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Nonlinear analysis of wheezes using wavelet bicoherence

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Abstract

Wheezes, as being abnormal breath sounds, are observed in patients with obstructive pulmonary diseases, such as asthma. The aim of this study was to capture and analyze the nonlinear characteristics of asthmatic wheezes, reflected in the quadrature phase coupling of their harmonics, as they evolve over time within the breathing cycle. To achieve this, the continuous wavelet transform (CWT) was combined with third-order statistics/spectra. Wheezes from patients with diagnosed asthma were drawn from a lung sound database and analyzed in the time-bi-frequency domain. The analysis results justified the efficient performance of this combinatory approach to reveal and quantify the evolution of the nonlinearities of wheezes with time.

Keywords: Wheeze analysis; Wavelet bispectrum; Wavelet bicoherence; Quadrature phase-coupling; Asthma

1. Introduction

From the years of Hippocrates, it has been known that breath sounds contain information about pulmonary dysfunction. After the introduction of the stethoscope by Laënnec in 1816 [1], stethoscope-based auscultation has been used until nowadays by physicians as an easy and noninvasive way to evaluate and diagnose patients with lung disease. Nevertheless, this procedure suffers from subjectivity in the interpretation of its diagnostic information, paving the way for the involvement of sound signal digitization [2,3] and novel objective processing techniques that track the diagnostic characteristics of the relevant pathology and assist the clinician in everyday practice.

From the variety of abnormal breath sounds, wheezes are frequently met, as they are related with obstructive airways diseases, such as asthma and chronic obstructive pulmonary disease (COPD) [4]. In particular, wheezes have been characterized as the acoustic manifestation of airways obstruction [5]. Moreover, wheeze monitoring has been used for the assessment of nocturnal asthma and response to therapy [6], as a parameter to rate the severity of asthma, as an indicator of airway obstruction in infants, or as a classifier in epidemiologic surveys [7]. Wheezes are continuous adventitious lung sounds with time duration greater than 150 ms [2], which discriminates them from other abnormal sounds, such as crackles, which typically last less than 20 ms [8]. The waveform of a wheeze in time domain resembles that of a sinusoidal sound, justifying its musicality; hence, wheezes appear as distinct peaks in the frequency domain (> 100 Hz) [8]. As being superimposed on normal breath sounds, either during inspiration or expiration, exhibiting varying duration, amplitude, frequency content and number of harmonics, wheezes justify their adventitious nature. The number of wheezes and their distribution across the chest are related to the distribution of the pathology. A single wheeze heard over a limited area indicates the presence of a single partially obstructed airway, while multiple wheezes, of varying pitch, starting and stopping at slightly different times, heard diffusely over both lungs are an indication of asthma and COPD. Although the pathophysiologic mechanisms that generate wheezes are not entirely clear [7], they are believed to be produced by periodic oscillations of the air and airway wall and are categorized into monophonic and polyphonic wheezes [2,10]. To this end, analysis of the harmonic interaction of wheezes becomes important.

The musical sound of a wheeze is easily recognized by the ear, but computerized analysis of lung sounds has been

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introduced in wheeze analysis because it allows a reproducible quantification of wheezing, in contrary to subjective auscultation [9]. The most straightforward methods that have been proposed for automatic wheeze detection are based on searching for peaks in successive spectra [7]. Efforts to further improve their reliability have combined spectra with criteria or rules concerning the amplitude, duration and pitch range of wheezes [9–11]. However, these algorithms show a great correlation of the number of detected wheezes with sound signal amplitude, therefore efforts have been made towards the design of wheeze detectors that are independent of sound attenuation [12]. Although significant scientific effort was placed on the detection of wheezes, a limited number of works dealt with the nonlinear interactions of their harmonic content. Some indicative works include bicoherence-based [13] and phase space analysis [14].

In the present study, wheeze analysis is performed combining continuous wavelet transform (CWT) with third-order statistics/spectra. More precisely, quadrature phase-coupling between wheeze harmonics is investigated, based on wavelet bispectrum (WBS) and wavelet bicoherence (WBC) as a means to track and quantify the evolution of the nonlinear characteristics of wheezes within the breathing cycle. The combination of wavelet transform with third-order statistics/spectra introduces the nonlinear analysis of wheezes in the time-bi-frequency domain. The proposed analysis was tested on breath sounds with wheezes recorded from asthmatic patients. The current work attempts to introduce a novel wheeze analysis based on a mathematical approach that sheds light to their nonlinear characteristics associated with the underlying pathology.

2. Materials and methods

2.1. Analysis of wheezes

The musicality that characterizes wheezes is reflected in the power spectrum as distinct peaks. Previous works [2,11] have set empirical criteria to distinguish wheezing from other spectral peaks associated with normal breath sound fluctuations, other abnormal breath sounds or ambient noise, such as speech. However, second-order statistics fail to reveal any characteristics of the nonlinear interaction of the distinct harmonics, as they are expressed in their phase relation. To this end, higher-order statistics, which preserve the phase information of the signal, can be used to detect the nonlinearity (quadrature phase-coupling) and deviation from Gaussianity of the signals. Nevertheless, with this approach, the evolution of nonlinearities with time is not taken into account. To be able to achieve this aim, higher-order statistics are combined with CWT, which offers a time-scale representation of a signal, hence, it allows the introduction of a time axis in a natural way, assisting the identification of nonlinearities of the localized features (i.e., wheezes) within the signal (i.e., breathing cycle). For the analysis of wheezes, WBS, WBC, summed wavelet bicoherence (SWBC) and evolutionary wavelet bicoherence (EWBC) were used. The proposed analysis was applied to breath sounds from patients with asthma, exhibiting a variety of wheezes (i.e., monophonic/polyphonic) during their breathing cycle. These signals were used as test-bed for the justification of the nonlinear characteristics of wheezes. The following subsections provide an insight to the mathematical background of the analysis methodologies used.

2.2. Continuous wavelet transform (CWT)

Wavelet analysis is based on the convolution of the signal under investigation with a set of finite wavelike functions, known as wavelets [15]. These functions reveal signal transient characteristics, which are obscured by the trigonometric functions used in Fourier analysis [16]. There are several types of wavelet transforms, among which one may be preferred to the others, depending on the application. In our case, the CWT was used, defined as [15]

$$W_x(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right) \mathrm{d}t, \tag{1}$$

where $x(t)$ is the signal in time-domain, $(x(t) \in L^2(\Re))$, $*$ is the complex conjugate and $\psi(t)$ is the mother wavelet scaled by a factor a, $a > 0$, and dilated by a factor b. In the CWT, the time and scale parameters (a, b) are continuous.

In the current study, the results are presented in the time-frequency domain, rather than in the time-scale scheme, for ease of interpretation. The frequencies are inversely proportional to the scales. For the realization of the CWT, various wavelets (Haar, Mexican Hat, Morlet, complex Morlet) have been tested, and the complex Morlet wavelet has been selected as the most appropriate for the proposed analysis. Specifically, the complex Morlet wavelet is a Gaussian-windowed complex sinusoid; hence, its second-order exponential decay results in very good time localization during the wavelet transform [17]. Moreover, the complex Morlet wavelet function provides information about both amplitude and phase [17], and it is better adapted for capturing coherence between wheeze harmonic frequencies. The complex Morlet wavelet is given by [18]

$$\psi(t) = \frac{1}{\sqrt{\pi f_{\mathrm{b}}}} \mathrm{e}^{-t^2/f_{\mathrm{b}}} \mathrm{e}^{j2\pi f_{\mathrm{c}} t}, \tag{2}$$

where f_{b} is a bandwidth parameter and f_{c} is the wavelet center frequency. By this equation it can be seen that this wavelet exhibits direct analogy to the Fourier transform.

2.3. Bispectrum (BS)–Bicoherence (BC)

The bispectrum (BS) $B(\omega_1, \omega_2)$ of a process $\{X(k)\}$ is defined as [19]

$$B(\omega_1, \omega_2) = E\{X(\omega_1)X(\omega_2)X^*(\omega_1+\omega_2)\}, \tag{3}$$

where $E\{\cdot\}$ is the expectation value, $X(\omega_i)$, $i = 1, 2$ is the complex Fourier coefficient of the process $\{X(k)\}$ at frequencies ω_i and $X^*(\omega_i)$ is its complex conjugate. The bicoherence (BC), or normalized BS, is defined as [19]

$$b(\omega_1, \omega_2) = \frac{B(\omega_1, \omega_2)}{[P(\omega_1)P(\omega_2)P(\omega_1+\omega_2)]^{1/2}}, \tag{4}$$