Comparison of Automatic Sleep/Wake Detection Algorithms for Cardiovascular Risk Assessment

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Abstract. We present the results of a study to compare the performance of a novel algorithm for sleep/wake identification based on actigraphy against the classical sleep/wake detection algorithms proposed by Cole, Sadeh, and Oakley. The comparison was performed using a database containing dominant and non-dominant hand actigrapy signals for 104 subjects (i.e. 208 actigraphy recordings). The new algorithm exhibits better minute-by-minute accuracy, as well as a significant improvement in the avoidance of invalid sleep-wake transitions with respect to the classical ones. These results demonstrate the advantage of the new algorithm over the classical ones for sleep/wake detection in ABPM applications.

1 Introduction

Many research and clinical applications call for the accurate identification of sleep and wake cycles. One of such applications is the diagnosis and management of hypertension, as well as the assessment of cardiovascular risk. Several studies have linked the absence of a reduction in nocturnal blood pressure (BP) with respect to the average diurnal value to increased risks of morbidity and mortality [1]. Proper determination of nocturnal versus diurnal BP requires a way to accurately determine the sleep and wake periods for a given patient. In recent years, actigraphy has been used to detect sleep/wake periods. Actigraphs are inexpensive wrist-worn devices that use accelerometers to measure and record movement in counts per minute. Several algorithms have been proposed to automatically identify sleep/wake periods from actigraphy. Examples of these algorithms are the ones proposed by Cole, Sadeh, and Oakley [2, 3, 4]. These have been mostly designed as an alternative to polysomnography (PSG) for the study of sleep/wake patterns in patients with sleep disorders and other conditions affecting quantity and quality of sleep. As a consequence, they exhibit a high sensitivity to sleep disturbances, and tend to generate multiple false wake identifications during sleep periods. This makes them unsuitable for cardiovascular risk applications, where the objective is not to detect wake events during periods of sleep, but rather to determine the boundaries between the main activity and rest periods. For this reason, short transitions between states during a main sleep or wake cycle are considered invalid in this application. We have developed a novel sleep/wake identification algorithm to be used in cardiovascular risk applications [5]. This algorithm was validated and its performance compared to some of the available sleep/wake detection algorithms. This paper describes the methodology and results of this study.

2 Methods

The algorithm performance comparison was conducted using a database containing 48-hour actigraphy recordings for 104 adult healthy subjects (22.43 ś 1.66 years of age). Two actigraphs (Mini-Motion-Logger, Ambulatory Monitoring Inc., Ardsley, New York, USA), were used to simultaneously measure and record actigraphy for 1-minute epochs on both dominant and non-dominant wrists. For the duration of the experiment, the subjects were asked to keep an accurate diary of the times when they went to sleep and woke up. In practice, diaries are typically inaccurate and unreliable. However, in this case the study included motivated and trained research volunteers, and the need for accuracy in the diary was strongly emphasized. The average number of sleep hours per night recorded by the subjects in the database ranged from

Tab. 1: Summary of the performance results of the different algorithms for the actigraphy records in the validation database. The values shown correspond to statistics of PM1 for the dominant and non-dominant hand actigraphy signals, as well as statistics for PM2. The last line displays the average number of false transitions per 48-h period, PM3.

PM1 (Dominant)				
	Cole	Sadeh	Oakley	Crespo
Median (%)	91.9	90.7	89.0	94.8
Mean (%)	90.2	89.2	87.7	94.3
Std Dev (%)	6.5	6.4	6.2	3.3
Max (%)	98.6	97.6	96.5	99.1
Min (%)	64.8	68.7	64.5	80.6
Avg. Invalid Trans. (48h)	68.0	73.2	200.8	0.02
PM1 (Non-Dominant)				
Performance Metric	Cole	Sadeh	Oakley	Crespo
Median (%)	89.1	88.4	86.0	94.8
Mean (%)	88.0	87.0	85.3	94.1
Std Dev (%)	7.2	7.1	6.7	3.2
Max (%)	98.5	97.3	96.3	99.1
Min (%)	61.1	60.4	60.8	81.5
Avg. Invalid Trans. (48h)	82.2	77.0	220.2	0.02
PM2 (Dominant vs. Non-Dominant)				
Performance Metric	Cole	Sadeh	Oakley	Crespo
Median (%)	92.9	93.0	90.4	97.3
Mean (%)	92.3	92.3	89.8	96.6
Std Dev (%)	4.3	4.3	4.4	2.4
Max (%)	98.2	97.8	96.7	99.7
Min (%)	77.2	76.3	73.7	86.9
Avg. Invalid Trans. (48h)	50.8	53.7	193.9	0.04

5 to 11 hours, with 67 out of the 104 subjects recording an average of 8-9 hours of sleep per night. Each of the evaluated algorithms was applied once to every signal in the database using the default input parameters. No parameter tuning, adjustment, or training was performed. The comparison of the algorithms was based on three performance metrics (PM). PM1 was defined as the coincidence between the algorithm output and the diary in 1-minute epochs, PM2 represents the coincidence between the algorithm output for the dominant and non-dominant hand signals in 1-minute epochs, and PM3 is the number of invalid transitions detected by the algorithm per 48-hour period.

3 Results and Discussion

Table 1 provides a performance comparison between the proposed algorithm and the classical algorithms proposed by Cole, Sadeh, and Oakley, based on performance metrics PM1 through PM3. The table shows higher values of PM1 for the proposed algorithm than the classical ones. In general, it displays higher mean and median values, lower standard deviations, as well as higher maximum and minimum values for both the dominant and non-dominant hand actigraphy signals. The classical algorithm performance in this metric is typically above 90%, which is consistent with the values reported for the rate of agreement between these algorithms and PSG in previous studies [4]. The proposed algorithm displays higher mean and median

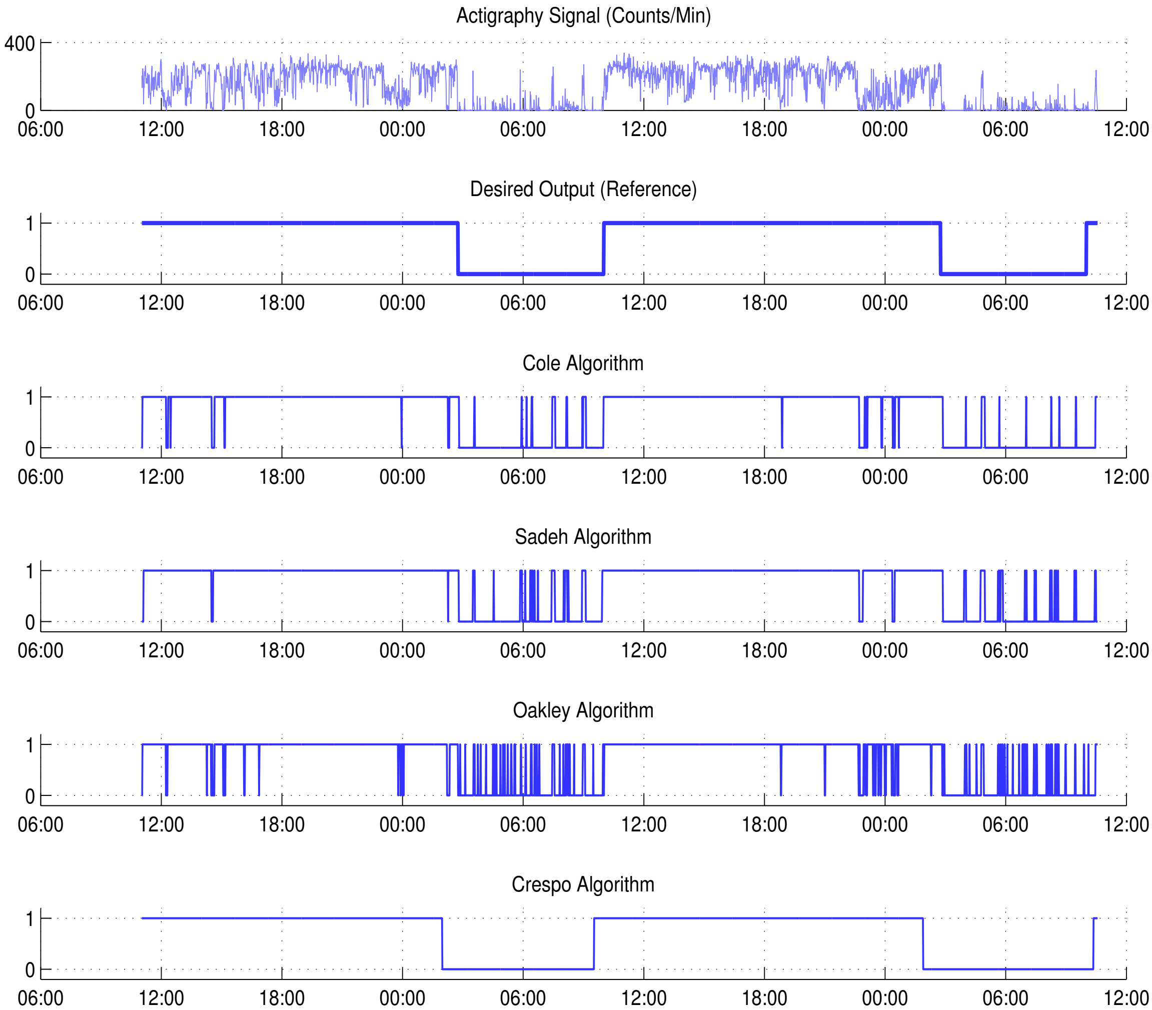

Fig. 1: Example of results illustrating the performance of the different algorithms on a real actigraphy signal collected with a wrist actigraph. The top plot displays the actigraphy signal. The second plot displays the desired algorithm output (diary). The remaining plots represent the outputs of the different algorithms included in the comparative study.

values for this metric than the classical ones, but where it significantly outperforms the others is in the average number of invalid transitions in 48 hours (PM3). The table displays values of 0.02 for the proposed algorithm, whereas the values reported for the classical algorithms are between 68 and 83 for *Cole* and *Sadeh* and over 200 for *Oakley*. This is an expected result, since the proposed algorithm was specifically designed to overcome the high number of invalid transitions associated with the classical algorithms. The fact that Oakley's algorithm displays such a higher number of invalid transitions is likely due to the fact that this algorithm was intended for use with a different actigraph (Actiwatch, Philips, Andover, Mass., USA). The proposed algorithm also exhibits more consistent performance than the classical ones, which is shown by the lower standard deviation values, 3.3 or lower for the proposed algorithm and between 6.2 and 7.2 for the classical ones. The table also shows better PM2 values for the proposed algorithm, indicating a better rate of agreement between the algorithm output for the dominant versus the non-dominant hands. The most significant improvement in this case is also the average number of invalid transitions in 48 hours, with a value of 0.04 for the proposed algorithm, and values of 50.8 for *Cole*, 53.7 for *Sadeh*, and 193.9 for *Oakley*.

Fig. 1 displays the output of the different algorithms for a real actigraphy signal. This figure serves to illustrate 1) the high number of invalid transitions of the classical algorithm, 2) the inability of the classical algorithms to handle actigraph disconnections, and 3) the robustness of the proposed algorithm to actigraph disconnections and its ability to avoid invalid transitions.

4 Conclusions

This paper presented the results of a study designed to compare the performance of a novel sleep/wake identification algorithm against the classical sleep/wake detection algorithms proposed by Cole, Sadeh, and Oakley. The study was conducted on an actigraphy database containing simultaneous dominant and non-dominant hand actigraphy recordings for 104 patients. The comparison was based on three performance metrics, PM1 through PM3. The results showed that the new algorithm exhibits better performance in every metric, with the most significant difference being associated with performance metric PM3. An algorithm intended for identification of sleep/wake periods for ABPM applications must not only provide accurate localization of sleep/wake boundaries, but also avoid detection of invalid transitions. Therefore, these results show that the proposed algorithm is a better choice than the classical ones for ABPM applications.

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