In Bed Contactless Cardiorespiratory Signals Monitoring Using Optical Fiber Interferometry

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Abstract

Monitoring of cardiac and respiratory activity results crucial in clinical settings. However, specific, expensive and usually wired devices are required, which results in cumbersome configurations. Therefore, there is a large research interest in the development of noninvasive monitoring systems. Some authors have proposed the use of fiber-optic speckle interferometry, enabling for contact-less patient monitoring. In this study, we exploited this technology, and explored the performance of different fiber-optic configurations, in combination with robust signal processing algorithms, for heart and respiratory rates estimation. Several configurations were tested, all of them resulting in very low estimation errors. A qualitative analysis revealed that our system can be suited to track fast changes in respiration, as well as the presence of apneas. Such a system might be useful for noninvasive patient monitoring, specially in overnight recordings (e.g., OSAS or AF) or specific scenarios, such as magnetic resonances.

1. Introduction

Cardiac and respiratory activity monitoring is of paramount importance not only in clinical settings, such as intensive care units [1], but also in ambulatory monitoring at home, where chronic syndromes as OSAS or AF require continuous scrutiny for detection and follow up. Therefore, many patients will benefit from constant biosignals monitoring, this requiring a multitude of specific, expensive and usually wired devices, resulting in cumbersome settings. For this reason, there are large research efforts focused on the development of noninvasive monitoring techniques [2], which allow to assess patients' vital signs in a time-continuous and cost-efficient manner.

One option, already exploited by various authors, is the use of fiber-optic-based systems [3, 4]. In this work, the concrete focus is on speckle interferometry, which is a measurement technique that exploits the multi-mode propagation in fibers-optics. Essentially, when a coherent light is propagated through the fiber, the existence of different transmission modes results in an interference pattern which can be captured using a digital camera. When the fiber is subjected to external stimuli, there are changes in the transmission modes and, consequently, in the interference pattern, so that it is possible to establish a relationship between the variations in the output interference pattern and the magnitude of the stimuli. These systems exploit thoracic movements during respiration, or ballistic forces generated by the heart, which are transmitted to the body surface and provoke variations in the speckle interference pattern of a fiber-optic placed close to it.

In view of the promising results reflected in the literature, in the present work we tested different fiber-optic speckle interferometry system configurations, in combination with robust algorithms for heart and respiratory rates assessment. We evaluated the capability of our system to respond to fast changes in respiration using a respiration protocol, as well as breath holding to simulate apneas.

2. Materials and Methods

2.1. Study protocol

Four volunteers agreed to participate in this preliminary study. They did not report any cardiac or respiratory disorder. Signal acquisition protocol was divided in 2 stages, during which the participants laid in supine position over a mattress. In a first basal stage, they were asked to remain silent and without moving during 3 minutes, breathing spontaneously. Later, they underwent a visually-guided stepwise-decreasing respiratory rate protocol. In this way, during 5 consecutive minutes the subjects breathed at a rate of 0.5, 0.4, 0.3, 0.2 and 0.15 Hz, 1 minute each. Some of the subjects also underwent a short breath holding protocol, consisting on spontaneous breathing periods during 20

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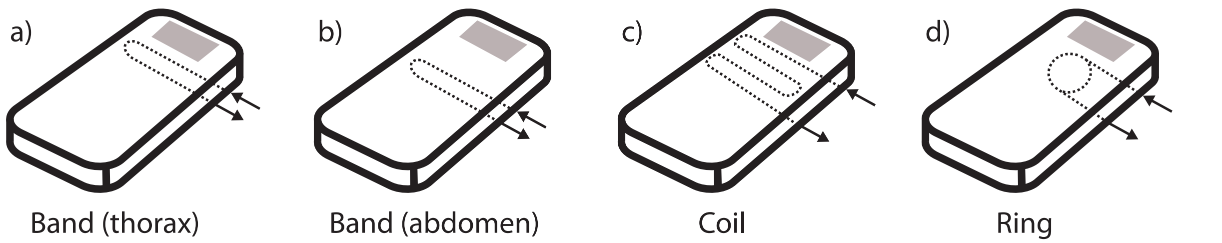

Figure 1. Schematic of the tested fiber-optic configurations. All the fibers were located beneath the mattress. Inward and outward arrows represent laser and camera, respectively, whereas the shadowed area indicates the position of the head.

seconds, followed by 10-second breath holding.

During the aforementioned protocol, electrocardiographic (ECG) and respiratory effort signals were acquired (at 1000 and 250 Hz, respectively), using a Medicom device (ABP10 module of Medicom MTD, Ltd, Russia). Additionally, fiber-optic interferometric signals were recorded, as described below.

2.2. Interferometric measurements

A polymer optic-fiber (POF) with a diameter of 980 μm, a 658 nm laser and a monochrome 5 MP CMOS camera with a sampling rate of 53 frames/s were employed, and 4 different POF configurations were tested. These configurations consisted on a 1-meter band placed at the thoracic region, another identical band placed at the abdominal region, a 5-meter coil distributed along the whole torso and a ring sensor, constructed with a 10-meter POF forming several loops, placed at the thoracic region (see Fig. 1). In all the cases the POF was placed beneath the mattress.

From the speckle patterns captured by the camera, we constructed two time-varying signals. The first one, $x_d(n)$, is a differential signal expected to account for rapid variations, such as those produced by the mechanical cardiac activity. Hence, $x_d(n)$ can be regarded as an optical ballistocardiographic (OBCG) signal, and it is defined as:

$$x_d(n) = \sum_{i=1}^{I} \sum_{j=1}^{J} |X_n(i,j) - X_{n-1}(i,j)|, \qquad (1)$$

where X_n represents the n-th frame captured by the camera, and I and J are the number of row and column pixels, respectively. On the other hand, we also obtained a signal representing the variation with respect to a fixed reference, which is expected to track slower variations, such as the thoracic and abdominal movements due to respiratory activity. This signal, $x_r(n)$, is calculated as:

$$x_r(n) = \sum_{i=1}^{I} \sum_{j=1}^{J} |X_1(i,j) - X_n(i,j)|, \qquad (2)$$

being X_1 the first frame of the recording. $x_d(n)$ and $x_r(n)$ were resampled at 100 Hz (using linear interpolation).

2.3. Reference heart and respiratory rates

ECG signals were high-pass filtered using a forward-backward filter (0.5 Hz cut-off frequency) to remove the baseline wander, whereas respiratory effort signals were forward-backward band-pass filtered (0.08 and 0.8 Hz cut-off frequencies) to eliminate non-respiratory related components. R waves of the ECGs (Frank's lead configuration, lead X) were detected using the wavelet-based approach described in [5], thus providing the reference heart rate (HR).

Respiratory effort signals were resampled at 4 Hz, and respiratory rate (F_r) was estimated using the spectra-averaging method proposed in [6]. An example of the ECG and respiratory effort signals, as well as of the HR and F_r during the respiration protocol is displayed in Fig. 2.

2.4. Heart and respiratory rates estimation

Signal $x_d(n)$ is expected to reflect cardiac mechanical activity, so it was high-pass filtered to remove the baseline wander, using the filter described in Section 2.3. Afterwards, it was filtered using a moving average with a 1-second Hamming window, since such a filter presents high-attenuation for frequency components larger than 2 Hz (i.e., 120 bpm, sufficient for the considered application). The resulting filtered OBCG is displayed in Fig. 2 c), where it can be noticed how the signal presents pulses corresponding to the mechanical cardiac activity. Pulses occurrence times were detected from the OBCG signal, using the pulse detection approach described in [7] (α = 0.1, refractory period = 300 ms), and HR series were estimated as the inverse of pulse-to-pulse intervals. 20-sample median filtering was applied to the HR estimation and to the reference HR for computing the estimation error.

On the other hand, $x_r(n)$ represents respiratory activity. In this way, it was band-pass filtered, resampled and used for F_r estimation, as described in Section 2.3. For those subjects undergoing a period of breath holding, the optic respiratory signals were qualitatively analyzed (see Fig. 3), but no HR or F_r information was extracted.

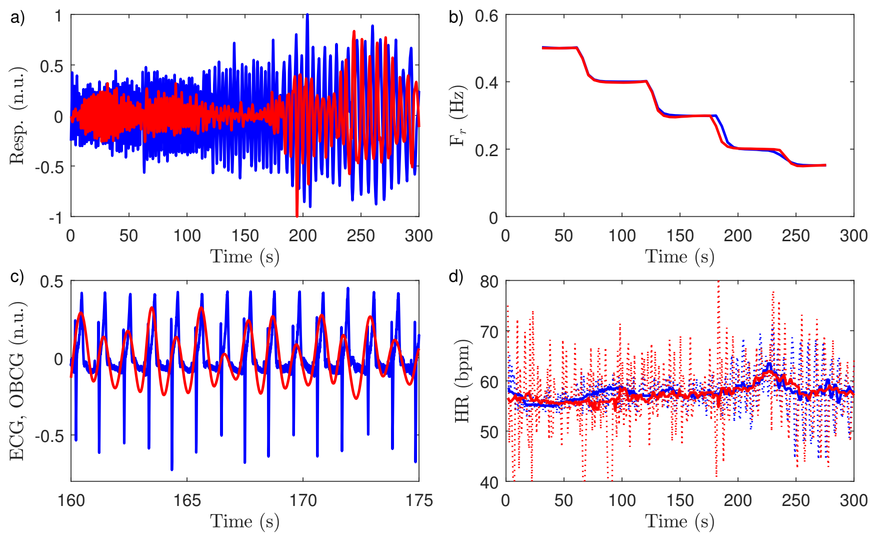

Figure 2. An example of the respiratory effort (a, blue) and ECG (c, blue) signals, and $x_r(n)$ and $x_d(n)$ (red), recorded during the respiration protocol is displayed. In b) and d), the reference (blue) and estimated (red) F_r and HR obtained from the signals on their left are shown (dotted lines represent the original signals without median filtering). The example corresponds to the abdominal band configuration. Note that, for representation purposes, the time scale is different in c).

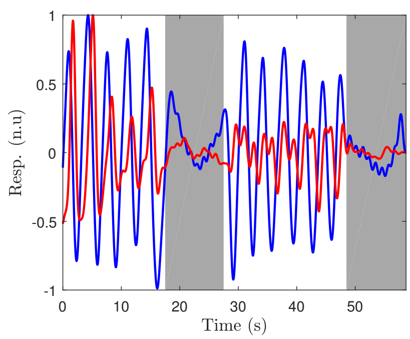

Figure 3. Example showing the respiratory effort (blue) and $x_r(n)$ (red) signals during breath holding protocol. Breath holding periods are indicated with shadowed areas.

3. Results

The performance of the HR and F_r estimation using the different POF configurations, during basal conditions and the respiration protocol (measured as the absolute estimation error), are displayed in Fig. 4. In the case of the HR, estimation errors were generally kept below 2 bpm in basal conditions, being them slightly higher during the respiration protocol. Mean HR estimation error for all the subjects and configurations was of 1.63 bpm in basal conditions, and 2.09 bpm in the respiration protocol. Regarding the F_r, mean estimation error was of 0.03 Hz for both basal conditions and respiration protocol.

Qualitatively, in Fig. 2 it can be noticed that temporal variations in HR and F_r can be tracked, which is specially remarkable in the case of the respiration protocol, with fast F_r transitions. On the other hand, we also observed a large decrease in the amplitude of the optic respiratory signal in response to breath holding, as displayed in Fig. 3.

4. Discussion

The use of fiber-optic speckle interferometry for biosignals monitoring has been already addressed in previous works [3, 4]. Although we employed the same principle, and the several configurations described here have been already proposed in the literature [4], some differences arise. In contrast to previous works, in our settings the POF is always placed beneath the mattress, this having the advantage that it does not have to be integrated in it. We also conducted several tests placing the POF over the mattress, resulting in much noiser recordings. In this way, the mattress acts as a filter that attenuates the low-amplitude components, so that only those related with cardiac mechanical activity are captured by our system. Another difference with previous works relies on the use of a respiration protocol, allowing to assess the response to fast F_r changes (see Fig. 2). Also, to the best of our knowledge, this is the first work in which the possibility of detecting apneic episodes was addressed. Since this is a preliminary study, we only explored it qualitatively, but the response of the system shown in Fig. 3 suggests that it might be possible to detect apneic episodes from the optic respiratory signal. Finally, we employed robust algorithms for HR and F_r estimation, yielding to a very high performance in most of the tested subjects, as displayed in Fig. 4. With the pro-

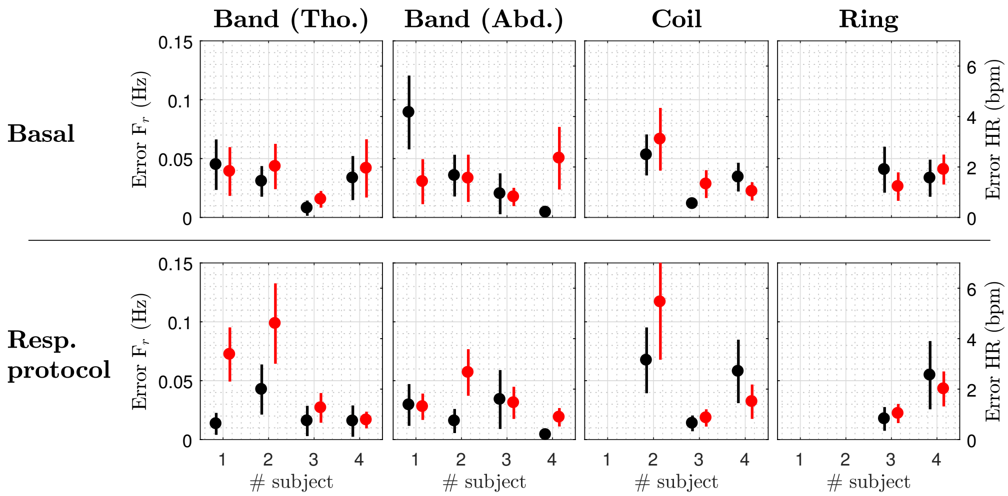

Figure 4. F_r (black) and HR (red) absolute estimation errors in the basal and respiration protocol stages, and for each of the tested fiber-optic configurations. Not all the configurations were tested in every subject.

posed methodology, similar performance was assessed in the different configurations, with slightly better results in the case of the abdominal band.

Despite this is a preliminary study involving a limited number of subjects, the assessed performance motivates further research on these systems, since they might have interesting clinical applications. On one hand, they could be used as a screening tool for those subjects under suspicion of sleep apnea, avoiding unnecessary polysomnographies and improving patient comfort. Equally, patients under suspicion of atrial fibrillation could be monitored during sleep in a very noninvasive and inexpensive manner. On the other hand, fiber-optic based systems could result useful in environments in which conventional monitoring devices are not suitable, such as during a magnetic resonance, when no metallic elements can be employed.

5. Conclusion

In this preliminary study, we assessed the performance of several configurations of a fiber-optic based system to estimate HR and F_r. Despite further research is needed, the high performance and the noninvasive nature of the proposed configurations suggest that they could be useful for patient monitoring, specially in overnight recordings or in some particular scenarios, such as magnetic resonances.

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