Segmented-Beat Modulation Method-Based Procedure for Extraction of Electrocardiogram-Derived Respiration from Data Acquired by Wearable Sensors During High-Altitude Activity

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Abstract

High-altitude sports are affected by hypoxic stress-related alterations and, consequently, may trigger severe events such as sport-related sudden death; thus, into-the-field monitoring of respiration is essential. A Segmented-Beat Modulation Method (SBMM)-based procedure was previously proposed to extract electrocardiogram (ECG) - derived respiration (EDR). The aim of this study is to validate SBMM-based procedure for EDR extraction in data acquired by wearable sensors during high-altitude physical activities. Respiration signal (RES) and ECG were recorded using BioHarness 3.0 by Zephyr from 3 expeditioners, while performing a trek up to 4,556m of altitude. EDR was extracted from ECG by SBMM-based procedure. RES and EDR were segmented into 60-second windows and characterized in terms of breathing rate (BR_{RES} and BR_{EDR}, respectively). BR_{RES} and BR_{EDR} were compared by absolute difference ($|\delta|$), concordance correlation coefficient (CCC) and linear regression analysis. Results confirmed EDR goodness, proved by low values of $|\delta|$ (2[1;4]cpm), satisfactory CCC (0.62; P-value<0.05) and good fit of regression line ($BR_{RES}=0.91 \cdot BR_{EDR}+4.47$cpm). In conclusion, SBMM-based procedure is a good method to extract EDR from data acquired by wearable sensors during high-altitude physical activities.

1. Introduction

High-altitude sports are becoming very popular [1]. Every year more than 10 million of people practice sport in Alps [2] and more than 35 million Americans travel to altitudes over 2,400m [1]. These activities are excellent as good life practice, and also proved to be efficient as rehabilitative therapies [3]. However, physical activity and exposure to high altitudes may trigger severe events, such as sport-related sudden deaths and emerging diseases [1]. One of the main causes of these fatal events is hypoxia, defined as a state in which oxygen is not sufficient at the tissue level to maintain adequate homeostasis [4,5]. Lack of oxygen requires higher respiratory activity, reflecting into an increase of respiratory and cardiac rhythms [6]. High respiratory efforts may be triggers of fatal events. Consequently, monitoring of respiratory parameters of athletes is essential to prevent sport-related death.

Nowadays, use of wearable sensors is spreading [7]. These sensors can directly record several biosignals [7], among which the respiration signal (RES), and also provide indirect physiological measures, such as breathing rate series (BRS). Athletes are used to use wearable sensors to monitor their activity and to optimize their performance, but these sensors are also potential efficient instruments to monitor athletes' respiration into-the-field, if the quality of measurements is clinically reliable. Recent studies suggest that, while the quality of direct recordings by wearable sensors is very high, the quality of indirect physiological measurements may not be [8]. Moreover, the battery and the memory of the device may not allow storage of long recordings in case of high number of biosignals [7].

To overcome these limitations, several studies in the literature propose to record the electrocardiogram (ECG), and to use it to derive not only cardiac but also other physiological information, such as respiratory one [9-11]. This approach guarantees good performance in long-term multi-parameter monitoring. The Segmented-Beat Modulation Method (SBMM)-based procedure is able to extract the ECG-derived respiration (EDR) [12,13] from single-lead ECGs, thus also providing respiratory information. Already tested in controlled low-noise conditions such as rest and sleep [12,13], this innovative method was never assessed in presence of high-noise, such as into-the-field exercise.

Given the into-the-field respiratory monitoring importance, this study aims to validate the SBMM-based procedure for EDR extraction in data acquired by wearable sensors during high-altitude physical activity.

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2. Materials and Methods

2.1. Data

Data consists of cardiorespiratory signals, recorded by the chest strap BioHarness 3.0 by Zephyr (www.zephyranywhere.com), a reliable wearable sensor [13-18] that directly records BRS (cpm; sampled at 1Hz), RES (mV; sampled at 17Hz) and ECG (mV; sampled at 250Hz). Data were acquired from 3 volunteers (Table 1) during a multidisciplinary expedition at Monte Rosa (Alps, Italy), from August 29th to September 2nd, 2021. Expeditioners performed a trek up to 4,556m of altitude, arriving to Capanna Margherita (the highest lodge of European mountains). The volunteers were monitored during the entire trek up; recording lengths are reported in Table 1.

Researchers from University of Chieti (Italy), who already tested the use of BioHarness 3.0 by Zephyr during previous expeditions [19], designed the study. All participants signed an informed consent; the study was an ancillary project of wider studies approved by institutional expert committees.

2.2. Electrocardiogram-Derived Respiration Extraction

ECG was processed to extract EDR according with the procedure represented in Figure 1.

Electrocardiographic R-peak positions were identified by a new procedure based on the ensemble empirical mode decomposition (EEMD) [20], which proved to be efficient in case of high level of noise. Then, R-peak positions and ECG served as inputs of the Segmented-Beat Modulation Method (SBMM), a robust template-based filter with the peculiarity of being able to maintain information about local heart-rate variations [5,6,21].

Breathing causes a low-frequency modulation of the ECG, usually considered as noise, and thus to be removed, by the SBMM. Therefore, the respiratory signal, together with other interferences and noises also affecting the ECG, is contained in the residual ECG (rECG), computed by subtracting the SBMM-filtered clean ECG (cECG) from the original ECG.

Table 1. Anamnestic data of the 3 volunteers involved in the study.

Volunteers	**1**	**2**	**3**
Sex	female	female	female
Height (cm)	161	163	161
Weight (kg)	52.4	62.7	59.1
Age (years)	25	28	26
Blood pressure (mmHg)	64/100	70/110	67/106
Recording lengths (hours)	17.9	13.7	19.1

To obtain a clean signal representing the breathing activity, the electrocardiogram-derived respiration signal (EDR, mV) was obtained by 3rd-order spline interpolation of the electrocardiographic R-peak positions on the rECG.

2.3. Feature Extraction and Statistics

BRS, RES and EDR were segmented into 60s windows. All signals were corrupted by high-level of noise (considering the highly intensive exercise), thus only simultaneous windows that presented reliable R-peak identification were considered and characterized in terms of heart rate (HR). Each BRS window was characterized by the BRS median breathing rate (BR_{BRS}). RES and EDR were processed to extract the breathing events, from which the corresponding breathing rate series were computed. Each RES window was characterized by the median breathing rate (BR_{RES}) of the breathing rate series corresponding to RES. Each EDR window was characterized by the median breathing rate (BR_{EDR}) of the breathing rate series corresponding to EDR.

Normality of distributions was assessed by Lilliefors' test. Not normal distributions are reported as 50th[25th;75th] percentiles. BR computations were assessed by test of equivalence (equivalence margins equal to ±2cpm), absolute difference (|δ|) analysis, concordance correlation coefficient (CCC) analysis and linear regression analysis, comparing BR_{BRS} vs. BR_{RES}, BR_{BRS} vs. BR_{EDR} and BR_{RES} vs. BR_{EDR}. Statistical significance was set at 0.05.

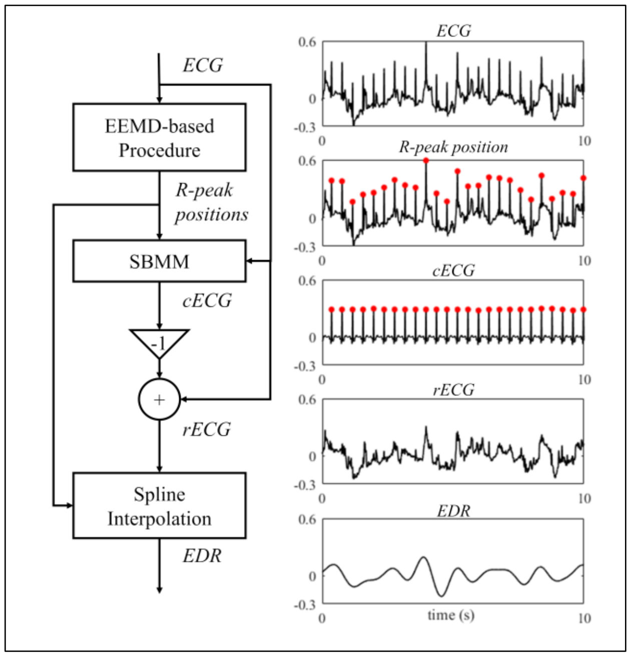

Figure 1. Procedure for the electrocardiogram-derived respiration signal (EDR) extraction from electrocardiogram (ECG) recording.

3. Results

Globally, 1347 windows out of 3037 (44%) were considered reliable for this study. Specifically, 97 windows out of 1073 (10%), 380 windows out of 821 (46%) and 870 windows out of 1143 (76%) were considered reliable for subject 1, subject 2 and subject 3, respectively.

Distributions of HR, BR_{BRS}, BR_{RES} and BR_{EDR} and results of |δ| analysis are reported in Table 2, while results of linear regression analysis and CCC analysis are depicted in Figure 2. BR_{BRS} values (median: 29cpm) were lower (not statistically equivalent; $P>0.05$) than BR_{RES} values (median: 38cpm) and BR_{EDR} values (median: 37cpm), which instead were equivalent ($P<0.05$). These results were also confirmed by the |δ| analysis, CCC analysis and linear regression analysis. Indeed, |δ| between BR_{EDR} and BR_{RES} (median: 2cpm) is lower than those computed between BR_{BRS} and BR_{RES} (median: 8cpm), and between BR_{BRS} and BR_{EDR} (median: 7cpm). Moreover, CCC (0.62; $P<0.05$) and regression line (BR_{RES}=0.91·BR_{EDR}+4.47cpm) confirmed a good agreement between BR_{EDR} and BR_{RES} (Figure 2.C), differently from what obtained for BR_{BRS} vs. BR_{RES} (Figure 2.A; CCC=0.27, $P<0.05$; regression line: BR_{RES}=0.29·BR_{BRS}+29.15cpm) and BR_{BRS} vs. BR_{EDR} (Figure 2.B; CCC=0.20, $P<0.05$; regression line: BR_{EDR}=0.18·BR_{BRS}+31.05cpm).

Table 2. Distributions of HR, BR_{BRS}, BR_{RES} and BR_{EDR} and results obtained from |δ| analysis.

	HR (bpm)	128[106;137]
	BR_{BRS} (cpm)	29[21;37]
	BR_{RES} (cpm)	38 [34;41]
	BR_{EDR} (cpm)	37 [34;39]
|δ| (cpm)	BR_{BRS} vs. BR_{RES}	8[3;14]
	BR_{BRS} vs. BR_{EDR}	7[3;13]
	BR_{EDR} vs. BR_{RES}	2[1;4]

4. Discussion

Data acquired by wearable sensors during high-altitude activity were used to validate the SBMM-based procedure for EDR extraction in exercise conditions. One of the main challenges of signal processing applied on data acquired during exercise is managing their low quality. These signals are usually corrupted by high level of noises, usually divided into physiological interferences (e.g., muscular noise) or technical issues (e.g., data loss). These noises make signals very difficult to be processed and, in case of ECG processing, the identification of fiducial point positions becomes very hard. SBMM-based procedure requires R-peak positions to be applied; thus, their reliable identification is essential. In this study, a novel EEMD-based method, specifically designed for ECG acquired during exercise, was applied to identify R-peak positions. Despite the very good performance of the EEMD-based method [20], several analyzed windows were not reliable for EDR extraction (56%), and thus have been excluded. High percentages of rejected windows suggest the need of a new denoising algorithm specifically designed for data acquired during exercise. Future studies will be focused on the definition of novel denoising procedures.

Obtained results confirmed what suggested by the literature [8], *i.e.*, physiological measurements indirectly provided by BioHarness 3.0 seem not to be clinically reliable such as biosignals directly recorded with the same wearable sensors. This result is confirmed by the BR_{BRS} distribution, which values clearly underestimate BR. On the other hand, BR_{RES} values are clinically reliable. High values of BR_{RES} better reflects the clinical situation of studied subjects that are performing trekking (high level of exercise) and in condition of possible hypoxia. Both these environmental conditions provoke an increase of cardiorespiratory rhythms, as depicted by the increase of BR, an overall indicator of exertion in the context of exercise physiology.

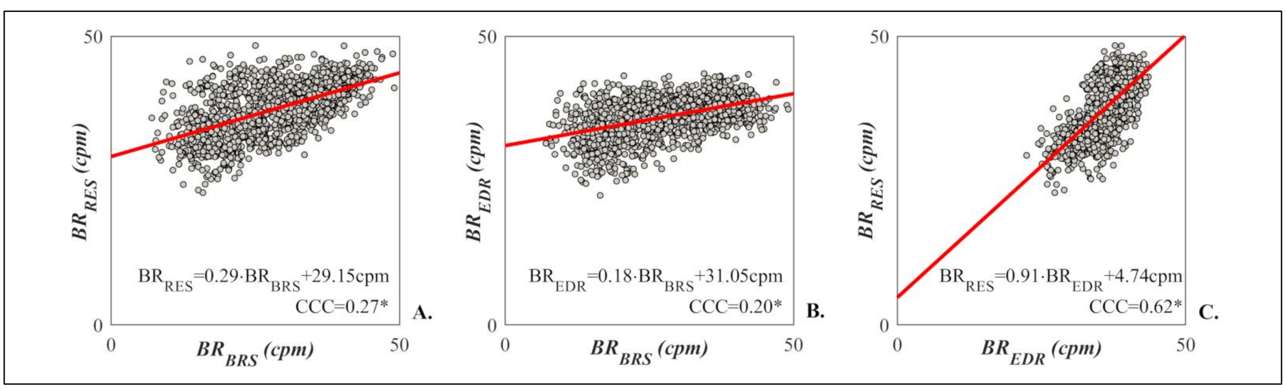

Figure 2. Scatter plots of BR_{BRS} vs. BR_{RES} (panel A), BR_{BRS} vs. BR_{EDR} (panel B) and BR_{EDR} vs. BR_{RES} (panel C). The regression lines are represented in red. Parameter values of regression lines and concordance correlation coefficients (CCC) are also reported. * indicates statistical significance (P) lower than 0.05.

Finally, comparison between BR_{EDR} vs. BR_{RES} confirmed the goodness of SBMM-based procedure, proved by the similarity between the distributions (BR_{EDR}: 38 [34;41]cpm; BR_{RES}: 37 [34;39]cpm), the low values of |δ| (2[1;4]cpm), the satisfactory value of CCC (0.62; $P<0.05$) and the good fit of the regression line ($BR_{RES}=0.91 \cdot BR_{EDR}+4.47$cpm). Considering the importance of respiration in high-altitude sports, future studies will investigate the possibility to estimate by EDR extracted by SBMM-based procedure other clinical important respiratory features such as volumes.

5. Conclusion

SBMM-based procedure is an effective method to extract EDR from data acquired by wearable sensors during high-altitude physical activities, providing reliable and clinically relevant features of the respiratory system.

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