

Laboratory and home comparison of wrist-activity monitors and polysomnography in middle aged adults.

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Manuscript word count: 4,403

Abstract word count: 247

ABSTRACT

Accurate measurement of time at lights out is essential for calculation of several measures of sleep in wrist-activity monitors. While some devices use subjective reporting of time of lights out from a sleep diary, others utilise an automated proprietary scoring algorithm to calculate time at lights out, thereby negating the need for a sleep diary. This study aimed to compare sleep-measures from two such devices to polysomnography (PSG) measures (In-Laboratory) and against each other when worn at home (At-Home). Fifty middle-aged adults from the Raine Study underwent overnight PSG during which they wore an ActiGraph™ and a Readiband™. They also wore both devices at home for 7 nights. The Readiband uses an automated proprietary algorithm to determine time at lights out whereas the ActiGraph requires completion of a sleep diary noting this time. In laboratory, compared to PSG: Readiband underestimated time at lights out, sleep onset, and wake after sleep onset, overestimated sleep latency and duration ($p < 0.001$ for all); while ActiGraph underestimated sleep latency and wake after sleep onset and overestimated sleep efficiency and duration ($p < 0.001$ for all). Similar differences between devices were observed on the laboratory night and when at home. In conclusion, an automated algorithm such as the Readiband may be used in the same capacity as the ActiGraph for the collection of sleep measures including time at sleep onset, sleep duration and time at wake. However, Readiband and ActiGraph measures of sleep latency, efficiency and wake after sleep onset should be interpreted with caution.

Keywords: actigraphy, algorithm, validation, polysomnography, sleep, technology

INTRODUCTION

The gold standard method of measuring sleep is laboratory-based polysomnography (PSG) (1). This method requires the careful application of many recording sensors around the head and face to differentiate periods of sleep from wake and to determine the different stages of sleep. While providing a comprehensive set of sleep-related data, PSG is costly, requires setup and analysis by a trained sleep technician, therefore is unsuitable for repeated measurements in the same individual over many days especially in “real-world” settings (2).

Accelerometry based techniques are becoming more widely used as an alternative to PSG to objectively distinguish periods of wake from sleep, within the period participants are in bed or at rest. Accelerometers measure movement and their general operating principle in sleep-measurement applications is to define sleep as periods of “no movement” and wake as periods of “movement” (3). A wrist-activity monitor permits long term, non-intrusive and cost effective assessment of sleep/wake patterns (4). Such devices have been used in a range of settings, including; in individuals who are shift workers, military personnel and athletes (5). Their ease of use has contributed to their popularity. Indeed, it is currently estimated that 69% of the United States population own and use a consumer-grade wrist activity monitor to assess their sleep and activity patterns (3).

Several algorithms have been developed to convert accelerometer-based measurements of movement into periods of wake and sleep (6, 7). In general, these algorithms have high sensitivity (*i.e.* they can accurately detect sleep periods within in the overall at rest period) but poor specificity (*i.e.* they cannot accurately detect

periods of wakefulness during the overall at rest period) (8). To optimise the accuracy of these algorithms the American Academy of Sleep Medicine (AASM) recommends that wrist-activity monitors be used in conjunction with a sleep diary (9) as a way to capture self-reported estimates of the time the individuals turned out their bedroom lights for the purpose of going to sleep (“time at lights out”). When combined with accelerometer-derived measurements of wake and sleep periods the measurement of lights out is necessary to calculate important sleep measurements such as sleep latency, sleep efficiency and time in bed.

The ActiGraph™ is one such wrist-activity monitor that has combined diary based information with accelerometer based data to objectively describe sleep in a wide range of health related and applied research projects (10-12). To calculate measures such as sleep efficiency, sleep latency and time in bed the ActiGraph software requires the user to enter the time of lights out from the sleep diary. However accurate assessment of these derived measures is critically dependent on the individual precisely recalling and recording the time they turned the lights out the previous night. This is potentially problematic given the reported variability between self-reported measures of sleep and actual sleep obtained (13).

In recent years, wrist-activity monitors use proprietary scoring algorithms to identify time of lights out, and therefore do not require input of subjective data from sleep diaries. One such device is the Readiband™ (14), a wrist- activity monitor developed for use in military environments unsuited to accurate and regular completion of a sleep diary. The Readiband has been used in a range of personnel and settings including police, physicians, mining, shift-workers, forestry industries (15-20) and in

elite athletes ([21-23](#)) including the US National Football League. Currently, only one technical report has been conducted on the validity of the Readiband and this reported an overall accuracy of 93% when compared to PSG ([14](#)).

The aim of the present study was to compare measurements of sleep obtained from the ActiGraph and Readiband devices to measurements obtained from PSG in a sleep laboratory, and to compare both devices against each other when worn at home for 7 nights. We were also interested in determining the accuracy and influence of algorithm derived estimates of time at lights out (Readiband) and the subjective estimates of time at lights out (ActiGraph) on measurements of sleep latency and sleep efficiency.

METHODS

Participants

A community sample of 50 middle-aged adults were recruited from the parents of participants in the 22-year follow-up study of the Western Australian Pregnancy Cohort (Raine) Study ([24](#)). Participants were recruited sequentially from September to December 2015 based upon their scheduled study night at the sleep laboratory.

Inclusion for the study was agreement to wear the two wrist-activity monitors at home for the night of the sleep study and for an additional 7 nights. There were no exclusion criteria.

Informed, written consent was obtained from each participant and ethical approval for the study was obtained from the University of Western Australia Human Research Ethics Committee.

Protocol

Each participant wore an ActiGraph and a Readiband on the same wrist (non-dominant) for eight successive nights. On the first night (Night 1) each participant slept at the University of Western Australia's Centre for Sleep Science where they underwent simultaneous PSG (the "In-laboratory" condition). Subsequent nights (Nights 2-8) were spent at home (the "At-home" condition). Following Night 8 (*i.e.* Day 9) participants returned the devices to the research team.

Anthropometric measurements

Measurements of height (cm) and weight (kg) were collected on Night 1 when participants arrived at the sleep laboratory. Body Mass Index (BMI) was calculated from weight/height² (kg/m²).

Sleep diaries

Participants were asked to complete a sleep diary every morning, noting the time they turned the lights out the previous evening ("time at lights out").

Polysomnography

Participants attended the sleep laboratory for an overnight PSG assessment for the In-laboratory condition. All PSG studies were performed on a weeknight (Monday, Tuesday, Wednesday or Thursday). Each participant was instrumented by a trained sleep technician as per AASM recommendations ([25](#), [26](#)) and data were collected using the Compumedics Grael system (Compumedics, Victoria, Australia). As the focus of the study was PSG identification of wake and sleep periods, the following electrodes were placed to facilitate the staging of sleep: 6 electroencephalogram

(EEG) sensors to the head utilising the 10/20 system (F3-M2, F4-M1, C3-M2, C4-M1, O1-M2, O2-M1); two electro-oculogram (EOG) sensors at the lower edge of the left eye and the upper edge of the right eye; and three submental electromyogram (EMG) electrodes were placed on the chin. Participants were awoken between 06:00-07:00 hr the following morning.

The PSG data were scored by a sleep technician according to the AASM (2012) rules for the staging of sleep ([27](#)).

Wrist-Activity Monitors

ActiGraph recordings were performed using GT3X+ activity monitors (ActiGraph, FL, USA). This device has been shown to have good validity (overall accuracy of 82%) when compared to sleep/wake epochs against PSG ([28](#)). Data from the ActiGraph devices were downloaded and analyzed using the ActiLife™ software (ActiGraph 2012, ActiLife 6) and scored in one-minute epochs as awake or asleep as per the Cole-Kripke algorithm ([7](#)).

Readiband recordings were performed using the Readiband version 3 (Readiband, Fatigue Science Inc., Canada). To the best of our knowledge the current and previous versions of the Readiband are similar, and most changes between versions have been aesthetic changes to the wrist-activity monitor and its interface. This Readiband device has been shown to be valid (overall accuracy of 93%) when compared to sleep/wake epoch scoring against PSG ([14](#)) and has been approved by the US Federal Drug Administration for measurement of sleep ([29](#)). Data from the Readiband devices were downloaded and analysed using the automated proprietary scoring algorithm Readiband Sync™ software.

ANALYSES

Sleep measures output by each device and PSG included: time of lights out (for PSG, it is the time the sleep technician turned off the lights to initiate sleep, for ActiGraph, the participant self-reported time at lights out by way of diary and Readiband time at lights out utilized an automated proprietary scoring algorithm); sleep latency (number of minutes from time at lights out to time of sleep onset); time at sleep onset (time of the first epoch of sleep between lights out and lights on); sleep duration (number of minutes from time of sleep onset to time at wake, minus number of minutes awake); wake after sleep onset (number of minutes awake after sleep onset); time at wake (the time of wake from sleep with no further sleep duration); time in bed (the total time spent in bed, from lights out until time at wake); and sleep efficiency (sleep duration divided by time in bed multiplied by 100).

Statistical analysis

Linear mixed models were used to compare sleep measurements derived from PSG, ActiGraph and Readiband for the In-laboratory condition and between ActiGraph and Readiband for the At-home condition for the measurements of: time at lights out, sleep latency, time at sleep onset, sleep duration, sleep efficiency, wake after sleep onset, time at wake. Fixed effects of measurement device (PSG, ActiGraph or Readiband), time; Night 1 (In-laboratory), Nights 2-8 (At-home) and their respective interaction terms (as appropriate) were included in the model along with random individual effects. Sleep latency and wake after sleep onset were transformed using a log transformation and statistical analyses were performed on the transformed data. Sleep efficiency and sleep period efficiency were transformed using an arcsine square

root transformation. The maximum likelihood estimation used in linear mixed-effects models effectively deals with the problem of missing data, as opposed to alternative methods which employ case-wise deletion should one individual have any observation missing.

Bland-Altman analyses were used to determine the agreement between devices for each sleep measure and are presented as the magnitude of difference between devices (bias) and the Limits of Agreement (LoA) (30). Data are presented as mean±standard deviation (SD) or mean±LoA and $p < 0.05$ was considered as statistically significant for all tests. All statistical analyses were performed using the R environment for statistical computing (31).

RESULTS

A total of 50 participants (30 females, 20 males) volunteered for this study. Their mean age was 57 ± 5 years (range 46-73 years), weight 76 ± 13 kg (range 50-110 kg), height 167 ± 10 cm (Range 134-186 cm) and BMI 27 ± 5 kg/m² (Range 20-45).

Comparisons of sleep measures between PSG, ActiGraph and Readiband for the In-laboratory and At-home conditions are shown in Table 1 and summarised as follows:

Time at Lights Out: In the In-laboratory condition, compared to PSG, the time at lights out estimated by ActiGraph (i.e. from morning diary) (Table 1 and Figure 1) was not different ($p = 0.81$), whereas the Readiband's automated estimation of time of lights out occurred 48 ± 136 min earlier (mean ±LoA) ($p < 0.001$). However, a proportional bias (i.e. magnitude of difference related to the magnitude of measurements) was observed for Readiband vs PSG and ActiGraph vs Readiband.

No difference was observed between ActiGraph vs PSG ($p=0.48$). In both the In-laboratory and At-home conditions the Readiband automated estimation of time at lights out occurred earlier than ActiGraph, by 47 ± 136 min and 45 ± 108 min, respectively ($p<0.001$ for both).

Sleep Latency: In the In-laboratory condition (Table 1 and Figure 2), compared to PSG, ActiGraph sleep latency was underestimated by 14 ± 35 min ($p<0.05$), while Readiband sleep latency was overestimated by 22 ± 74 min ($p<0.05$). A proportional bias was observed for Readiband vs PSG, ActiGraph vs PSG and ActiGraph vs Readiband. In both the In-laboratory and At-home conditions the Readiband sleep latency was longer than ActiGraph, by 36 ± 60 min ($p<0.05$) and 22 ± 36 min ($p<0.001$), respectively.

Time at Sleep Onset: In the In-laboratory condition (Table 1 and Figure 3), compared to PSG, the ActiGraph was not different ($p=0.17$), while the Readiband was earlier by 27 ± 96 min ($p<0.05$). A proportional bias was observed for Readiband vs PSG and ActiGraph vs Readiband. The estimated time at sleep onset was not different between the ActiGraph and Readiband for either the In-laboratory condition ($p=0.37$) or the At-home condition ($p=0.13$).

Sleep Duration: In the In-laboratory condition (Table 1 and Figure 4), compared to PSG, sleep duration was overestimated by both ActiGraph and Readiband, by 64 ± 106 min and 58 ± 122 min, respectively ($p<0.001$ for both). A proportional bias was observed for ActiGraph vs PSG and ActiGraph vs Readiband. Sleep duration was not different between the two devices for the In-laboratory condition ($p=0.58$), however

for the At-home condition Readiband sleep duration was 38 ± 61 min longer than the ActiGraph ($p<0.001$).

Wake after Sleep Onset: In the In-laboratory condition (Table 1 and Figure 5), compared to PSG, the time spent awake after sleep onset was underestimated by both the ActiGraph and Readiband, by 48 ± 85 min and 70 ± 101 min, respectively ($p<0.001$ for both). A proportional bias was observed for Readiband vs PSG, ActiGraph vs PSG and ActiGraph vs Readiband. In both the In-laboratory and At-home conditions the Readiband estimated wake after sleep onset was less than ActiGraph, by 22 ± 60 min and 32 ± 52 min, respectively ($p<0.001$ for both).

Time at Wake: In the In-laboratory condition (Table 1 and Figure 6), compared to PSG, there was no difference in the estimated time the participants woke for either the ActiGraph ($p=0.67$) or Readiband ($p=0.99$). The estimated time at wake was not different between the ActiGraph and Readiband for either the In-laboratory condition ($p=0.66$) or the At-home condition ($p=0.16$).

Sleep Efficiency: In the In-laboratory condition (Table 1 and Figure 7), compared to PSG, the ActiGraph overestimated sleep efficiency by 13 ± 20 % ($p<0.001$) with no difference for the Readiband ($p=0.45$). A proportional bias was observed for ActiGraph vs PSG and ActiGraph vs Readiband. In both the In-laboratory and At-home conditions the Readiband estimated sleep efficiency was less than ActiGraph, by 12 ± 20 % and 5 ± 14 %, respectively ($p<0.001$ for both).

DISCUSSION

This study compared measurements of sleep obtained from two wrist-activity monitors (the Readiband and ActiGraph), to the gold standard sleep assessment, laboratory-based PSG. In addition, these devices were compared against each other when worn at home for 7 consecutive nights. The major finding of the study was that the automated scoring algorithm estimation for time at lights out (as used by Readiband) was inaccurate compared to self-reported time at lights out (as used by ActiGraph) and technician reported time of lights out (as used by PSG). Sleep measurements that were not reliant on this measurement (e.g. time at sleep onset, sleep duration and time at wake) were similar between devices when used in the laboratory.

Accelerometer-based measurements of sleep can be considered in terms of variables that are either ‘directly’ measured by the device or required to be inputted (e.g. time at lights out, time at sleep onset, wake after sleep onset and time at wake) or variables that are derived from these measures (e.g. sleep latency, sleep duration and sleep efficiency). The accuracy of the latter variables are entirely dependent on the accuracy of the former.

Currently, the main guidelines for use of wrist-activity monitors to assess sleep (9) recommend using a diary to enter a value for time at lights out, although new commercially available devices on the market have developed proprietary algorithms to automatically estimate time at lights out. A benefit of such an automated algorithm is that they are not reliant on the input of subjective data and thus not influenced by the potential variability associated with this (32). It is also recommended that accelerometry data be collected for at least seven nights to adequately represent sleep

when using wrist-activity monitors ([33](#), [34](#)). Hence, a comparison of the behaviour of these devices against each other when worn at home for 7 nights in the current study, and against the results on the PSG night.

Directly Measured Sleep Variables

Accurate measurement of the time at lights out is essential for the calculation of sleep latency and sleep efficiency. On the PSG night, Readiband (Automated) underestimated time at lights out by 48 min (vs PSG) while the ActiGraph (Self-reported) was the same as PSG (within 1 minute). Similar differences in time at lights out were observed between the two devices when worn at home, suggesting that the underestimation by Readiband persisted during the At-home condition. Automatic measurement of time at lights out is challenging, and the precise algorithm used by the Readiband is unknown. Other devices use a light sensor to identify time at lights out, however this is problematic as the measurement will be inaccurate when the device is worn under clothing or under bed covers ([34](#)). Other devices use an event marker for participants to identify time at lights out, however this too can be problematic as it requires an individual to remember to actuate this marker each night in order for accurate measurements of time at lights out to be obtained ([34](#)).

The time at sleep onset is used in the calculation of sleep latency and sleep duration. On the PSG night, the Readiband estimated time at sleep onset to occur 27 min earlier than PSG defined time at sleep onset while the ActiGraph was not statistically different. Similar differences in time at sleep onset were observed between the two devices when worn at home, suggesting that the earlier time at sleep onset recorded by Readiband, relative to the ActiGraph persisted during the home condition. While

many wrist-activity monitors studies using wrist activity report measures such as sleep latency and sleep duration, ([32](#), [35](#), [36](#)) to date none have reported time at sleep onset against PSG.

The time at wake is used to signal the end of the sleep period and to calculate sleep duration. The Readiband and ActiGraph accurately estimated the time at wake against the PSG defined time at wake. In the home condition participants tended to wake later, however there was no difference between the Readiband and ActiGraph. Generally, studies that compare wrist-activity monitor data to PSG or between actigraphy devices, in general do not report results relating time at wake or investigate the validity of such measures ([32](#), [35](#), [36](#)).

The time spent awake after sleep onset (WASO) is used to calculate sleep efficiency and is a commonly reported sleep measure in studies comparing wrist-activity monitors to PSG ([8](#), [28](#), [37](#)). In the present study both the Readiband and ActiGraph devices significantly underestimated WASO by 70 and 48 minutes, respectively. It is likely that both devices continued to underestimate WASO in the home environment as the magnitudes of WASO and the differences between devices were similar when recorded in the laboratory and at home. These findings are consistent with many other studies that have reported that wrist-activity monitors are poor at correctly identifying periods of WASO ([8](#)), with some studies reporting overestimation of WASO compared to PSG ([8](#), [38](#)) and others reporting underestimation ([39](#)).

Derived sleep variables

Sleep latency is defined as the time taken to fall asleep. Errors in the calculation of sleep latency can therefore result from inaccurate measurements of time at lights out or time at sleep onset. In this current study, compared to PSG, sleep latency was s greater for the Readiband and less for the ActiGraph device. These differences were due to an earlier estimate of time at lights out and an earlier estimate of time at sleep onset for the Readiband; and an earlier estimate of time at sleep onset for the ActiGraph.

Previous studies have reported accelerometer-derived measures of sleep latency to be increased (37), decreased (8) or no different to PSG-derived measures (39, 40). While the reasons for these differences have not been explored in any previous studies, the findings of the present study highlight that errors in the estimations of times at lights out and/or time at sleep onset as potential sources of such variability in sleep latency (as sleep latency is calculated from these).

Sleep efficiency is a derived variable that is directly affected by the accuracy of the measurements of sleep latency and WASO. Specifically, WASO influences the measurement of sleep duration and sleep latency influences the measurement of time in bed. In the present study, the measurement of time in bed was affected by the significant underestimation of sleep latency using the self-reported method (ActiGraph) and significant overestimation by the automated scoring algorithm (Readiband). Both devices were poor at assessing WASO (underestimation by an average of 59 min compared to PSG) resulting in an overestimation of sleep duration, thereby affecting sleep efficiency. The overestimation of sleep efficiency by ActiGraph of 13% is likely to have continued in the home environment as the

magnitude of sleep efficiency and the differences between devices were similar between the laboratory and home conditions.

Sleep duration is derived from time at sleep onset to time at wake minus any periods spent awake (WASO). Compared to PSG, both the Readiband and ActiGraph devices similarly overestimated sleep duration (by an average of 61 min). When used in the home setting sleep duration increased for both devices compared to sleep duration measured on the laboratory night. This was particularly the case for the Readiband which reported almost a one hour increase in sleep duration. There is probably no single reason for the difference in sleep duration between the two devices in the home setting as the Readiband reported an earlier time at sleep onset, later time at wake and decreased WASO compared to the ActiGraph, all of which could contribute to an increased sleep duration.

Previous studies comparing sleep duration when measured from wrist-activity monitors and PSG have reported both an underestimation (41) and overestimation (42) in sleep duration. Rupp and Balkin (43) suggested that such variability in sleep duration is mainly due to the inaccuracy of wrist-activity monitors to identify periods of wake during sleep. The similarity in the present study between the magnitude of underestimation of WASO and overestimation of sleep duration is consistent with the conclusions of Rupp and Balkin (43).

A strength of the current study is its use of an unbiased selection of the general population as the participants in this study (n=50) were part of the broader parent cohort of participants in the Raine study (24), an internationally recognised and well-

published birth cohort study. As such the findings of this study are generalizable to other studies using such devices in the general population.

Limitations

A limitation of this study is the potential inclusion of individuals with health issues such as sleep disorders and other comorbidities, which could influence accelerometry derived sleep variables. However, such a limitation will exist in any community-based study and therefore not influence the generalizability of the current findings. Further, each participant simultaneously wore both devices during the full laboratory-based PSG study, and as such served as their own control for this study when comparing measurements between devices.

Another limitation of the study is the inability to access information regarding the proprietary algorithm used by the Readiband device. This is a problem common to many devices that contain automated scoring algorithms (e.g. FitBit, Jawbone, Garmin, Apple Watch). In the case of the Readiband the proprietary automated algorithm is owned by the United States military with Fatigue Science Inc., being the authorised distributor under license. To the best of our knowledge the underlying Readiband algorithm has not changed, with earlier versions of the device differing only in aesthetic changes to the watch and its interface.

Summary

The substantial challenges associated with automated measurement of time at lights out and sleep latency provide a strong reason for not including sleep latency in the calculation of time in bed and sleep efficiency. Similar issues regarding imprecise

time in bed or rest interval period were found in another study using a default automated algorithm (44).

In such a scenario, both time in bed and sleep efficiency would be derived from a measurement of 'sleep period time,' being the time elapsed between the first onset of sleep and the final awakening (45). Indeed, such an approach is being applied to automated scoring algorithms of several consumer based wrist-activity monitors (32, 36), possibly in response to the substantial challenges in automatically determining time of lights out. However, a consequence of this approach is that such devices will provide higher values of sleep efficiency as well as not providing measures of sleep latency.

This study highlights the challenges of accurately measuring the time at lights out as the primary reason for differences in sleep measurements between the ActiGraph and Readiband devices. The use of an event marker for time at lights out may improve the accuracy of measurements of sleep latency, time in bed and sleep efficiency, however such a method is completely reliant on the wearer remembering to press the event marker each night, and to do this at the correct time. The accurate recall of time at lights out in the present study adds support for the potential use of an event marker or time stamp (44). However it must be noted that these data were obtained in the setting of a sleep laboratory and it remains unknown how accurate diaries or event markers are for measurement of lights out in applied settings such as shift workers, military or athletes (46).

Conclusion

In conclusion, this study has shown that the Readiband device may be used in the same capacity as other wrist-activity monitor devices such as the ActiGraph for the collection of sleep measures including time at sleep onset, sleep duration and time at wake. However, Readiband and ActiGraph measures of sleep latency, sleep efficiency and wake after sleep onset should be interpreted with caution.

Acknowledgements

We acknowledge and thank the Raine Study participants, their families Raine study team for cohort management and data collection. Many thanks to Fatigue Science, Vancouver, British Columbia for the supply of Readibands™.

Disclosure statement

The Raine Study 22 year follow up was supported by NHMRC project grants 10277449, 1021858, 1031617 and 1044840. Core funding for cohort management was provided by the University of Western Australia, the Telethon Institute for Child Health Research, Raine Medical Research Foundation, University of Western Australia Faculty of Medicine, Dentistry and Health, Women's and Infant's Research Foundation, Edith Cowan University and Curtin University. Professors Straker and Eastwood were funded by National Health and Medical Research Council of Australia (NHMRC) Senior Research Fellowships (1019980, 1042341).

Compliance with Ethical Standards

Conflict of Interest

Ian C Dunican and John A Caldwell have previously undertaken consultancy work for Fatigue Science, but neither are currently engaged in any capacity with the company.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study and ethical approval was obtained from the University of Western Australia Human Research Ethics Committee.

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