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Analysis of Heart Rate Variability Using Time-Varying Frequency Bands Based on Respiratory Frequency

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Abstract— **In this paper a methodological approach for the analysis of nonstationary heart rate variability (HRV) signals using time-varying frequency bands based on respiratory frequency is presented. Spectral analysis of HRV is accomplished by means of the Smoothed Pseudo Wigner Ville distribution. Different approaches to the definition of the low frequency (LF) and high frequency (HF) bands are considered which involve respiratory information, derived either from a respiratory signal or from the ECG itself. Results are presented which derive from recordings acquired during stress testing and induced emotion experiments.**

I. INTRODUCTION

Spectral analysis of heart rate variability (HRV) is widely used as a non-invasive technique for the assessment of the autonomic nervous system (ANS) activity on the heart and of the balance between its two main branches, the sympathetic and parasympathetic systems. Standards of measurement, physiological interpretation and clinical use of HRV have been published, involving three different components: a very low frequency (VLF) component in the range between 0 and 0.04 Hz, a low frequency (LF) component between 0.04 and 0.15 Hz, and a high frequency (HF) component between 0.15 and 0.4 Hz [1]. The power in the LF band is considered to be a measure of the sympathetic activity on the heart, at least when expressed in normalized units, although its interpretation is controversial, as e.g. when the respiratory frequency lies in the LF band. The power in the HF band is considered to be a measure of the parasympathetic activity and mainly due to respiratory sinus arrhythmia (RSA).

The respiratory frequency is not restricted to the band from 0.15 to 0.4 Hz. For instance, the respiratory frequency can be as low as 0.1 Hz during relaxation and as high as 0.7 Hz during intense exercise. In these situations the analysis of HRV within the standard frequency bands would yield inaccurate estimates of the ANS activity. This is of particular importance in situations where the goal is to track changes in sympathetic and parasympathetic balance, observed during, e.g. stress testing, induced emotion experiments, Valsalva maneuver, and tilt testing. Several methods for nonstationary analysis of HRV have been proposed in the literature [2]. Information of respiratory frequency has been included in HRV analysis for the estimation of the parasympathetic activity in different ways [3], [4], [5], [6].

The purpose of this paper is to introduce a method for nonstationary HRV analysis, using time-varying frequency bands related to the respiratory frequency. The proposed method was originally developed in the context of stress testing, but it is equally suitable for many other nonstationary situations.

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II. METHODS

A. Limitations of HRV analysis

Prior to any analysis of HRV there is a limitation that should be taken into account. The intrinsic sampling frequency of HRV is given by the heart rate (HR). As a result, the maximum frequency with physiological meaning which can be analyzed is defined as half the mean HR in the analyzed interval [7]; spectral components above this frequency are due to spectrum repetitions. Another consequence of this limitation is that when the respiratory frequency exceeds this frequency, aliasing occurs already at the natural sampling of the heart, which will be present even at frequencies below half the mean HR.

B. Time-frequency analysis

An approach to analyze nonstationary HRV is the use of time-frequency (TF) methods, which can be divided into three main categories: nonparametric linear TF methods based on linear filtering, including the short-time Fourier transform [9], [8] and the wavelet transform [4], [5], nonparametric quadratic TF representations, including the Wigner-Ville distribution and its filtered versions [10], [11], [3], [12], and parametric time-varying methods based on autoregressive models with time-varying coefficients [13], [14], [15].

In this paper the Smoothed Pseudo Wigner-Ville distribution (SPWVD) is preferred since it provides better time-frequency resolution than nonparametric linear methods, an independent control of time and frequency filtering, and power estimates with lower variance than parametric methods when rapid changes occur [11]. The main drawback of the SPWVD is the presence of cross-terms, which should be suppressed by the time and frequency filtering.

The SPWVD of the discrete signal $x(n)$ is defined by [16]

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$$X(n,m)=2\sum_{k=-N+1}^{N-1}|h(k)|^2\sum_{p=-M+1}^{M-1}g(p)r_x(n+p,k)e^{-j2\pi km/N}, \quad (1)$$

where n and m are the discrete time and frequency indexes, respectively, $h(k)$ is the frequency smoothing symmetric normed window of length $2N-1$, $g(p)$ is the time smoothing symmetric normed window of length $2M-1$ and $r_x(n,k)$ is the instantaneous autocorrelation function, defined as $r_x(n,k) = x(n+k)x^*(n-k)$.

C. Frequency band definitions

As stated above the standard definitions of the LF and HF bands are inappropriate when the respiratory frequency is not restricted to 0.15–0.4 Hz. Different approaches can be considered to overcome this limitation:

C.1 The HF band can be extended to include the whole range of potential respiratory frequencies during the recording [9], [4], [6]. The upper limit of the HF band must be limited by half the mean HR.

C.2 The HF band can be centered on the respiratory frequency [3], [5], [6]. The HF bandwidth can be constant [3] or time-dependent [5], [6]. For example, in [5] the HF bandwidth was defined from the power spectrum of the respiratory signal.

In both approaches the LF band can be defined either from its lower limit 0.04 Hz to the lower limit of the HF band, or in its standard way (0.04–0.15 Hz), assuming that the sympathetic activity always lies within this band. In the latter case, a note of caution should be considered when the respiratory frequency is lower than 0.15 Hz and the LF and HF bands overlap.

The right choice of the frequency band definitions depends to some extent on the application.

D. Respiratory information

The above frequency band definitions require the knowledge of respiratory information, which can be obtained either from a simultaneously recorded respiratory signal or from an ECG-derived respiratory signal [17]. The latter option avoids direct recording of a respiratory signal, thus being preferable during, e.g., stress testing.

III. RESULTS

A. Stress testing

The first application of the proposed methodology is the analysis of HRV during stress testing. A database of standard 12-lead ECG and respiratory signals, simultaneously recorded during stress testing at the University Hospital of Lund, is used. The ECG is sampled at 1 kHz and the respiratory signal at 50 Hz. The stress test was performed on a bicycle ergometer whose intensity increased at a steady rate each minute. The subjects were asked to cycle at a rate of 60 rpm. A detailed description of the database is described in [17].

The HRV signal is obtained as follows. First, QRS detection marks are obtained by ARISTOTLE [18] using a rule based on the QRS complex gravity center. The HR signal is derived from the QRS detection marks, following a method based on the integral pulse frequency modulation (IPFM) model, which also accounts for the presence of ectopic beats [19]. Then, the mean HR signal is obtained by low-pass filtering the signal with a cut-off frequency of 0.03 Hz. Finally, the HRV signal is the result of subtracting the mean HR from the instantaneous HR signal. The HRV signal is resampled at 8 Hz.

The SPWVD is applied as in (1), $x(n)$ being the analytic signal of the HRV signal. A 12.625-second rectangular window $g(p)$ is used for time smoothing while an exponential window $h(k)$, with decaying factor 16^{-1} s^{-1} and frequency resolution 128^{-1} Hz, is used for frequency smoothing.

In this application the standard LF band definition is used, whereas the HF band is defined according to *C*.2, i.e., centered on the respiratory frequency with a bandwidth of 0.25 Hz (the standard HF bandwidth).

Figure 1 displays the SPWVD of a HRV signal during a stress test. Half the mean HR, expressed in Hz, is superimposed in solid line representing the upper limit for HRV analysis. Limits of the standard LF and HF bands are plotted in dotted lines. The limits of the HF band, defined in this application as centered on the respiratory frequency, are shown in dashed lines.

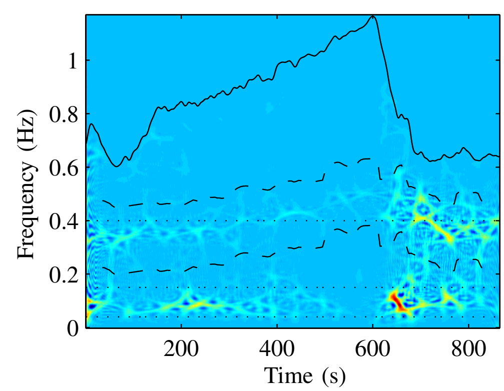

Fig. 1. The SPWVD of a HRV signal during a stress test. Half the mean HR (in Hz) is plotted in solid line. Limits of the standard LF and HF bands are plotted in dotted lines. The limits of the new HF band centered on the respiratory frequency are shown in dashed lines.

It can be appreciated from Fig. 1 that the respiratory frequency exceeds the upper limit of the standard HF band from about second 400 to 700 of the stress test. Therefore, analysis of HRV in the standard frequency bands would have yielded an inaccurate interpretation of the evolution of the parasympathetic activity. The new definition of the HF band allows the tracking of the parasympathetic activity changes. It can be observed that the power in the HF band decreases during exercise, reflecting a parasympathetic withdrawal, while it increases during recovery. The LF power exhibits a similar behaviour. A decrease in LF power is observed during exercise becoming nearly suspended when the exercise intensity is maximal and no variability is observed in the HR. At that point the HF power has been decreased but not suspended, maybe reflecting a mechanical stretch of the sinus node due to respiration [20]. Once exercise finishes, the increase in LF power may be attributed to sympathetic activation and a rapid decrease in HR, which leaks from the VLF to the LF band.

Another example is displayed in Fig. 2. Here the respiratory frequency exceeds the standard HF band during most of the stress test, further underlining the need for respiratory frequency information to define the frequency bands in HRV analysis.

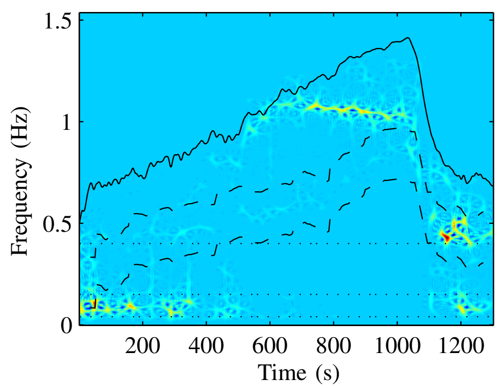

Fig. 2. The SPWVD of a HRV signal during a stress test, showing the effect of the subject's cycling at 60 rpm. Notation as in Fig. 1.

Note that in this case if the HF band would have been defined using approach *C*.1, i.e., extended from 0.15 Hz to half the mean HR, the power of the spurious component at 1 Hz would have been interpreted as an increase in the parasympathetic activity. However, this spurious component is thought to be induced by the cycling of the subjects at 60 rpm, causing a synchronized rotation of the heart's electrical axis originating a variability of approximately 1 Hz in the QRS detection marks. This spurious component has been observed in some of the stress tests analyzed, being more evident in cases of reduced RSA. It has also been noticed that the power of this component is dependent on the leads used for the QRS detection.

B. Induced emotion experiments

Another application is the analysis of HRV during induced emotion experiments. A database of ECG, respiration, blood pressure, skin temperature and galvanic skin response has been recorded during induced emotion experiments at University of Zaragoza. The limb ECG leads I, II and III were recorded at 1 kHz and the respiratory signal at 125 Hz. Four emotions (sadness, anger, fear and happiness) were induced by videos in two sessions of two emotions each. Each emotion video was preceded by a relaxing video which served as physiological parameters' baseline, and followed by another relaxing video to ensure that the subject's physiological parameters returned to the baseline.

The HRV signal is obtained and analyzed in a way similar to that described in Section III-A.

Figure 3(a) displays the SPWVD of a HRV signal during an induced emotion experiment in which the beginning and end of the emotion video which induced fear are plotted in dotted line.

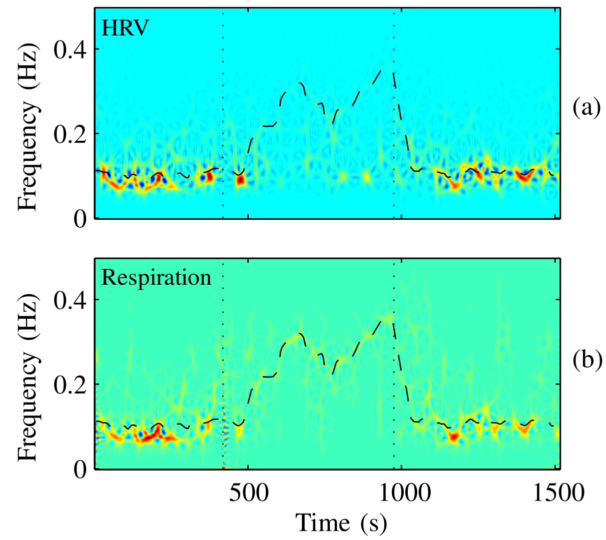

Fig. 3. The SPWVD of (a) a HRV signal and (b) the simultaneous respiratory signal during an induced emotion experiment. The respiratory frequency is superimposed on dashed line. Dotted lines indicate the beginning and end of the emotion video which induced fear.

Standard analysis of HRV would have revealed a predominant sympathetic activity while a suspended parasympathetic activity during both relaxing videos. During the fear-inducing video, standard analysis of HRV would have shown a considerably reduction of sympathetic activity as well as an increase in parasympathetic activity. However, this analysis does not take into account respiratory frequency information.

The analysis of the simultaneously recorded respiratory signals reveals a respiratory frequency of about 0.1 Hz during the relaxing videos and frequencies around 0.3 Hz during the fear video. Figure 3(b) displays the SPWVD of the simultaneous respiratory signal of the HRV signal shown in Fig. 3(a). This result suggests that, in the relaxing videos, the LF power accounts for both sympathetic activity and RSA, thus invalidating the previous interpretations.

IV. DISCUSSION

The methodology proposed in this paper has been developed in the context of stress testing, whose characteristics determine some of the choices made. However, it is general and flexible enough to be applied to a variety of situations.

The spectral analysis of nonstationary HRV signals has been addressed by means of the Smoothed Pseudo Wigner Ville distribution because of its properties stated in Section II-B, but other time-frequency methods can be applied depending on the nonstationarity of the HRV.

Two approaches have been presented for the definition of the HF band which accounts for respiratory frequency information. The main limitation of the approach *C*.1 (from 0.15 Hz to half the mean HR) is that it may include HF components nonrelated to the parasympathetic activity, as shown in Fig. 2. That is the reason why approach *C*.2 (centered on respiratory frequency) is preferred in this paper.

The HF bandwidth has been taken 0.25 Hz, as the standard HF bandwidth. However, a bandwidth of 0.1 Hz was used in [9], closer to the standard LF bandwidth. A different approach is to considered a variable HF bandwidth, as in [5] where it is defined from the power spectrum of the respiratory signal. The main limitation of this approach is that it requires the direct recording of respiratory signal, which is not always suitable. If the bandwidth would be estimated from the power spectrum of the HRV signal itself, the much higher variability may yield inaccurate estimates. Further analysis would be needed to determine the optimum HF bandwidth.

In this paper, the standard LF band has been used. When the respiratory frequency is below 0.15 Hz, the LF and HF bands overlap so that estimates of sympathetic and parasympathetic activities are no longer valid. In this situation, an entrainment between the two rhythms occurs and the separation of the two activities is not trivial since non-linear mechanisms and interactions are involved [21]. This was exemplified in Section III-B. Different approaches have been considered to define the LF band. In [9] the LF band is defined from 0.04 Hz to the lower limit of the HF band. This definition is inaccurate when respiratory frequency is below 0.15 Hz. Another approach has been to define the LF band from the HR power spectrum, searching for the maximum in the region from 0.02 to 0.15 Hz and locating the two minima surrounding the peak [5]. This approach has the limitations of the high variability of the HR power spectrum and the overlapping of the two rhythms when the respiratory frequency is below 0.15 Hz.

It has made evident the need for the inclusion of respiratory information in HRV analysis. However, this does not require the direct recording of respiratory signal, since the information needed can be derived from the ECG itself [17].

V. CONCLUSION

A methodological approach for the analysis of nonstationary HRV using time-varying frequency bands based on respiratory frequency has been presented. The methodology has been developed and applied in the context of stress testing, although it is general enough to be applied to a variety of situations, such as induced emotion experiments.

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