A Smartphone Based Cardiac Coherence Biofeedback System

J. De jonckheere, I. Ibarissene, M. Flocteil, R. Logier

***Abstract*—Cardiac coherence biofeedback training consist on slowing one's breathing to 0.1 Hz in order to simulate the baroreflex sensitivity and increase the respiratory sinus arrhythmia efficiency. Several studies have shown that these breathing exercises can constitute an efficient therapy in many clinical contexts like cardiovascular diseases, asthma, fibromyalgia or post-traumatic stress. Such a non-intrusive therapeutic solution needs to be performed on an 8 to 10 weeks period. Even if some heart rate variability based solutions exist, they presented some mobility constrain rendering these cardiac / respiratory control technologies more difficult to perform on a daily used. In this paper, we present a new simplified smartphone based solution allowing people to process efficient cardiac coherence biofeedback exercises. Based on photo-plethysmographic imaging through the smartphone camera, this sensor-less technology allows controlling cardiac coherence biofeedback exercises through a simplified heart rate variability algorithm.**

I. Introduction

Heart Rate Variability (HRV) is a commonly used non-invasive method allowing studying the Autonomic Nervous System (ANS) which is divided in two sub systems: the parasympathetic and the sympathetic nervous systems [1].

Nowadays, ANS analysis through HRV is used in a large number of clinical applications (cardiology, Anesthesia, Intensive care, Obstetric, sleep disorder…) [2]. Several studies have shown that HRV in the high frequency range (between 0.15 Hz and 0.4 Hz) is exclusively meditated by parasympathetic activity whereas low frequency variations (between 0.004 Hz and 0.15 Hz) are mediated by both sympathetic and parasympathetic outflows [3,4].

More recently, some studies showed that parasympathetic activity was influenced by the emotional state and decreases in situations of stress or discomfort [5, 6] or increases with the feeling of wellbeing [7].

HRV high frequency variations are mainly modulated by respiration. Indeed, inhalation temporarily suppresses the parasympathetic system influence and increases heart rate while exhalation decreases heart rate by stimulating the parasympathetic system. These rhythmic oscillations, which are caused by breathing, are called respiratory sinus arrhythmia (RSA).

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Therefore, controlled respiration is a commonly used method to modify the ANS parasympathetic activity. For example, the cardiac coherence training consists on slowing the breathing frequency around 6 cycles per minutes (0.1 Hz) in order to stimulate the baroreflex sensitivity, increase the respiratory efficiency [8] and improve psychological state for example in terms of emotional stability [9]. Such an exercise will also increase RSA effect.

Several studies have shown that such breathing exercises increase the vagal tone activity and can constitute an efficient therapy in many clinical contexts like cardiovascular diseases [10], asthma [11], fibromyalgia [12] or post-traumatic stress [13].

Such a therapeutic protocol is generally performed during 8 to 10 weeks with a 30 minutes weekly exercise performed with a therapist and 2 daily exercises performed at the patient place [14].

Several HRV biofeedback based technologies have been developed in order to assist people in such controlled exercises. Such technologies also allow users to control the cardiac coherence exercises efficiency.

Freeze-Framer, from the institute of Heartmath proposed hearts rhythm coherence biofeedback exercises based on HRV time frequency analysis.

Symbioline (Symbiofi™, France) is a stress / anxiety management tool based on a HRV time analysis solution primary developed for the monitoring of pain during general anesthesia [15] and adapted to stress / anxiety management therapy through cardiac coherence and relaxation [6].

Such a technology embedded in a mobile phone could therefore provide an efficient way for daily cardiac coherence biofeedback training. However, all these systems have been designed to be used on a classical personnel computer with dedicated external sensors. Therefore, time consuming signal processing algorithms as well as the need of external sensors are more often not adapted for a mobile phone implementation.

In this paper, we present a new simplified smartphone based solution allowing people to process efficient cardiac coherence biofeedback exercises.

II. Methods and Materials

A. Cardiac coherence index computation

In order to check the cardiac coherence exercises efficiency, we have to check 1) that the subject is breathing at a 0.1 Hz respiratory rate, 2) that this controlled ventilation influences heart rate variability through RSA.

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For the first target, we decided to provide users a breathing guide allowing them to adapt their ventilation to the desired frequency. This respiratory guide represent a gauge which fill up during inhalation phase and clear up during exhalation phase at a 0.1 Hz frequency with a 45 % cyclic ratio.

It is known that, in the case of a well done cardiac coherence exercise, the cardiac coherence biofeedback will result on a smooth 0.1 Hz sinusoidal pattern in the heart rate time evolution [16].

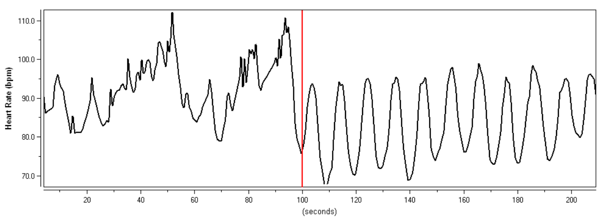

Fig. 1: Effect of the cardiac coherence training on heart rate variability. The subject is breathing naturally between 0 and 100 s. After 100 s, the subject is following a breathing guide allowing him to control is ventilation to 6 cpm. The heart rate 0.1 Hz sinusoidal pattern is then visible till the beginning of the exercise.

Regarding this observation, we needed to develop algorithms allowing translating this qualitative information into a quantitative value. In order to achieve this challenge, we decided to detect the HRV low frequency main oscillation and to quantify the difference between this oscillation frequency and the desired 0.1 Hz respiratory frequency corresponding to a 10 seconds respiratory period.

The first step for these algorithms realization was the acquisition of the heart signal. Photo-plethysmographic imaging allows the acquisition of a pulse wave using an image issued from a camera. Therefore, such a technological solution allows heart signal acquisition with a mobile phone using the mobile phone camera and without any need of additional sensors [17]. The measuring principle of the mobile phone based photo-plethysmographic sensor is described in Fig. 2.

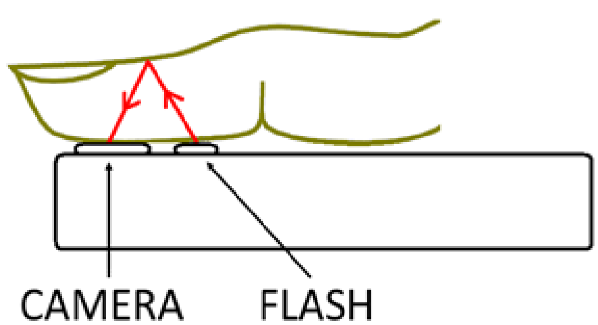

Fig. 2: Classical setup for plethysmographic waveform acquisition using a smartphone.

The finger is placed both on the mobile phone camera and the flash. The system works as a classical plethysmographic waveform sensor in a reflected mode. Flash continuously illuminates the finger and light is reflected on the camera. The image issued from the camera is then analyzed in order to extract the plethysmographic waveform.

The camera allows obtaining 3 matrixes corresponding to each pixel color in Red, Green and Blue at a 30 Hz sampling frequency. In order to obtain a numerical data representing the instantaneous pulse wave (Pv) value, we compute Pv as the mean value of the 50x50 matrix situated in the center of the Red channel matrix. Pv series is then low pass filtered at 1 Hz in order to avoid any noise, light or motion artifact. Pv value is then mean-centered in a 1 s (30 samples) moving window as follow. In a first step, the mean value (M) is computed as:

$$M = \frac{1}{30} \sum_{i=-29}^{0} (Pv_i) \tag{1}$$

Where Pv_i represents the instantaneous Pv samples values. Then M is subtracted from the last sample of the 30 s window as:

$$\mathbf{Pv2_i = Pv_i - M.} \tag{2}$$

We then detect the Pv2 series zero crossing.

$$\textbf{If } Pv2_i>0 \textbf{ and } Pv2_{i-1}<0 \textbf{ then } \text{Heart Detect} = \text{true} \tag{3}$$

We consider the time delay (RR), in s, between the two last detections as a representation of the time between two heart beats. Finally, Heart Rate (HR), in beat-per-minute, is deducted from RR.

$$\mathbf{HR = 60 / RR} \tag{4}$$

HR is then re-sampled at a 4 Hz sampling frequency in order to obtain equidistant HR samples. Sampled HR series is then band pass filtered between 0.05 and 0.15 Hz in order to obtain a low frequency band centered around 0.1 Hz.

We then detect the HR series zero crossing considering this detection as the beginning of a new low frequency oscillation.

$$\textbf{If } HR_i>0 \textbf{ and } HR_{i-1}<0 \textbf{ then } \text{RespiDetect} = \text{true} \tag{5}$$

We compute the HR low frequency main oscillation period (OP) as the time between the two last detections.

The time delay, between OP and 10 s is then computed.

$$\text{Delay} = \text{absolute } (OP - 10). \tag{6}$$

Delay therefore represents the time delay between the main oscillation in the Low frequency band and the desired RSA period. In order to keep a good coherence between visual HR series interpretation and Cardiac Coherence index, we then compute a CarCoh value (in %) as follow:

$$\text{CarCoh}=100.0-20.0*\text{Delay} \tag{7}$$

The more CarCoh is important, the more the subject low frequency main oscillation period is close to 10 s and the more the patient is in cardiac coherence.

B. 3D video user interface

Finally, a specific graphic interface (Fig. 3) has been developed in order to allow users to visualize:

1) The respiratory guide.
2) The cardiac frequency instantaneous value (HR).
3) The cardiac coherence score (CarCoh).

Fig. 3: Smartphone application user interface. On the right side of the screen, a respiratory guide allows users to breath at a 6 cpm respiratory rate. Cardiac frequency as well as cardiac coherence scores are visible on the top of the screen. A timer allows user to visualize the elapsed time till the beginning of the exercise.

In order to improve exercises attractivity and efficiency, the system has been developed as a serious game offering real time continuous interactive 3D animation related to the cardiac coherence level (Fig. 4).

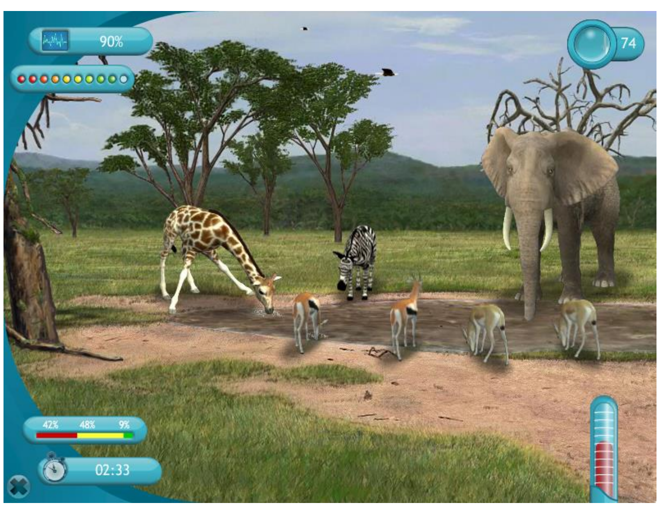

Fig. 4: All along the exercises some animals will come or go from the screen in accordance to the cardiac coherence score. The more elevated is the cardiac coherence score, the bigger animals are and the more important is the number of animals on the screen. Fig. 3 screen corresponds to a 59 % cardiac coherence score. Fig. 4 screen corresponds to a 66 % cardiac coherence score.

C. Clinical validation

To evaluate the system efficiency, we studied the cardiac coherence score evolution during 6 cpm controlled ventilation phases and spontaneous (without any guide) ventilation phases on healthy volunteers. Exclusion criterions were: history of autonomic or cardiac disease, body mass index (BMI) over 40 and diabetes or autonomic nervous system altering medications.

We then gave the smartphone application to healthy volunteers and asked them to position their finger on the smartphone camera as shown in Fig. 2. Application was then started and heart rate and cardiac coherence were continuously recorded.

Healthy volunteers were then asked to follow the 6 cpm respiratory guide during 2 minutes. In a second phase, while keeping on recording parameters, subjects was blind to the respiratory guide and asked to retrieve a spontaneous respiration during 2 minutes. Subjects then followed again the 6 cpm respiratory guide during 2 minutes.

We then compared the cardiac coherence values measured at T = 60 s, 120 s, 180 s, 240 s, 300 s and 360 s using a Friedman non-parametric statistical test followed by a Wilcoxon test for repeated measures when significant. The statistical tests were considered significant at a p value of 0.05. All tests were performed with SPSS 22.0.

III. Results

Nineteen subjects aged from 22 to 60 years have been included in this study (sex ratio 10/9). Cardiac coherence showed significant differences between the different time measurements (Friedman, $p<0.0001$). Cardiac coherence index at T = 180 s and T = 240 s were significantly lower than at T = 60 s, 120 s, 300 s and 360 s. No significant differences have been shown between measures at T = 60 s, 120 s, 300 s and 360 s. No significant difference has been shown between T = 180 s and T = 240 s.

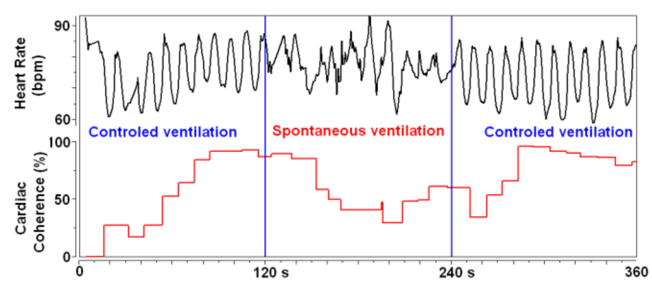

Fig. 5: Heart rate and cardiac coherence index evolution example. The heart rate pattern showed 0.1 Hz sinusoidal shape during the controlled ventilation phases; cardiac coherence is then upper than 50 %. The heart rate pattern became more chaotic and the sinusoidal shape pattern disappeared during the spontaneous ventilation phase; cardiac coherence values are then lower than 50 %.

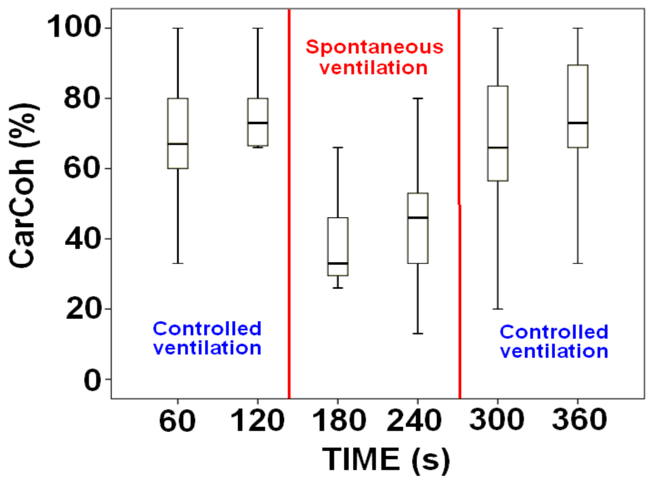

Fig. 6: Cardiac coherence index at T = 60s, 120s, 180s, 240s, 300s and 360s. Data are presented as median and 25 – 75 centiles.

IV. CONCLUSION

In this paper, we described a smartphone based solution allowing people to process efficient cardiac coherence biofeedback exercises.

In the preliminary efficiency study, we observed that our cardiac coherence index was significantly higher during breathing exercises than during spontaneous ventilation.

Despite a low number of cases, these results suggest that this biofeedback system could provide an efficient solution for mobile cardiac coherence application.

A further validation will be conducted in order to test the system correlation with existent computer based technologies as Freeze-Framer and Symbioline.

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