On the Relationship of Arousals and Artifacts in Respiratory Effort Signals

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Abstract— **Arousals are vital and thus very important for healthy sleep. Physiologically they manifest in cardiorespiratory signals or body movements. Generally, the acquisition of such signals is much easier than with the standard electroencephalogram (EEG). In this work we visually analyzed respiratory effort (RE) signals acquired with a respiratory induction plethysmography sensor (RIP) during whole-night polysomnography (including sleep stage and arousal annotations done with EEG) and annotated the artifacts. Artifacts are present when a change or distortion of the respiratory signal occurs. In total, the data from 15 subjects were acquired in two different sleep laboratories. The performance of detecting arousals only with the use of artifacts was evaluated. Since arousal and artifact sections are not always aligned in time, arousals have been widened by detection windows of 15 s and 30 s around it. If one artifact is present within this window the arousal was marked as detected. Median detection rates using this new approach of 69.81%, 77.36%and 83.02% were achieved for the original arousals on 15 s and 30 s window expansion, respectively. It is shown that in average 40.7% of the artifacts belong to the wake state, reducing the capability of detecting arousals that occur by definition only during sleep. During sleep, much more artifacts than arousals are present in the rapid eye movement (REM) stage, which is related to the fact that respiration is much more irregular during REM than during non-REM sleep and thus leading to increased artifacts.**

Keywords— **arousals, artifacts, manual annotation, respiratory effort, respiratory induction plethysmography.**

I. INTRODUCTION AND OBJECTIVES

A certain number of arousals during sleep are very important for a healthy sleep architecture [1]. Too many arousals disturb the sleep architecture and are suggested to have similar consequences as sleep deprivation, too few arousals might be life threatening as incidences or obstruction during sleep would not be noticed without them [1, 2]. It is known that an increased occurrence of arousals is correlated with certain sleep disorders, like parasomnia or obstructive sleep apnea (OSA).

Arousals and their relation to sleep disordered breathing have been analyzed, e.g. by Thomas [3] who found that arousals were initiated very closely to the termination of an apnea event and progressed through the breathing phase. Furthermore, arousals are linked to the response of the cardiac system, such as sudden increase in heart and breathing rate or blood pressure, and also to the locomotor system resulting in body movements. It was shown in previous work that the detection of arousals enhances sleep/wake classification when using actigraphy sensors, since a major part of falsely detected wake stages are related to arousals [4].

OSA is the most common sleep-related breathing disorder, that is known to increase arousal thresholds, especially when comparing rapid eye movement (REM) and non-REM sleep [5]. To detect sleep disorders, cost- and time-intensive analyses in sleep laboratories are generally performed. The gold standard for annotation of sleep and related parameters, such as arousals, is the polysomnography. Therefore it is motivated to develop less obtrusive systems for the measurement of vital signals that are related to sleep and lead to the identification of arousals [2, 6]. The respiratory effort is one eligible candidate as it is measurable with a non-disturbing respiration belt with minimal technical complexity. On the one hand it is possible to detect changes in the respiratory signal, e.g. for the discrimination of REM and non-REM sleep [7]. Drinnan *et al.* [8] showed that there is a phase change between ribcage and abdominal respiratory effort (RE) signals that are related to apnoe-related arousals. On the other hand, since those belt are very sensitive to movements and interactions, they are also useful to detect motion artifacts, e.g. when a subject turns around or moves a limb.

Thus, instead of discarding disturbed segments of the signal, which are generally not useful for respiration analysis (e.g., when looking into respiration rates, in/expiration ratios or flow estimations), we isolate the disturbed segment and investigate their respective relationship to arousals. In this work we examined RE signals acquired during the night and manually annotated artifacts on a visual inspection. Afterwards, the segments are compared to annotated arousal segments in time and duration.

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II. MATERIALS AND METHODS

The data have been acquired through 15 whole-night polysomnographic recordings of sleepers without any known sleep disorder, where six subjects were measured in Eindhoven (The Netherlands), at the sleep laboratory of the High Tech Campus and nine subjects in Boston (USA), at the Sleep Health Center. The data were recorded and annotated according to the American Academy of Sleep Medicine (AASM) guidelines [9], including arousal annotations according to the American Sleep Disorders Association (ASDA) [10]. Afterwards, RE signals derived from a Respiratory Induction Plethysmography (RIP) sensor attached to the thorax were visually inspected in the time domain. Each section, which did not contain any valid respiratory signal was marked as an artifact. They were identified by alterations in signal amplitude, distorted shapes or sudden irregularities, e.g. due to very irregular breathing during REM sleep [11], in the respiratory cycle plot. An example of such a disturbance is shown in Fig. 1. In this sample the artifact starts at about 70 s and lasts for more than 30 s. Within this time, an EEG-based arousal also has been annotated. Before and after the artifact, normal respiration cycles are visible. It is known that sudden arousals or short awakenings are potential sources for such type of artifacts since they are often accompanied by body movements causing artifacts in the RE [8]. Also apnoe/hypopnea events followed by sudden hyperpnea are likely to distort the respiratory signal shape [12] and may indicate an onset of wakefulness [11].

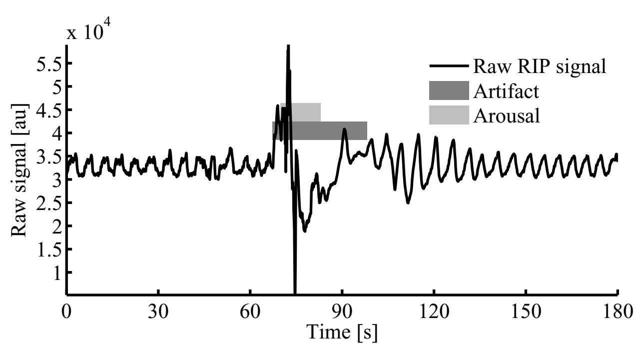

Fig. 1: Example of raw RIP signal with artifact and arousal annotation.

After the annotation of artifacts, for each arousal section it was checked whether an artifact segment is present within a certain window $t_{win} \in \{0\text{ s}, 15\text{ s}, 30\text{ s}\}$ around the corresponding arousal. Often, artifact intervals, as in Fig. 1, do not exactly match the beginning, ending or length of an arousal and last much longer than the arousal itself. Therefore, we analyzed whether artifacts are in the surrounding of an arousal within window widths of 0, 15 and 30 s around it. A window width of 0 s means that the original arousal annotation is analyzed. For detecting the presence of arousals, the following conditions have to be fulfilled:

$$t_{aro,start} - \frac{t_{win}}{2} \leq t_{art,end} \tag{1}$$

$$t_{aro,end} + \frac{t_{win}}{2} \geq t_{art,start}\,, \tag{2}$$

where $t_{aro,x}$ and $t_{art,x}$, $x \in \{start, end\}$, describe the starting points of the arousal and artifact sections, respectively. An arousal is detected when an artifact segment is overlapping the arousal segment, defining the detection rate as the number of detected arousals divided by all arousals.

III. RESULTS AND DISCUSSION

The procedure described in the previous section was performed with different window widths around each arousal. Descriptive statistics about the annotated arousals and artifacts, by subject and overall, can be found in Table 1. The columns include the total number of arousals and artifacts, their total and average lengths with standard deviations. The table reveals that many artifacts are not necessarily related to arousals. A total of 1330 arousals and 4085 artifact sections were annotated with total durations of 9258 s and 58378 s, respectively. Hence, artifacts (#art) are present three times more than arousals (#aro) and the total arousal length d_{aro} is only one sixth compared to the total artifact lengths d_{art}. This is due to the large amount of artifacts occurring during the wake stage (40.7%) and the average artifact length $\bar{d}_{art}$ which is about two times larger than the mean arousal length $\bar{d}_{aro}$. By definition, arousals are only present during sleep stages. Since artifacts also occur during wake states, the amount of detected artifacts intrinsically is always higher than the number of arousals.

The average arousal (and standard deviations) lengths are quite consistently distributed over all subjects. This is not true for artifact lengths, that show high standard deviations. One explanation for this can also be linked to the wake states. Therefore, we also computed the average artifact lengths during wake and sleep, $\bar{d}_{art,wake}$ and $\bar{d}_{art,sleep}$, respectively. Since wake states are defined to last at least 30 s, the artifacts, at least those occurring during wake, are also very likely to be more than 30 s long, which is shown with $\bar{d}_{art,wake}$. $\bar{d}_{art,sleep}$ is the same dimension as $\bar{d}_{aro}$.

The detection rates for each subject and the pooled results are shown in Fig. 2. It can be seen that in most of the 15 subjects more than 50% of the original arousals are already within an artifact section. For some subjects (i.e. 2, 5, 6 and 10), the detection rates are below or around 50%, even when

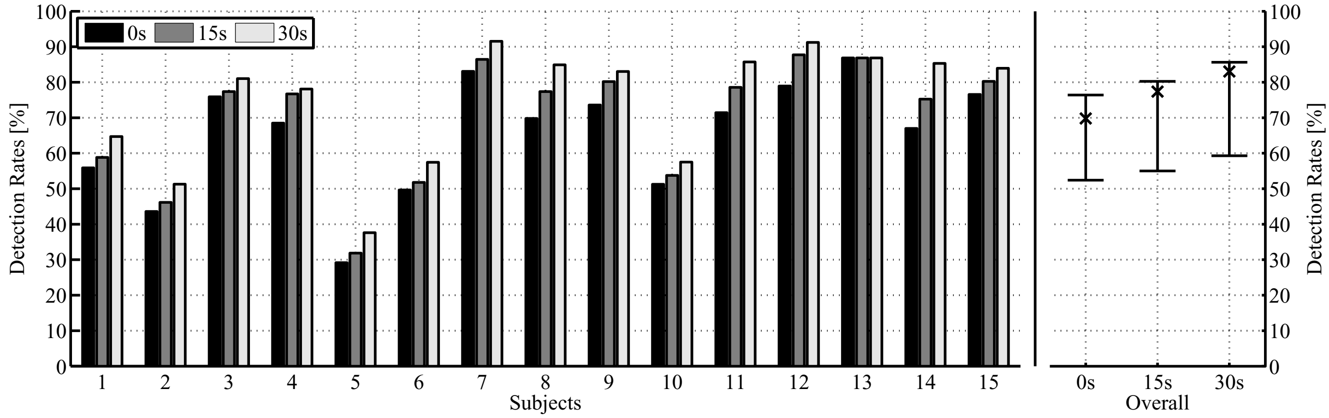

Fig. 2: Detection rates by subjects and overall pooled results with different detection windows.

Table 1: Arousal and artifact occurrences listed by subject. Standard deviations are parenthesized.

	Arousal / artifact occurences and durations d [s]								Artifacts in [%]	
Sub	**#aro**	**#art**	d_{aro}	d_{art}	$\bar{d}_{aro}$	$\bar{d}_{art}$	$\bar{d}_{art,wake}$	$\bar{d}_{art,sleep}$	**wake**	**sleep**
1	34	167	269	1716	7.9 (2.7)	10.3 (10.9)	16.5 (17.1)	7.4 (6.3)	40.6	59.4
2	39	131	260	1481	6.7 (2.8)	11.3 (12.7)	16.9 (16.5)	5.6 (4.2)	63.4	36.6
3	137	256	965	2802	7.0 (2.3)	10.9 (12.7)	15.9 (19.5)	7.6 (5.6)	43.3	56.7
4	73	232	499	3094	6.8 (2.7)	13.3 (19.6)	17.5 (29.8)	9.2 (10.4)	44.8	55.2
5	295	185	1759	2131	6.0 (1.7)	11.5 (12.0)	22.2 (21.5)	8.2 (5.7)	39.1	60.9
6	141	221	874	2825	6.2 (2.3)	12.8 (16.8)	23.4 (44.4)	9.5 (5.9)	27.5	72.5
7	59	197	384	2156	6.5 (2.5)	10.9 (6.0)	11.9 (11.0)	10.1 (5.3)	8.9	91.1
8	53	282	441	3908	8.3 (3.0)	13.9 (10.2)	16.3 (18.3)	11.6 (6.8)	24.5	75.5
9	106	289	654	3614	6.2 (2.2)	12.5 (9.3)	12.1 (12.2)	11.0 (7.7)	15.6	84.4
10	80	161	683	2560	8.5 (2.9)	15.9 (26.3)	15.5 (37.3)	11.2 (8.7)	49.9	50.1
11	28	306	218	5790	7.8 (2.6)	18.9 (37.9)	22.0 (49.5)	14.1 (15.4)	63.4	36.6
12	57	626	390	11792	6.8 (2.6)	18.8 (44.8)	30.8 (67.1)	9.5 (6.4)	68.6	31.4
13	38	333	280	4953	7.4 (3.5)	14.9 (19.1)	23.0 (34.4)	11.1 (6.4)	41.5	58.5
14	109	452	830	6056	7.6 (2.4)	13.4 (33.6)	28.7 (80.6)	9.9 (5.2)	35.9	64.1
15	81	247	752	3499	9.3 (3.2)	14.2 (17.1)	19.2 (27.6)	11.7 (7.8)	42.9	57.1
All	**Σ1330**	**Σ4085**	**Σ9258**	**Σ58378**	**∅7.0 (2.6)**	**∅14.3 (26.5)**	**∅22.2 (47.6)**	**∅10.0 (7.5)**	**∅40.7 (16.9)**	**∅59.3 (16.9)**

the arousal definitions are expanded by the 15 or 30 s window. This is often due to long intervals having bad RE signal quality where artifact annotation on a visual basis is very difficult. However, subject 13 shows good detection rates of nearly 90%, independently from the window width. Very low number of isolated arousals and relative high artifact annotations automatically lead to good precision. The very low detection rates of subject 5 are due to the combination of a very good and hardly disturbed RE sensor signal (visually verified) and the number of arousals, which is larger than the number of artifacts (see Table 1). Additionally, for this subject nearly 40% of the artifacts are during wake, therefore not usable for arousal detection. Nevertheless, a high amount of artifacts during wake stage is not necessarily responsible for low detection rates, e.g. seen in subjects 11 and 12. For all subject the expansion of arousals by 15 s or 30 s clearly improves detection rates. This means that an arousal is very often accompanied by an RE artifact in the surrounding. On the right hand side of Fig. 2 the [25^{th}, 50^{th} and 75^{th}] percentiles of arousals present within an artifact segment relative to the total amount of arousals over all the subjects show [52.41%, 69.81%, 76.39%], [55.02%, 77.36%, 80.23%] and [59.30%, 83.02%, 85.62%] for the 0, 15 and 30 s detection windows, respectively. The distribution of detection rates is heavily skewed towards the 75^{th} percentile value showing that most of the higher detection rates are only slightly above the median value performing nearly equally well (about $\pm 10\%$).

Since the relative amount of artifacts during the wake state is very important (i.e. 40.7% of all artifacts), we separately analyzed the occurrence of arousals and artifacts during sleep only. In Fig. 3 the occurrences during different sleep stages - rapid eye movement (REM: R) and three non-REM stages (NREM: N1-N3) are shown. The major difference can be found between R_{aro} and R_{art}. Where arousals occur in less than 20% during REM sleep, more than 20% of the artifacts are located in this sleep stage. At first sight it seems paradox, since during REM sleep the muscle activity is reduced and therefore a body movement is less likely to arise. But during REM sleep the respiration is very irregular causing annotations of artifacts. Nevertheless, most arousals and artifacts can be found in N2. In general, during NREM sleep, the distributions are very similar and comparable.

IV. Conclusion

The precision of detecting arousals with artifacts manually derived from the RE yields high median values of 83.02% when using expanded detection windows of 30 s. Nevertheless, the number of artifact sections is much higher than the number of arousal sections that were annotated, giving low sensitivity. Many artifacts are related to the wake state and are therefore not usable for arousal detection, since arousals only occur during sleep. Within sleep, artifacts and arousals are similarly distributed in N1 and N3 stages, in N2 the amount of occurrences is much higher than in other sleep stages. A major difference is noticeable when comparing REM stages. In this study, different types of artifacts, i.e. amplitude/shape changes or irregularities are merged, making it impossible to distinguish between a moving artifact or the irregular breathing during REM sleep. However, the results motivate the development of automatic algorithms that process the RE signal, to find possible arousals with the aid of artifacts. False detections can be reduced by analyzing the context of the signal, e.g. by removing artifact sections that are too long or too short or by finding possible wake sections before doing the artifact evaluation. Also the use of more complex analysis methods, e.g. in the frequency instead of the time domain, would increase the detection capabilities. For scenarios where a cardiac sensor (e.g. electrocardiogram - ECG) is also available, the cardiorespiratory combination is very likely to improve the sensitivity as well since arousals are also directly linked to the cardiac system.

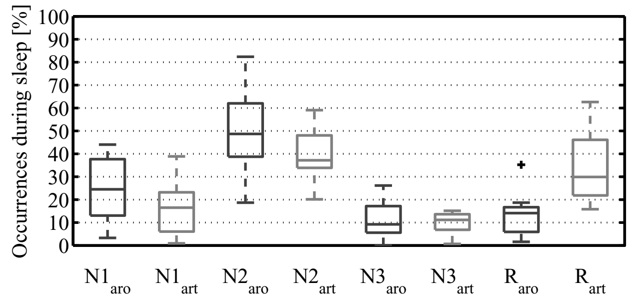

Fig. 3: Occurrence by sleep stage for arousal and artifact annotations.

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