for most of the patients who took part in this investigation.

A limitation of this study is that the results were not correlated to focal radiographic findings; the patients were not exposed to X-rays at the time of the sound acquisition since that would require medical indication.

5. Conclusion

Despite the widespread use of the subjective lung auscultation as a tool for screening and diagnosis of respiratory diseases, modern computerized lung sound analysis systems do not provide quantitative indexes to assist the examiners.

Partly, the current limitation is due to the different specifications of the systems used to acquire the sounds, hampering the exchange of consistent data among researchers. This motivated the ERS to publish the CORSA guidelines.

Higher HPFCF attenuates the baseline wandering due to normal breathing sounds. Thus, higher frequency components attenuated by the thorax and thorax-coupler interface can be recorded by using a higher gain which affects the indexes in the time and frequency domains.

The presented results show that by using a HPFCF of 200 Hz, a higher maximum frequency can be registered without changing the 2CD and IDW indexes significantly. Therefore, a higher HPFCF than the one suggested by the CORSA guidelines may be more suitable for crackles analysis.

The application of DPWD and MGM allows for the objective detection of the maximum frequency of crackles from various diseases. The maximum frequency and the 2CD allow distinguishing the crackles generated by fibrosis from the ones generated by the heart failure and pneumonia. It is not possible, however, by means of these two indexes, to differentiate between pneumonia and heart failure crackles. The extraction of additional features to characterize the crackles may help to circumvent that [30].

Pneumonia and heart failure crackles have lower maximum frequencies and higher 2CD indexes than fibrosis. The broader 2CD index standard deviation in pneumonia and heart failure (Table 4) suggests that the crackles are generated from airways opening with and without large regions of recruitment, indicating the presence of atelectasis regions in both diseases and its absence in fibrosis [2].

The presented results were not obtained prospectively and the study included only a small number of subjects. Therefore, they cannot be employed as definitive indexes to diagnosis the investigated lung diseases. Nevertheless, this study proposes methods to measure the parameters from the crackles and makes data available to be compared to results of additional investigations.

It should be observed that the crackles acquired according to the CORSA guidelines have higher frequencies and shorter 2CD indexes than those previously reported. These indexes may be also affected by the microphone sensitivity. Thus, it is very important to completely characterize the acquisition system to allow for the assessment of the measurements related to the lung sounds.

The frequency content of the crackles is also affected by the thorax and thorax-coupler interface attenuation. Since the transmission channel attenuation changes among individuals, methods to compensate it may produce more consistent indexes.

The constant development of microelectronics may allow the electronic respiratory sound analyzers to keep their portability while providing indexes to make the auscultation screening less susceptible to the examiner experience, helping to reduce the patient’s exposure to X-rays. The parallel development of discrete-time signal processing techniques should also contribute to that.

Nevertheless, further investigations are necessary to improve the diagnostic value of the indexes measured from the crackles.

Funding

This project was partly funded by the Federal Institute of Piauí-PROAGRUPAR program.

Ethical approval

The acquisition of the lung sounds was carried out in three Hospitals located at Santa Catarina (Brazil) after approval by their respective ethics committees. The Hospitals are: Hospital Universitário, Federal University of Santa Catarina (Process: 175/09); Hospital Regional de São José (Process: 41/10) and Instituto de Cardiologia de Santa Catarina (Process: 086/10).

Acknowledgement

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Appendix A.

To determine the maximum frequency of crackles sounds without the adoption of an arbitrary threshold, the modified geometric method (MGM) was used. The MGM was proposed to detect the maximum frequency envelope of sonograms obtained from DFT applied to Doppler ultrasound [21].

In this work, the MGM was applied to the DPWD of crackles to estimate their maximum frequencies. The integrated fractional energy squared curve (IEC) was used to better identify where the signal energy ceases:

\[
\text{IEC}(K) = \sum_{k=0}^{K-1} \text{DPWD}(k, f, n)^2
\]

(A1)

The highest frequency of the spectrum is assumed to correspond with the point where the perpendicular distance between the IEC and a reference line is maximum. A reference line is drawn from the origin to the end of the IEC curve (Fig. 6b).
To illustrate this, two examples are presented below. In the first one, a simulated crackle was generated multiplying a cosine by a Gaussian:

$$y(n) = \cos(2\pi fn) \cdot e^{-n^2/2\sigma^2}$$  \hspace{1cm} (A2)

where $n$ is the discrete time. Fig. 6a shows a crackle generated by means of Eq. (A2) for $f=900$ Hz and $\sigma=0.0008$. These values were chosen to generate a crackle similar to the ones acquired from fibrosis patients in terms of duration and maximum frequency. Since the Gaussian falls slowly, the spectral resolution and window length restrain the maximum frequency that can be estimated by the technique. The maximum frequency of the Gaussian ($\sigma=0.0008$) obtained by using DPWD and MGM (Hamming window of 64 points; sampling rate of 10KSPS) was 262 Hz, which corresponds to the frequency component with an energy 85% below the maximum one. Therefore, the maximum frequency expected by the product of Gaussian with cosine with frequency 900 Hz (Eq. (A2)) was 1162 Hz ($900 + 262$ Hz). The maximum frequency of Eq. (A2) (Fig. 6b) estimated by MGM and DPWD was close to the expected value ($1134.6$ Hz).

The maximum frequency of a 5 ms fibrosis crackle was measured using the Piirilä et al. [12] and the DPWD–MGM methods acquired with a HPFCF of 60 Hz. With the Piirilä et al. [12] method, DFT was applied to a 200 ms segment containing the crackle (Hamming window of 4096 samples) and the arbitrary threshold (−20 dB criteria) was used to detect the maximum frequency: 270 Hz. Applying MGM and DPWD to the same crackle, the estimated maximum frequency was 689 Hz.

To observe the HPFCF effect on the measurement, the DPWD–MGM obtained a maximum frequency of 727 Hz for the same crackle recorded with a 150 Hz HPFCF that allowed the use of a higher gain.

**Conflict of interest**

There is no conflict of interest.

**References**