A PROPOSAL OF A NOVEL CARDIORESPIRATORY LONG-TERM MONITORING DEVICE

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Abstract: Monitoring of respiratory movements is an important feature in planning of medical care. We present here a simple, portable, accelerometer-based device suitable for long term-monitoring of the breathing and heart rates, along with postural changes, during sleep and wakefulness. Recordings of respiratory frequency, heart rate, posture and voluntary cough were obtained from a group of volunteers who also participated in sleep studies (6-8 hrs). A pair of capacitive MEMS tri-axial accelerometers was positioned at the level of the 10^{th} rib along the mid-axillary line bilaterally; simultaneous recordings of respiratory movements, heart rate and body position could be easily performed. The signal were digitized and used to detect body position and relative movement between accelerometers. Conventional spirometry was performed in parallel when appropriate. During resting breathing, qualitative analysis revealed that the accelerometric assessment of respiratory pattern correlated well with that obtained by spirometry. Values of respiratory rates were identical with the two techniques. Recordings of respiratory and cardiac activity during sleep were satisfactorily obtained except for short lasting episodes corresponding to changes in body position. These devices seem to be also suitable for detecting the motor pattern of cough.

1 INTRODUCTION

It has repeatedly been shown that detailed analysis of breathing pattern can provide valuable information regarding the respiratory system (Tobin, 1983). In patients with respiratory and sleep disturbances, including the chronic obstructive pulmonary disease (Pauwels, 2001) and the sleep apnoea syndrome (Britton, 2003), continuous monitoring of simple vital functions may provide useful therapeutic options. COPD is a prevalent and disabling condition that results in significant personal impact to patients and their carers, and financial cost to health services. (Pauwels, 2001) More than half of these costs relates to hospital admissions for acute exacerbation (Britton, 2003). Reducing exacerbations and hospitalizations are therefore key goals in COPD management (Pauwels, 2001).

Obstructive sleep apnoea syndrome (OSAS) is a highly prevalent disorder (Panossian, 2009) characterized by instability of the upper airway during sleep, which results in markedly reduced or absent airflow at the nose/mouth. Episodes are typically accompanied by oxyhemoglobin desaturation and terminated by brief micro-arousals that result in sleep fragmentation (Panossian, 2009). Despite having significant breathing problems during sleep, most patients have no readily detectable respiratory abnormality while awake (Redline, 1993).

Conceivably, continuous monitoring of respiratory and heart rates, cough frequency and motor pattern, and time spent daily in physical activities may provide early information on deterioration of clinical conditions in patients with respiratory diseases, thus allowing prompt medical intervention and possibly reducing both the severity of disease exacerbations and the need of sudden hospitalization of the patient (Deegan, 1995). In addition, domestic sleep monitoring by means of a simple device that allows simultaneous assessments

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of cardiorespiratory rates and posture may represent a useful tool in the management of OSAS patients.

Several devices have been proposed to measure ventilation indirectly. Respiratory monitoring is usually achieved by having a subject breathing through a mouthpiece or face mask attached to a pneumotachograph or spirometer. Although these devices permit the accurate measurement of ventilation and its variables, they also alter the pattern of breathing and minute ventilation (McNicholas, 2008). They are not useful for monitoring ventilation in any circumstance in which keeping a mouthpiece and nose clip in place is too difficult or impossible, as it may be the case of continuous monitoring at home and/or during sleep (Hurst, 2009). Devices that measure changes in thoracic volume (respiratory inductance plethysmography), and airflow at the airway opening (oro-nasal thermistors) have been fully validated and largely employed in the clinical assessment of sleep disturbances; however, it is widely recognised that their use for recording respiratory activity during daily life is impractical, mainly due to their limited portability.

We present here a simple, mini-invasive, accelerometer-based device that can be used for long term-monitoring of respiratory movements and cardiac activity, thus allowing the detection of the breathing frequency and heart rate, along with the ongoing postural changes, during sleep and wakefulness. The device can also provide useful information on the motor pattern of cough and other expulsive efforts. In this connection, it seems worth to recall that the cough reflex is an important airway defensive mechanism and the assessment of its functionality is becoming increasingly important, especially in elderly patients who are at risk of aspiration pneumonia (Perez, 1985). The intensity of a cough effort, generally indexed in terms of expiratory flow rate and/or electromyographic abdominal muscle activity (Que, 2002) is of pivotal importance in the assessment of cough effectiveness. Specifically, the purposes of this paper are i) to determine whether the accelerometer-based device is suitable for short- and long-term recordings of respiratory and heart rates in conditions such as sleeping and daily activities; ii) to obtain preliminary information on the feasibility of non-invasive recording of more complex respiratory motor acts such as the cough.

2 MATERIALS AND METHODS

The proposed device consists of two MEMS capacitive tri-axial accelerometers (*MMA7260Q, Freescale Semiconductor*) which were chosen for their high sensitivity (800 mV/g @1.5 g).

Due to manufacturing process and physical structure of each sensor, measures could be affected by a systematic error; to offset the output of the accelerometers used in the experimentation, a calibration procedure was devised.

Accelerometric sensors were mounted on two small circuit boards, as illustrated in figure 1, containing a first conditioning module and a voltage regulator.

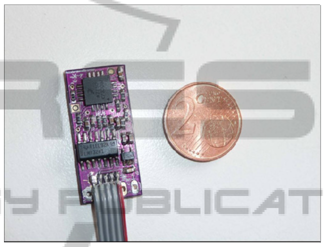


Figure 1: Accelerometer mounted on the circuit board. Note the small size of the device compared with a 2 Euro cent coin.

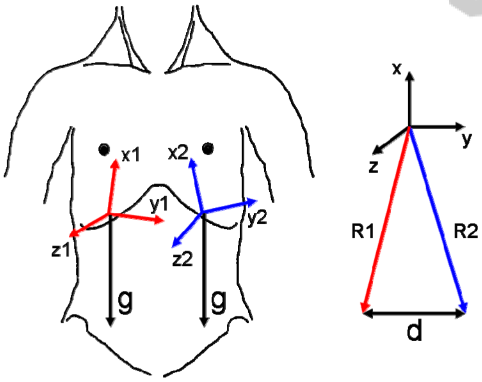
Accelerometric sensors were positioned bilaterally on the skin of the anterior thoracic wall at the level of the 10^{th} rib along the mid-axillary line, by using paper adhesive bandage. In preliminary experimental sessions, several different attempts at identifying the most suitable thoracic area for sensor positioning were carried out. The margin of the 10^{th} rib on the mid-axillary line was selected as it turned out to provide a respiratory signal consistent with that obtained with conventional spirometry.

Both sensors were connected with a flexible flat cable to a data acquisition board, containing analogue conditioning circuits, A/D converter, a real time clock for acquisition management and power supply. The acquisition board is embedded in a 12 cm x 7 cm x 3 cm lightweight plastic case equipped with a clasp on the back side for hanging the device to the subject's belt in order to improve monitoring device's portability.

Acceleration signals were sampled at 340 Hz, stored in a removable mass memory device and later transferred to the computer for off-line processing, which included digital filtering, offset correction and study of frequency components.

During offline processing two digital FIR filters were used to extract the respiratory and cardiac components from the raw signal, respectively in the

[0.1, 0.6] Hz and [1, 15] Hz frequency range. However, the use of a digital filter “per se” is not effective in removing signal components originating from body movements unrelated to respiratory activity; in facts, the frequency components of non-respiratory body movements are generally lower than 15 Hz and therefore comprised in the range of respiratory and cardiac signals. In consequence, the influence of non-respiratory thoracic movements was minimised by considering the difference ‘d’ between the sensor’s resultant vectors ‘R1’ and ‘R2’ (figure 2). By subtracting the common components acquired from the two accelerometers, a signal of purely respiratory origin was obtained. Once positioned on the chest wall, however, the reference co-ordinate systems of the two sensors were not aligned, leading to a systematic error due to an imbalance between common components. To avoid imbalance, we developed a procedure that rotates the reference system of one sensor in order to align it to the reference system of the other sensor. With this procedure, the accelerometric signals deriving from non-respiratory thoracic movements were minimised.



(a) (b)

Figure 2: Sensors location on the chest wall (a), representation of resultant vectors ‘R1’, ‘R2’ and their difference ‘d’ (b).

We recruited six subjects of both sexes (age range 19 – 64) among faculty personnel and students; none of them complained of any relevant respiratory or cardiac disturbance and agreed to participate in accelerometric recordings of respiratory frequency and heart rate. Three other subjects were selected to perform a series of maximum voluntary cough efforts starting either from near total lung capacity or from functional residual capacity. Accelerometric measurements in awaken patients were always performed in parallel with conventional spirometry by using a mouthpiece connected to a pneumotachograph which provided standard outputs of respiratory volume and flow. Nine additional subjects participated in sleep studies lasting 6-8 hrs during which simultaneous recordings of posture, respiratory and heart rate by means of the accelerometers were obtained.

3 RESULTS

As expected, accelerometric recordings of respiratory activity provided a precise measure of respiratory rate in all subjects tested (figure 3, upper panel); similar consideration were also valid for heart rate recordings (figure 4). Furthermore, with the subject seated in the upright position, qualitative analysis of the recordings revealed that the pattern of breathing obtained by considering the difference ‘d’ between the two accelerometers was fairly coherent with that obtained with the spirometer (figure 3, lower panel). In more detail, the different patterns of rapid shallow breathing and deep breathing were correctly detected by the accelerometers (figure 3).

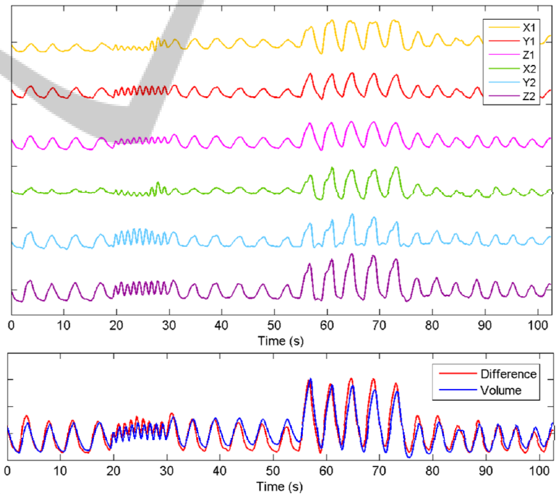


Figure 3: Upper panel: respiratory signals from the accelerometer pair: X, Y and Z are the signals originating from each of the two tri-axial accelerometers. For the purpose of morphological comparisons, all traces are in arbitrary units and displayed at different levels. Lower panel: morphological comparison of the spirometric volume (in blue) and of the accelerometer signal difference (in red) during normal breathing, rapid shallow breathing and deep breathing. Signals were differently amplified to allow superimposition.

As shown in figure 5, the accelerometric tracings recorded during voluntary cough efforts of variable intensity turned out to be clearly distinguishable from those of resting breathing. The intensity of

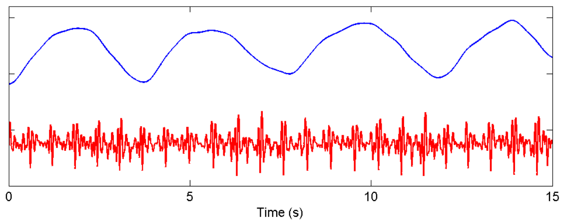


Figure 4: 15 s recording of cardiorespiratory activity by means of an accelerometer in an awake subject at rest. Traces derive from the Y axis of an accelerometer positioned on the chest wall projection of the cardiac area and were digitally filtered (see methods) to obtain the signals of the ongoing respiratory (in blue) and cardiac activities (in red). Traces are in arbitrary units and were similarly amplified.

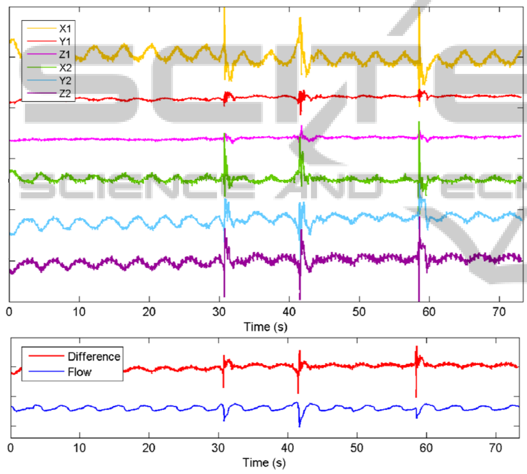


Figure 5: Upper panel: accelerometric recordings of three single cough efforts obtained by means of the accelerometer pair: X, Y and Z are the signals originating from each of the two tri-axial accelerometers. Traces are in arbitrary units and displayed at different levels to facilitate comparisons of their morphology. Lower panel: morphological comparison of spirometric flow (in blue, cough expulsions marked by downward swings) and accelerometer signal difference (in red, expulsions marked by upward swings) during three single cough efforts. Signals were differently amplified to facilitate morphological comparison.

each cough event can be appreciated in terms of the magnitude of the corresponding spirometric flow signal. At the present stage of development it seems likely that the accelerometric signals are suitable to detect cough appearance but not to quantify its intensity.

Long term accelerometric recordings of cardiorespiratory activity and postural behaviour during sleep were successfully accomplished in all of the nine normal subjects. Respiratory and cardiac activity could be recorded only during stable body

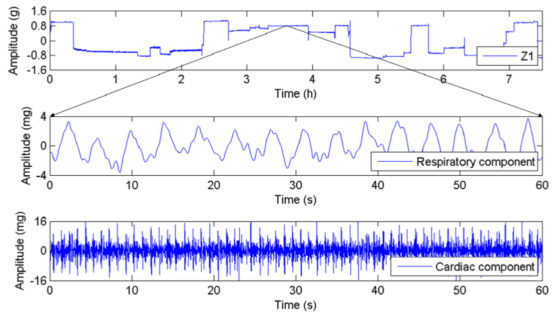


Figure 6: Upper panel: 7.5 h recording of cardiorespiratory and postural activities during sleep in one representative subject using an accelerometer. The signal of respiratory activity was derived from a single axis of one of the two accelerometers (see methods). Sudden variations of signal mark the changes in body position that occurred throughout the recording period. Middle and lower panels: 60 s - time window of respiratory and cardiac activities obtained from the upper panel tracing.

posture; in fact, during changes in body position, the signal related to general movement masked the cardiorespiratory signal (figure 6, upper panel). As a consequence, the device allowed us to accurately detect the number of postural adjustments that occurred during the recording period.

4 DISCUSSION

This study shows that the use of an accelerometer pair positioned on the chest wall seems to be suitable for non-invasive detection of cardiorespiratory and postural behaviours, both during wakefulness and sleep; furthermore, the device may also be useful for recording the number and the motor pattern of cough events.

Any signal derived from each of the sensors can provide information about the frequency of cardiac activity. The latter is displayed as a sequence of peaks corresponding to the systole. Further analyses revealed that the Z axis is the most sensitive one in picking vibrations of the chest wall caused by heart activity, especially when the sensor is positioned on the chest wall area corresponding to heart projection.

Qualitative analysis also revealed that the signals obtained by the two accelerometric sensors, particularly the difference signal, strictly matched with the respiratory thoracic movements. The preliminary results seem also to suggest that not only respiratory frequency, but also the amplitude of each breath, is correctly detected by the accelerometer pair. Indeed, values of respiratory rate obtained by spirometry and accelerometers were identical, in keeping with previous findings (Reinvuo, 2006) and (Hung, 2008). However, this study is the first to show that voluntary changes in the depth of breathing can also be accurately detected by the device.

This study is also the first to demonstrate that the motor pattern of voluntary cough can successfully be distinguished from that of normal breathing by means of an accelerometer pair. In addition, the accelerometric pattern of cough was fairly coherent with that recorded spirometrically, and revealed high frequency components due to speed of the expulsive activity and related chest wall vibrations. However, inaccuracies still exist as far as the accelerometric evaluation of cough intensity is concerned.

Accelerometric long-term recordings of cardiorespiratory activity during sleep in normal subjects provide some advantages compared with standard techniques. Although not formally tested here, it seems obvious that our device offers better portability than the conventional ones and that the possibility of simultaneous recording of body posture may represent an important tool in the evaluation of sleep disturbances.

It could be argued that, in order to monitor cardiorespiratory activity, the use of an accelerometer-based device is somewhat limited by the interfering signals of body motion, especially during daily activities. Whilst we acknowledge that this limitation may exist at least to some extent, we also feel that the recording a cardiorespiratory signal “disturbed” by that originating from body movements is “per se” of clinical usefulness. It may be inferred that patients with respiratory disturbances must present a ratio of resting-to-activity time that is inversely related to the general clinical condition. Therefore, an increase in the above time ratio could be interpreted as an index of a deteriorating clinical condition. In addition, in patients with respiratory diseases, the detection of an increase in cardiac and respiratory activity at rest could also point to an increased metabolic demand such as in the event of a respiratory exacerbation.

5 CONCLUSIONS

Simultaneous recordings of respiratory movements, heart rate and body position can easily be accomplished by using pairs of tri-axial accelerometers; these devices seem to be also suitable for the detection of the motor pattern of cough.

The device can be employed for daytime and nocturnal long-term monitoring thanks to its small dimensions, small weight and easy positioning of sensors on the chest wall, that warrant non-invasive measurements. It could be employed in the diagnosis of sleep disturbances such as the sleep apnoea syndrome, or in the monitoring of the elderly. Even at the present stage of development, the device presented here appears to be ready for accurate and reliable long-term sleep studies. Being easily portable and not bulky, the device seems to be particularly suitable for sleep studies in the domestic environment.

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