Automatic Sleep-Wake and Nap Analysis with a New Wrist Worn Online Activity Monitoring Device Vivago WristCare®

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Study Objective: Vivago WristCare® is a new activity monitoring device, which allows long-term online monitoring of the activity of the user. This study evaluates the ability of the device to discriminate sleep/wake patterns during nighttime and during napping.

Design: Participants spent one night in the sleep laboratory where signals from polysomnography, actigraphy and WristCare® were acquired. In addition, actigraphy and WristCare® were used for 3-6 days for nap-analysis.

Setting: NA

Patients or Participants: Participants were 32 adults aged 26-89 years. The participants were studied in three study groups: all subjects, senior subjects (age>65 years) and middle-aged subjects (age<65 years).

Interventions: NA.

Results: Sleep/wake patterns were extracted from polysomnography, actigraphy and WristCare® for the night slept in sleep laboratory. The agreement percents between the scorings of polysomnography and actigraphy, and between polysomnography and WristCare® were about 80 % for all study groups. As total sleep time was estimated and the algorithm was optimized for this measure, the performance of the WristCare® and actigraphy were similar. Both actigraphy and WristCare® overestimated appreciably total sleep time (TST). Also in nap-analysis, actigraphy and WristCare® performed similarly as the number of naps and the length of the naps were compared.

Conclusions: The performance of the WristCare® can be assumed to be well comparable to actigraphy in sleep/wake studies. The study suggests that the device may be used in long-term monitoring of sleep/wake patterns with similar performance to actigraphy.

Keywords: Vivago WristCare®; actigraphy; polysomnography; reliability; automatic scoring

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INTRODUCTION

POLYSOMNOGRAPHY (PSG), CONSISTING OF SEVERAL PHYSIOLOGICAL MEASURES SUCH AS ELECTROENCEPHALOGRAPHY (EEG) AND ELECTROMYOGRAPHY (EMG), IS WIDELY CONSIDERED AS THE GOLDEN STANDARD TO DIFFERENTIATE SLEEP FROM WAKEFULNESS IN SLEEP RESEARCH. However, it is not well suited for long-term and large-scale studies or for measurements outside of the laboratory. Therefore, unobtrusive, user-friendly and low-priced devices are called for measuring sleep/wake data. Several methods have been proposed to quantify sleep quality, such as sleep diaries, video-monitoring, transducers attached to the body or different mattresses measuring activity during sleep, and various active or passive switches detecting the sleep onset.

Wrist actigraphy is the most widespread alternative to PSG to evaluate rest-activity cycles. An actigraph measures acceleration providing information on the activity of the user. The device can output either an acceleration measure or counts exceeding a given acceleration threshold, e.g. 0.1 g. In sleep studies, the latter choice is popular. The acceleration signal is sampled frequently and aggregated into epochs lasting e.g. 1 minute. Sleep/wake classification is made in epoch-by-epoch basis using mathematical methods.[1-3] The ability of actigraphy to detect sleep/wake states is based on the fact that the wrist is moved more awake than asleep. Actigraphy is an unobtrusive and low-priced technique, but it is also less accurate than PSG, and it cannot separate different sleep states. As Sadeh et al[4] listed results from several studies, the agreement rates, i.e., the agreement percents in epoch-by-epoch basis, were around 90% between PSG and actigraphy. The range was 85-96% for normal individuals and heterogeneous groups of patients. In addition, high correlation in total sleep time (TST) (r=0.90) was reported (range 0.81-0.98).[4] The accuracy of actigraphy is considerably worse in insomniacs than in subjects suffering no sleep disorders.[4] However, actigraphy is well suited to track trends in patients' sleep cycles for prolonged periods.[5] In addition to nighttime analysis, actigraphy can be used for 24-hour recording allowing nap analysis.[6] Accelometers can also be applied, for example, to the problems related to the activity of the patient[7] or to the evaluation of energy consumption.[8,9]

Potentially, actigraphy might provide valuable information in long-term monitoring of changes in health status, effects of therapy or medication, etc.[10] However, a limiting factor with the currently available actigraphs is the monitoring period, which is typically limited to a few weeks. Furthermore, the data are not available online. The Vivago WristCare® (IST International Security Technology Oy, Helsinki, Finland; http:\\www.istsec.fi) is a wrist-worn online activity monitoring device, which is designed to be used as an automatic personal alarm system for the elderly and chronically ill (Figure 1). The system is essentially a social alarm system with a manual alarm button, but, in addition to this, it has advanced automatic features, which enable it to call help if the wearer is not capable of doing so, e.g., due to loss of consciousness. The wrist unit provides an activity signal, which is constructed from the measured force change at the unit's movement sensor. The sensor is sensitive enough to record, e.g., muscle movements inside the wrist in addition to the hand movements. The automatic alarm functions are mainly based on the activity data, e.g., alarms are generated in case of unusually long period of passivity or total lack of movements. In addition the unit measures wrist temperature that may also be used for alarming. Skin conductivity measurement is used to automatically detect whether the unit is worn on the hand. The complete system consists of a wrist unit

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(battery powered, battery life 3-6 months) and a base station (mains powered with a battery backup) connected to an alarm handling PC software. The wrist unit uses a radio transmitter to communicate with the base station. The range covers a typical flat or house. In a home system the base station is typically connected to a call center via the public telephone line. The alarms and technical notifications can be flexibly routed to different receivers, also to mobile phones. In an institutional installation the base stations are networked and connected to a local PC, which handles the alarms and displays the activity signals of the users living in the institution. In addition to these alarm features, the device hence provides an activity signal that resembles traditional actigraphy. The system is designed for long-term use, i.e., use over many years.

The objective of the current study was to validate the activity signal provided by the WristCare® in detecting the sleep/wake patterns in normal adults and elderly. We report the accuracy of WristCare® compared to PSG during nighttime. A parallel analysis is carried out for actigraphy for comparison. In addition, a nap analysis is made for WristCare® and actigraphy signals measured during daytime, and the results are compared.

METHODS

Subjects

Thirty-two subjects (8 males and 24 females) with mean age 62 years (range 26-89 years, SD, 19 years) participated in the study. Four subjects were, however, excluded from the study because either WristCare® or actigraphy signals were corrupted or lacking. The measured data were analyzed in three groups. The first group contained all subjects (N=28). For the second group (N=15), only senior citizens (> 65 years, mean 78 years, SD 7 years) were chosen. Most of the subjects in this group were from day centers for senior citizens, which are typical users of the WristCare®. The third group (N=13) consisted of middle-aged persons (< 65 years, mean 44 years, SD 10 years).

Procedures

WristCare® (manufactured by IST International Security Technology Oy) and actigraphy (ActiWatch, Cambridge Neurotechnology, AW4) signals were recorded for each subject for at least three days and nights (range 3-6 days). Although Motionlogger and Actillume have been reported to produce better sleep scoring results than ActiWatch, ActiWatch was considered as a good reference because of its wide distribution in clinical practice. Most of the middle-aged subjects did not, however, wear the WristCare® during daytime, as all the senior subjects did. PSG was monitored during the last night, except in one case, where the PSG was monitored during the third night of six nights. The WristCare® and actigraphy devices were placed on the nondominant wrist.

The channels recorded in the PSGs were: EEG from C3-A2 and C4-A1, submental EMG, electrooculography (EOG) from the left and the right eye referenced to A1 according to the montage suggested by Häkkinen et al.[11] EMG from the nondominant arm was recorded with an electrode placed over the extensor carpi radialis muscle referenced to an electrode over the biceps brachi muscle. The PSG with 30-second epochs was scored using the standard Rechtschaffen and Kales (R&K) criteria.[12] Thereafter, the data were transformed to the epochs of one minute by rescoring “wake” whenever both sleep and wake states were present within the epoch, as was done by Sadeh et al.[1]

The epoch length of one minute was used for the analysis of wrist activity data. The activity value of an epoch in WristCare® is aggregated from the measured activity levels within the epoch. The data from actigraphy were processed accordingly, i.e., the original file containing epochs of 10 seconds was transformed to the epochs of one minute.

Both WristCare® and actigraphy signals were scored using a similar algorithm allowing more reliable comparison of the performance of the devices; the scoring software provided by the manufacturer of the actigraphy device was not used. Two scoring algorithms were tested.

The method proposed by Jean-Louis et al[2] utilizes a simple thresholding technique combined with post-processing. The epochs containing higher activity than a given threshold were scored as wake and lower activity as sleep. Then, arousals lasting 3 minutes or less were rescored as sleep. Moreover, other post-processing criteria can be also used. Cole et al[3] proposed several rules: 1) the sleep of 1, 3, or 4 minutes was rescored as wake if it preceded at least 4, 10, or 15 minutes of wake, respectively, and 2) the sleep of 6 or 10 minutes surrounded by at least 10 or 20 minutes of wake was rescored as wake, respectively. Jean-Louis et al. determined the optimal threshold as an average of optimal thresholds for each subject. In this study, this technique is referred to as AMAES (Average of Maximum Agreement for Each Subject). The optimal threshold for each subject was defined by minimizing the difference in TST between the activity and PSG signals. However, agreement percent, i.e., percentage of all epochs classified similarly in the activity and PSG data, was used in this study as an index of comparison. In general, AMAES does not provide the optimal threshold for the whole data. Therefore, we used a threshold that maximizes the average agreement rate for all subjects. This technique is referred to as MAAS (Maximum Agreement for All Subjects). In the Results section, differences between these techniques are demonstrated.

The second method applied was reported by Sadeh et al.[1] Five activity variables were computed for each epoch in the activity signals: original value, mean, standard deviation, number of epochs above a specified activity level, and the natural logarithm. Thereafter, logistic regression was performed for the variables while the sleep/wake classification of PSG acted as the dependent variable in the analysis. The scoring function produced gives negative values when awake and positive when asleep, i.e., the function provides a sort of sleep probability. Sadeh et al used discriminant analysis instead of logistic regression. Logistic regression is, however, a more general method because no assumption of the normality of the data is made.

Study A: Sleep/wake detection during nighttime. The WristCare® and actigraphy signals were scored applying both scoring methods described above. Thereafter, the WristCare® and actigraphy results were compared to the PSG scorings, and the agreement percents were determined. In addition, TST was used as an additional comparison criterion in this study. The correlation coefficient and the absolute difference are reported.

Study B: Nap analysis during daytime. The algorithms used to analyze nighttime data were also applied to daytime signals. However, no reference data (PSG) existed for the nap analysis during daytime. Hence, the scorings of WristCare® and actigraphy were compared to each other,

Table 1—The optimal thresholds (Th) and the logistic regression models for various subject groups.

WristCare®	**Th**	**Logistic regression**
All subjects	1.1	PS=1.472-0.099s-1.008mean+0.086nat-1.847sd-0.492log2
Senior subjects	0.7	PS=1.110-0.145s-0.935mean-0.031nat-1.539sd-0.539log2
Middle-aged subjects	2.3	PS=2.354-0.528s-1.154mean+0.248nat-1.981sd-0.239log2
ACTIGRAPHY	**Th**	**Logistic regression**
All subjects	8	PS=1.687+0.003s-0.034mean-0.419nat+0.007sd-0.127log2
Senior subjects	2	PS=1.439+0.001s-0.042mean-0.433nat+0.010sd-0.114log2
Middle-aged subjects	68	PS=2.006+0.005s-0.032mean-0.304nat+0.006sd-0.131log2

s is the activity of the scored epoch; mean is the mean activity in the window of 7 epochs around the scored epoch; sd is the standard deviation of the activity in the window of 8 epochs around the scored epoch; nat is the number of activity counts above a given threshold in the window of 11 epochs around the scored epoch (the threshold was 1 for WristCare® and 10 for actigraphy); log2 is the natural logarithm of the activity during the scored epoch + 0.1.

Figure 1—WristCare® wrist unit.

and the results are discussed only qualitatively.

Besides the qualitative nature of the comparison, a few quantitative parameters were determined to facilitate the interpretation. The agreement percent epoch-by-epoch between the WristCare® and actigraphy scorings was computed. In addition, the number of naps per day, and the mean duration of the naps, were computed and compared between the actigraphy and WristCare®. The naps defined in the sleep diary were also compared to the naps found by the scoring algorithm.

Software package, SPSS 10.0, was applied for statistical computations. The optimization and testing of the performance of the scoring algorithms was carried out by jack-knife method. The P-value 0.01 was used to detect statistically significant differences between two variables. As two variables were compared, nonparametric Wilcoxon Signed Ranks Test was used because of small number of subjects in the study.

RESULTS

Figure 2 visualizes WristCare® and actigraphy signals for one subject during the PSG night as well as the corresponding PSG scoring. WristCare® is more sensitive to low-intensity activity while the dynamics of actigraphy is better at high-intensity activities, as the figure also illustrates. The Pearson correlation coefficient was r=0.52 between the activities. Linear correlation is not, however, a good measure for the signals that are not linearly dependent.

Study A: Sleep/wake detection during nighttime. The optimal thresholds related to the scoring algorithm of Jean-Louis et al[2] were determined for WristCare® and actigraphy signals. The approach based on the logistic regression was also applied to same data for comparison. As PS (probability of sleep) gives negative values for an epoch, the epoch is scored as wake, otherwise as sleep. The thresholds without post-processing and regression equations are presented in Table 1. The thresholds as well as regression equations were defined separately for each subject as the jack-knifing procedure was used, i.e. the number of thresholds and regression equations was equal to the number of subjects in a study group. In Table 1, the thresholds and the regression equation are, however, the best choices as the whole study group was used to define the values. The thresholds and the coefficients of the regression equations were found to be statistically different ($p<0.01$), as seniors and middle-aged were compared.

The agreement percents with optimal scoring parameters (Table 1) are shown in Table 2. As the results of WristCare® and actigraphy are compared statistically, both devices provide equal agreement rates.

The effect of the post-processing criterion proposed by Jean-Louis et al was also tested. The change in the accuracy was, however, only on the scale of a percentage unit (not significant).

The ability of WristCare® and actigraphy to determine the TST is reported in Table 3. Actigraphy was found to produce better estimate of TST than WristCare® as all subjects were analyzed and the thresholding technique was used ($p<0.01$). When logistic regression was applied, the performances were equal in all study groups. The Pearson correlation coefficients for TST defined from WristCare® and PSG, and from actigraphy and PSG, were 0.43 and 0.70, respectively ($p<0.01$). The values were computed for all subjects. For comparison, the average sleep time of the subjects according to PSG was 5 hours 15 minutes.

Next the scoring algorithm was optimized for TST, i.e., the absolute difference in TST between PSG and WristCare®, or PSG and actigraphy was minimized. The new thresholds for all subjects were 0.7 and 1.5 for WristCare® and actigraphy, respectively. The corresponding TST differences were 59 and 41 minutes for WristCare® and actigraphy, respectively (not significant). The agreement rates changed about one percentage unit.

In the results reported above, the optimal threshold is determined using the method MAAS. The difference to the method AMAES is demonstrated. For all subjects, the optimal thresholds using MAAS and AMAES were, respectively, 1.1 and 1.0 for WristCare®, and 8 and 43 for actigraphy. As we applied the thresholds defined by AMAES, WristCare® was found superior in determing the TST ($p<0.01$) for all subjects.

Study B: Nap analysis during daytime. The thresholding technique without post-processing was applied for nap analysis. Only the group of senior subjects was chosen for the analysis as the younger subjects did not have WristCare® data available during daytime to allow nap analysis. Nighttime, i.e., the time the subject was in the bed according to the sleep diary, was excluded from the analysis. Minimum duration of 10 minutes and maximum duration of 120 minutes were set for the naps.

The agreement rate between WristCare® and actigraphy sleep/wake scorings in nap analysis was 87%. The average number of naps per day was 4.9 for WristCare® and 3.8 for actigraphy (not significant). The Pearson correlation coefficient between the number of naps was 0.82 ($p<0.01$). Consequently, the mean duration of the naps was 19 minutes for WristCare® and 17 minutes for actigraphy (difference not significant) and correlation 0.58. The scorings were compared also to the naps reported in the sleep diaries. Overall 13 naps were documented from which 12 were found by WristCare® and 11 by actigraphy.

DISCUSSION

The results of the present study indicate that the WristCare® and actigraphy have equal accuracy in sleep/wake detection as agreement percentages are compared. The agreement rates of about 80% were on the normal range for actigraphy but lower than about 90 % achieved in some reports.[4] Several reasons can cause the lower values. 1) The agreement was 10 percentage units higher for the middle-aged subjects than for the senior subjects. The result is natural because senior citizens are known to sleep more restlessly and shallowly.[13] The effect could also be seen from the sleep efficiency defined from the PSG measurements: sleep efficiency was 67% for the senior subjects and 84% for the middle-aged subjects. Senior citizens may have relatively more arousals with no associated limb movements than middle-aged subjects. 2) The subjects were not pre-selected, and an abnormal sleep behaviour was detected in a few cases. 3) Short wake periods were not filtered out from

Table 2—The agreement percent (on the left of the slash) and the standard deviation (on the right of the slash) for WristCare® and actigraphy signals in the calibration and validation groups. In thresholding technique, no post-processing was used.

AGREEMENT (%)		
All subjects (N=28)	**WristCare®**	**Actigraphy**
Thresholding	77/13	78/10
Logistic regression	78/12	81/11
Senior subjects (N=15)		
Thresholding	77/7	75/7
Logistic regression	77/7	78/9
Middle-aged subjects (N=13)		
Thresholding	84/11	85/10
Logistic regression	85/10	86/11

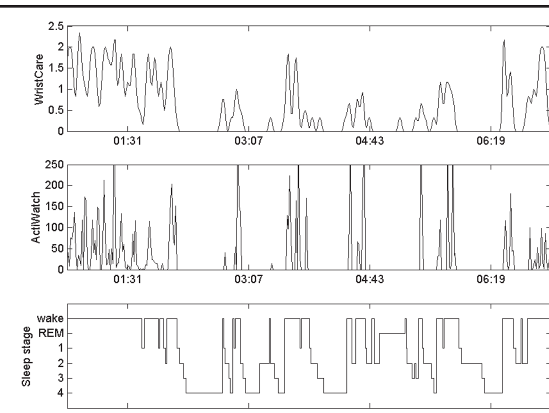

Figure 2—WristCare®, actigraphy and scored PSG signals.

the results in our study. As PSG was post-processed as well as WristCare® and actigraphy, we found that the agreement rate increased 4-5 percentage units. 4) In addition, it is worth noting that sleep is defined differently in PSG and actigraphy. Sleep stages in PSG are determined from the changes in EEG, EOG, and submental EMG, whereas in actigraphy, sleep and wakefulness are estimated by the amount of movements of a limb. Therefore the sleep/wake scoring of a PSG signal detects mainly the state of the brain, and actigraphy detects motor activity sufficient enough to cause a limb movement.

The TST was also used as an index of comparison. Both WristCare® and actigraphy appeared to overestimate TST from 30 to 70 minutes. The overestimation is a common phenomenon for actigraphy. However, the TST estimates produced using our data were considerably worse than the values reported in Jean-Louis et al[2]: 12 minutes for healthy subjects and 49 minutes for insomniacs. The trend of overestimation was visible both for WristCare® and actigraphy. If the agreement rate was used as a criterion of comparison, actigraphy was more accurate when MAAS was used to define the optimal threshold. On the other hand, WristCare® was more accurate when AMAES was used. As the optimal threshold was determined based on TST and all subjects were compared, TST estimates from WristCare® and actigraphy were equal. However, the correlation coefficient between the WristCare® TST and PSG TST was poor when compared to that between the actigraphy and TST. The poor correlation was due to two outliers, in which the WristCare® largely underestimated the TST. In these cases the subjects slept very restlessly (on the basis of PSG) but still the TST was relatively high. WristCare® underestimated TST in these cases, probably due to its high sensitivity to small movements, which occur in these subjects during their restless sleep. If these cases were removed from the data, the correlation coefficients would be similar to actigraphy.

The thresholding and logistic regression techniques were applied to score the signals. If only agreement rates are compared, logistic regression produces better results both in practice and in theory. Neither of the techniques was, however, superior as TST estimates were compared. In this study, the number of subjects in each subject group was reasonably small. A reliable comparison of the techniques would require more subjects. However, small changes in the scoring parameters, especially in the thresholding technique, did not affect the agreement rate or TST appreciably.

Two methods were tested to define the optimal threshold: MAAS and AMAES. The problem of AMAES is that if data contain a few cases for which the optimal threshold differs considerably from the rest of the cases, the optimal threshold is shifted toward these abnormal cases. Therefore, the threshold defined is not necessarily satisfactory to any of the subjects, and hence MAAS should be preferred.

Post-processing of scored signals was also studied by removing short wake periods around sleep periods or removing short sleep periods around wake periods. The process produced, however, only minor changes in the accuracy, which were far from being statistically significant. Cole et al[3] reported also improvements of the order of only one percentage unit. For these reasons, we do not see a clear justification for the use of post-processing in our study. However, if post-processing was used, filters should be different for WristCare® and actigraphy. Since the peaks are much smoother in WristCare® signal than in actigraphy, the filter should remove more lower frequency components from WristCare® signals than from actigraphy

Table 3—The TST difference (on the left of the hyphen) and the standard deviation (on the right of the slash) for WristCare® and actigraphy signals in the calibration and validation groups.

TST DIFF (min)	Calibration group	
All subjects (N=28)	**WristCare®**	**Actigraphy**
Thresholding	74/48	52/49*
Logistic regression	67/45	54/50
Senior subjects (N=15)		
Thresholding	56/39	59/46
Logistic regression	54/41	63/50
Middle-aged subjects (N=13)		
Thresholding	57/41	52/37
Logistic regression	52/41	47/34

The difference between WristCare® and actigraphy is significant at the level: *p<0.01

Several nights are needed to obtain reliable sleep parameters; even more than 7 nights might be required to get stable individual values with some sleep measures.[14] Even though the exact values of sleep parameters are essential in clinical practice, the main objective of this study was the comparison of WristCare® and actigraphy to detect sleep/wake states. The emphasis was on the relative performance between WristCare® and actigraphy. Hence, the number of nights used should not significantly affect the main results of this study.

In nap-analysis, PSG signal was not available and sleep diaries also have their limitations, e.g., by underestimating napping.[15] Therefore, the performance of the WristCare® or actigraphy was only compared with each other in nap analysis. No statistically significant differences were found in the parameters tested. As the scorings of WristCare® and actigraphy were compared to sleep diaries, both devices were highly sensitive to detect the reported naps. The agreement rate was high (87%) between the scorings. However, clear discrepancies were revealed between individual naps as the scorings of the devices were inspected visually. Despite this fact, we believe that both devices can provide useful information on subjects' napping behavior and its changes.

The automatic analysis of activity signals revealed many more naps than reported in the sleep diaries. Evans and Rogers[7] found this phenomenon also. In their study, 1.79 naps per day were found from sleep diaries as 5.2 naps per day were recorded by actigraphy. The number of naps per day found in our study corresponds fairly well the results of Evans and Rogers.

Activity signals from healthy subjects with no severe sleep disturbances were analyzed in the present study. The functioning of the WristCare® with other subject populations, such as insomniacs, should be studied separately. Although the WristCare® and actigraphy produced approximately equal results in this work, their measurement technology is different. Therefore, the recommendations and applicability stated for actigraphy can not be directly applied to the WristCare® without validation. In addition, as the number of subjects in this study was relatively low, final conclusions of WristCare's® accuracy to measure sleep parameters compared with actigraphy can not be made.

The fact that the WristCare® is designed to be a security device, especially for senior citizens, should not be forgotten. An accurate analysis of sleep/wake states are not crucial in the environment originally planned for the device. The main objective for the device is to detect and announce possible problems in daily activity pattern and sleep/wake rhythms for the user or for nursing staff. However, the WristCare® appeared to exceed the expectations posed for the sleep/wake analysis of the device and gave comparable results with actigraphy. In addition, WristCare® has an advantage that it is used in the normal living environment, provides real time data without data extraction, and can be used for long periods of time, which can not be done with actigraphy. According to the results the performance of the WristCare® can be assumed to be well comparable to actigraphy in sleep/wake studies.

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