Effects of Respiration on Heart Sounds Using Time-Frequency Analysis

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Abstract

The time-frequency diagrams of three recording sets at the aortic area are compared: normal breathing, held inspiration, and held expiration. The time-frequency (TF) analysis of heart sounds is proposed as an auxiliary method in cardiac auscultation. The Continuous Wavelet Transform (CWT), using the Morlet wavelet, is applied to the cardiac cycles in order to observe the timing and frequency of the events. Time-frequency diagrams of sounds from pathologic and non-pathologic subjects are presented. Comparing the different manoeuvres provides extra information that may not be obvious in recordings during normal breathing, allowing a better identification of cardiac events.

1. Introduction

Cardiac auscultation remains the first diagnostic tool used to detect abnormalities in the mechanical activity of the heart. The accuracy of this method depends on the experience and hearing ability of the examiner. It is therefore crucial that physicians develop their auscultation skills.

The art of listening to heart sounds and interpreting their meaning is difficult to master as they are the result of several events of short duration that occur simultaneously or very close in time. In addition, the human ear has low sensitivity in the frequency region where heart sounds are found. Also, there are many variables that change from patient to patient such as physical constitution, age, and health condition. This implies an arduous training in order to achieve proficiency.

The recording of heart sounds is one of the techniques that has proved very useful in the description of cardiac events as well as a teaching aid [1]. The main advantage is that the sounds can be played back at any time and compared with past and future recordings allowing a follow up of the patient's condition. The graphic display in portable equipment has also been used successfully to complement auscultation with visual feedback [2,3]. However, a display of time-amplitude of the sounds is not always easy to interpret and does not show clearly events that occur simultaneously. The use of TF analysis techniques can overcome these disadvantages.

The CWT is a time-scale analysis technique. A relationship between scale and frequency can be established [4]. Its application to the analysis of heart sounds was first reported by Khadra et al. [5]. Its performance against other TF techniques has also been reported [6].

Experience with earlier heart sound recording and analysis has showed us that the extraction of features from the signal collected during normal respiration sometimes becomes impossible, mainly in patients with cardiac abnormalities, whose characteristics are important to obtain [7,8]. It is well known that the use of certain manoeuvres in respiration during auscultation is essential for differential diagnosis [1]. However, an evaluation of these manoeuvres and the utilisation of TF techniques has not been reported as far as we are aware.

A new set of recordings has started in order to assess the information provided during held inspiration and held expiration. This contribution presents preliminary results comparing, by visual inspection, TF diagrams of the three different recordings.

2. Methods

2.1. Data acquisition

Data has been collected at the Cardiology Research Department of the Royal Sussex County Hospital. The heart sounds from 16 volunteers have been recorded, 7 subjects without pathologic signs and 9 diagnosed as suffering from aortic stenosis. Before beginning the examination full written consent was obtained and the manoeuvres required were explained. A contact sensor HP21050A was placed on the aortic area with the patient in semi-supine position. The heart sound signal was filtered below 10 Hz and above 750 Hz, amplified, and then digitised with 12-bit resolution at a sample frequency of 4096 Hz using an A/D converter installed in a PC.

Three recordings per subject were taken: 1) during the normal respiratory cycle, 2) during maximum held inspiration and, 3) during maximum held expiration. A three-lead electrocardiogram (ECG) was recorded simultaneously. All data was saved in hard disc for off line processing.

2.2. The wavelet transform

Analysis is achieved using the wavelet transform [4]. It has been used, amongst others, in a number of biomedical areas [9]. This transform basically decomposes the signal on to a series of functions that are the result of the shifting and scaling a basis function called "mother wavelet". The CWT is defined as:

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int h^{*}\left(\frac{t-b}{a}\right) s(t)dt \qquad (1)$$

Where *h(t)*, *s(t)*, *a*, and *b* are the mother wavelet, analysed signal, scale, and shifting factor, respectively. CWT(a,b) is a matrix of coefficients whose value indicate the similarity of the analysed signal to the mother wavelet. The selection of the latter then is very important and depends on the purpose of the study and the characteristics that are required to observe [9]. The Morlet wavelet was selected for this application. It is a modulated Gaussian function that can be expressed as:

$$h(t) = \exp(j\omega_0 t)\exp(-t^2/2) \qquad (2)$$

when ω_0 takes the value of 5 rad/sec [10]. It provides the best compromise in time and frequency resolution compared with the other mother wavelets available in the wavelet toolbox of Matlab™.

2.3. Data analysis

The QRS complex of the ECG signal was detected and used as a reference to segment the heart sounds into cycles. The heart sound signal was further filtered in software with a second order high-pass filter at 30 Hz cut-off frequency in order to attenuate low frequency components that mask some of the events, preventing their identification by visual inspection of the graphic display. Then, five cycles of each recording were selected and the Hilbert transform of each cycle was analysed with the Matlab™ function CWT. Eighty scales were used to cover a frequency range from 16 to 500 Hz. They were calculated to have the same number of voices per octave with the formula:

$$a = 2^{j+\frac{m}{M}} \qquad (3)$$

where j=3,4,...,7 is the number of octaves, M=16 is the number of voices per octave, and m=1,...,M.

The coefficients of the 15 cycles analysed were plotted showing time, frequency and intensity. The latter was represented in a colour scale as it shows best the different components. Contour plots with grey scale are presented in this paper as they show best the features in black and white. The amplitude has been normalised, representing the maximum intensity in white and the minimum in dark grey.

3. Results

In order to emphasise the variation of characteristics from patient to patient even with non-pathologic condition, the heart sounds from 4 young adults are presented.

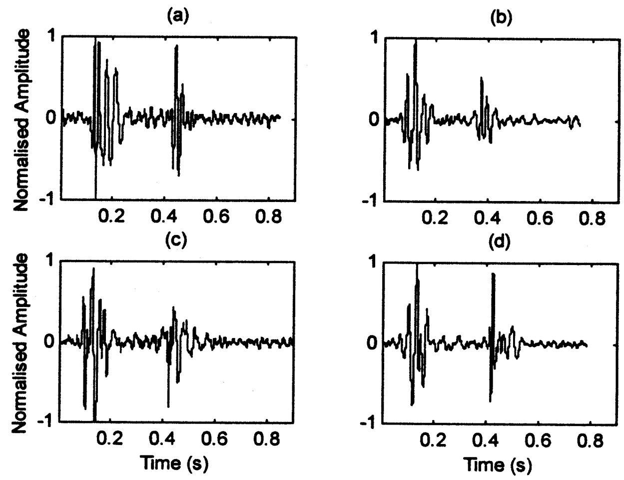

Figure 1. Time-amplitude display of one cardiac cycle from 4 young male subjects with healthy heart. Recording during held expiration. Age (years): (a) 29, (b) 25, (c) 30, (d) 29.

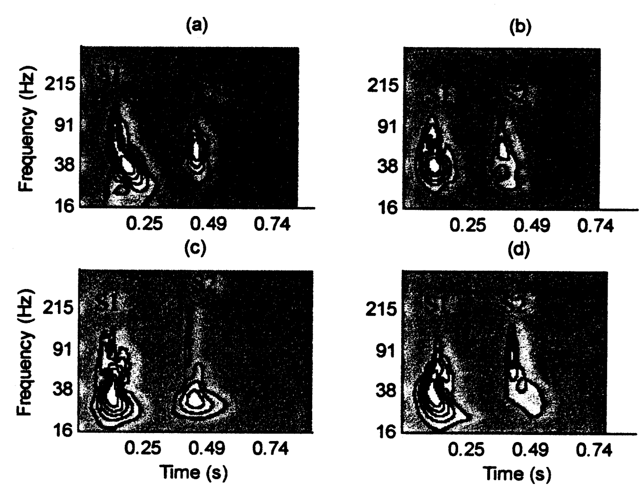

Figure 2. Time-frequency display of one cycle, from patients presented in figure 1.

Figure 1 shows the time-amplitude display. Note that the first (S1) and second (S2) heart sounds, the two main sounds in a heartbeat, are easily identified but not their components. Figure 2 shows the time-frequency display of the same sounds. Note that in three of them (2b, 2c, 2d) the two components of S2 become evident even when they are overlapped in time as in figure 2b and 2c.

An example of the heart sounds from a 27 years old patient with aortic stenosis caused by having a bicuspid aortic valve is depicted in figures 3 to 5. This abnormality is the commonest form of congenital heart disease. The diagnosis was confirmed by echocardiography.

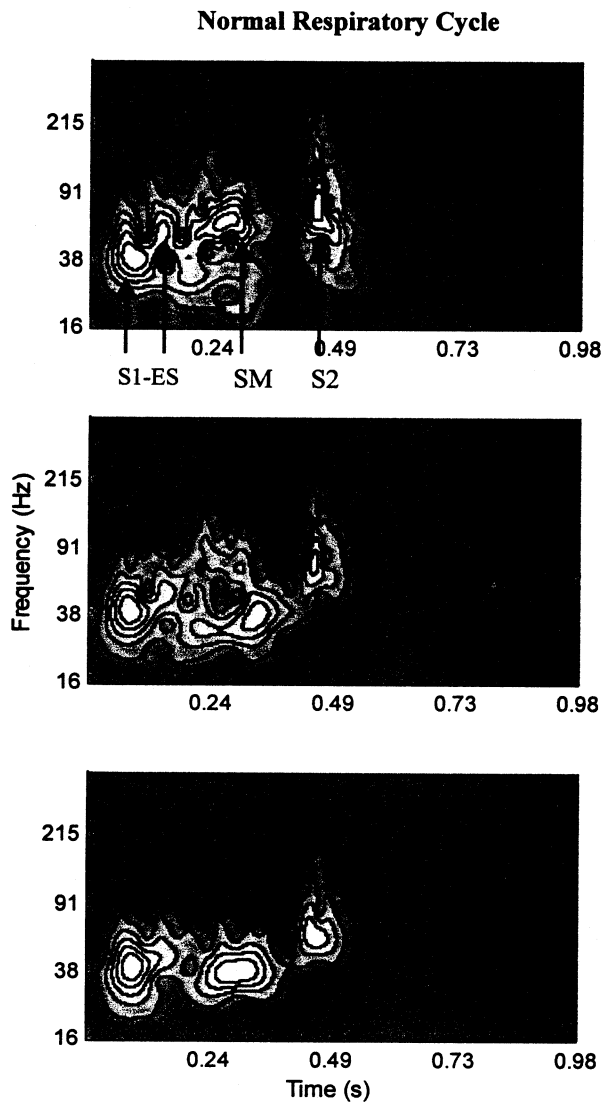

Figure 3. Three consecutive cycles recorded during normal respiratory cycle.

Three consecutive cycles during normal breathing (fig 3) show S1, S2 and the systolic murmur (SM). The presence of an ejection sound (ES), typical in a bicuspid aortic valve, is not clearly resolved. The three cycles during held inspiration (fig 4) show that the ejection sound becomes closer to S1 whereas, the three cycles during held expiration (fig 5) clearly show S1 and the ejection sound as separate events.

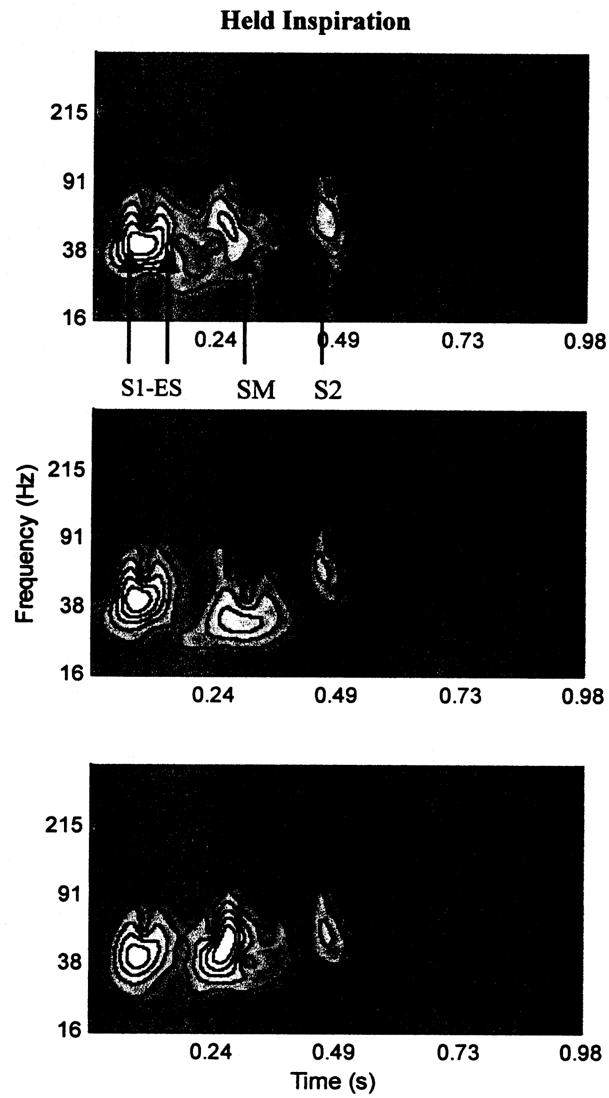

Figure 4. Three consecutive cycles recorded during held inspiration.

The observations made about the presence of split S2 and ejection sounds are only two examples in which the combination of time-frequency display and manoeuvres in respiration can help. Although these events are fairly easy to distinguish by experienced specialists, they are usually missed or misinterpreted by the non-experienced. For instance, the ejection click can be interpreted as a split S1, but looking at their separation in the graphic display this can be confirmed.

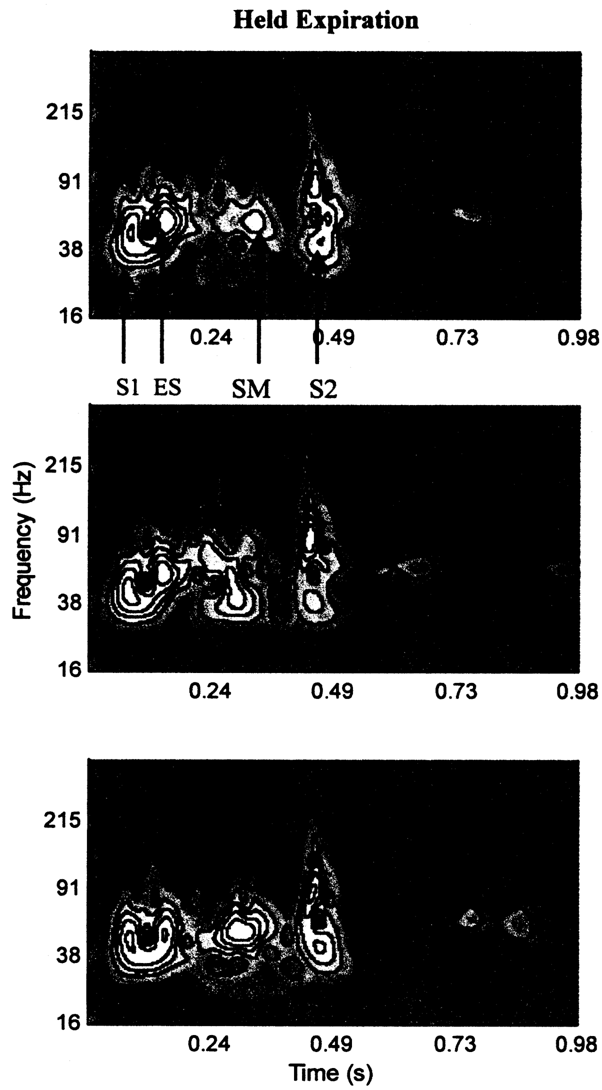

Figure 5. Three consecutive cycles recorded during held expiration.

4. Discussion and conclusions

The advantages of the time-frequency display combined with the manoeuvres in respiration are demonstrated. It is known that the time resolution can not be improved without losing resolution in frequency. The detection of events that occur very close in time could be observed if the time resolution were increased. However, events that occur simultaneously but with different frequency would not be seen. On the other hand, increasing the frequency resolution more details about the frequency components would be observed but resolution in time would be affected. The recordings during manoeuvres in respiration overcome this disadvantage. Typical results taken from the set of 16 patients are presented.

The implementation in real time of this signal processing technique could be used to assist cardiac auscultation either to improve physicians' skills or to overcome human ear limitations.

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