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AASM standards of practice compliant validation of actigraphic sleep analysis from SOMNOwatch™ versus polysomnographic sleep diagnostics shows high conformity also among subjects with sleep disordered breathing

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Abstract

In recent AASM practice, parameter actimetry is cited to measure total sleep time in obstructive sleep apnoea patients, when polysomnography is not available. An actigraph was therefore compared to polysomnographic data in 28 subjects with known sleep disordered breathing. Total sleep time (TST), sleep period time (SPT), sleep efficiency (SE), sustained sleep efficiency (SSE), sleep onset latency (SL) and sleep/wake pattern were compared to gold standard polysomnography. The results of an epoch-by-epoch comparison of sleep/wake from actigraphy to sleep stages from polysomnography gave a sensitivity of 90.2%, a specificity of 95.2% and an overall accuracy of 85.9%. Correlations were moderately strong for SE (0.71, $p < 0.001$) and SSE (0.65, $p < 0.001$) and high for TST (0.89, $p < 0.001$), SPT (0.91, $p < 0.001$) and SL (0.89, $p < 0.001$). It was concluded that actigraphy is not identical with PSG recording but gives good results in sleep/wake patterns and predicting TST, SPT, SSE, SE and SL also in sleep apnoea patients not suffering from other sleep disorders. The difficult detection of correct sleep onset causes SSE and SL to be less predictable. Therefore a 15-epoch criterion was introduced and resulted in high correlation of 0.89 for sleep latency, but has to be tested on a bigger population.

Keywords: actigraphy, polysomnography, validation, AASM, sleep apnoea, SOMNOwatch

(Some figures in this article are in colour only in the electronic version)

Introduction

For more than 30 years actigraphic methods have been used for objective recording of motor activity (Kripke *et al* 1978). An actigraphic unit usually consists of an acceleration sensor that is sensible in two or three dimensions, a microprocessor and internal memory. Some devices additionally have an ambient light sensor. The predominant sampling rate for accelerometric data is about 30 Hz, which covers most human movements. Actigraphy is a convenient method of monitoring human rest/activity cycles, especially to study circadian rhythm (Ancoli-Israel *et al* 2003).

Sleep/wake patterns can be obtained by means of automatic analysis of the actigraphic data based on the simple observation that there is less movement during sleep and more movement during the awake state. Sadeh *et al* (1995) conclude that actigraphy provides useful information and that it may be a cost effective method for assessing specific sleep disorders. According to the 'AASM Standards and Practice', actigraphy is not suitable for routine diagnosis, for assessment of severity or for management of sleep disorders, but is useful to diagnose insomnia, circadian rhythm disorders and excessive sleepiness (Ancoli-Israel *et al* 2003). It is also useful in detecting sleep wake patterns in normal populations (Lehnkering *et al* 2006, Lehnkering and Siegmund 2007, Fietze *at al* 2009).

An actigraph is usually placed on the wrist of the non-dominant arm and is utilized to measure the motor activity from which sleep and wake periods as well as circadian rhythm can be estimated. Typically derived parameters are time in bed (TIB), total sleep time (TST), sleep period total (SPT), sleep efficiency (SE), sleep onset latency (SL), daytime inactivity (DIA) and circadian rhythm (CR) information. The parameters used for this study are listed and defined in table 1.

The detection of motor activity as an indicator for sleep and wake episodes used in this study is based on the finding of Sadeh *et al* (1989). Since then numerous different actigraphs have been developed and adapted to new demands of the AASM (2007). The Actiwatch® (Philips Respironics, The Netherland) has an ambient light sensor, but a short battery-lifetime. The ActiTrac® (Individual Monitoring Systems, USA) with a LiIon-Accu is already designed for long-term recordings and has an ambient light sensor too, but only a small storage capacity. Besides the long recording time of up to 26 days thanks to a LiIon-Accu and an ambient light sensor, the SOMNOwatch™ (SOMNOmedics, Germany) has a high storage capacity of 8 MB. In addition, the SOMNOwatch is not limited to the use of predefined storage or sampling rates during long-term recordings. The SOMNOwatch™ is waterproof, includes a button to mark events and has one external channel for various additional sensors. The SOMNOwatch™ is FDA approved and the software was compatible with the one available in the sleep lab of the investigator. So we decided to use this device for the comparison of actigraphy versus polysomnography.

In this study we tested the accuracy of the results from actigraphy data versus gold standard polysomnography. Therefore we have compared the results of both methods by using regression analysis as well as checking the specificity, sensitivity and overall accuracy by an epoch-to-epoch comparison of sleep/wake patterns. We compared the automatically scored results of the actigraphy to the manually scored results of a full polysomnographic recording. To get comparable results from the two different devices we applied the two devices on the same subject during the same night.

One of our aims was to test the improved accuracy of the software algorithm and hardware in epochs where actigraphy indicates wake where sleep should have been scored, thus looking at the sensitivity. We expected that PLM and apnoea periods might cause movement on actigraphy during sleep. The opposite situation where actigraphy indicates sleep where wake

Table 1. Definitions of sleep parameters for the DOMINO light software.

Time in bed (TIB) (min)	Period of time between the lights-off and lights-on markers
Total sleep time (TST) (min)	Period of time between the lights-off and lights-on markers excluding all the wake stages
Sleep efficiency (SE) (%)	Total sleep time/Time in bed
Sleep onset latency (SL) (min)	Period of time between TIB and sleep onset stage 2
Sustained sleep efficiency (SSE) (%)	Total sleep time/(Time in bed – Sleep latency stage 2)
Sleep period time (SPT) (min)	Period of time between sleep latency stage 2 and the beginning of the last wake period

should have been indicated (specificity) is unavoidable with actigraphy only, because the subject can lie in bed awake without movement (Ancoli-Israel *et al* 2003). In accordance with a national standard, we decided to use SL stage 2, because this stage is easy to define via graphoelements in EEG. For detection of sleep stage 2 sleep onset using actigraphy a new criterion was introduced. According to Hobson there is at least a time of 7.5 min of rest before sleep stage 2 occurs (Hobson 1990). This finding was introduced in a retrospective analysis of the data as the 15-epoch criterion and used to determine SL sleep stage 2.

Methods

Twenty-eight simultaneous recordings with polysomnographic and actigraphic data were conducted in a sleep lab using SOMNOwatch and PSG on the same subject on the same night.

Participants

The subjects had an average age of 56 $\pm$ 10 years (7 females, 21 males) with a range from 37 to 76 years. The average BMI was 32 $\pm$ 5 kg m^{-2} with a range from 22 to 40 kg m^{-2}. For all subjects the tentative diagnosis of obstructive sleep apnoea syndrome (OSAS) was made. The polysomnographic recordings were done during diagnostic night (9 recordings) or therapy night (19 recordings) with 17 patients on CPAP and 2 on BiPAP. In 12 subjects PLM was found and 3 subjects suffered from arrhythmia absoluta.

Polysomnography

A SOMNOscreen^{TM} (SSC) system was used as an online wireless PSG device with maximum subject comfort as it is small and lightweight. The polysomnography was programmed to record C4, C3, A2, A1, EOGl, EOGr, EMG, ECG, flow (canula), snore, effort signals, SpO_2, pulse, plethysmogram, ambient light and body position.

The data were manually scored by a certified sleep practitioner. Sleep staging was done by applying the standardized R&K rules with 30 s epoch windows. The resulting full PSG was used as a reference. The PSG recordings were done online for the purpose of easier synchronization with actigraphic data from SOMNOwatch. The clock of the actigraph was synchronized to the online recording during start from the same computer taking the time from the internal clock.

Actigraphy

A SOMNOwatch™ (SOW) system was used to record the acceleration in three axes. The data from the x-axis, y-axis and z-axis can be stored separately or as a magnitude signal, corresponding to the square root of the sum of each of the three axes squared. The range is within ± 8.7 G at a sensitivity of 0.004 G. The data are transferred to a computer via USB.

We applied the actigraphy device to the wrist of the non-dominant arm of a subject and recorded the motor activity overnight with a sampling rate of 32 Hz and a storage rate of 1 Hz. The light signal was stored every 30 s. After the recording, the actigraphic raw data were transferred to a computer and analysed automatically. The 'lights on' and 'lights off' markers were set manually in the SOW data to match to the TIB markers of the PSG data. As no manual scoring is done for the actigraph the staging is definitely blinded. In addition the TIB from light analysis was determined.

The algorithm implemented in the DOMINO light software to calculate the sleep/wake periods is based on the algorithm in the paper published by Gorny *et al* (1997) in San Francisco (Gorny *et al* 1996): if $(A_{act} + B_{act} + E_{act}) \geqslant K$, epoch is scored as wake.

Else if $(A_{act} + B_{act} + E_{act}) < K$, epoch is scored as sleep.

Here E_{act} is the overall activity in the current epoch, A_{act} is the overall activity in four previous epochs and B_{act} is the overall activity in next four epochs; K is the critical value delineating sleep and wake. The algorithm scores an epoch as an artefact if $(A_{act} + B_{act} + E_{act}) \geqslant K$ and $(A_{act} + B_{act}) = 0$.

The parameters for activity analysis in actigraphy software were as follows: activity threshold for sleep/wake analysis was set to 28 units, 'extension of wake phase' was set to 0 epochs and 'number of epochs before/after' was set to 4 epochs in accordance with the algorithm based on the paper published by Gorny *et al* (1997). An epoch of the sleep/wake analysis is 30 s and therefore of equal length as the epochs created for manual staging from PSG.

Statistical analysis

We calculated Pearson correlations and plotted Bland–Altman plots (Bland and Altman 1986). In addition, a two-tailed t-test at a significance level of 0.001 was done and the Passing–Bablok correlation was calculated. Looking at the fact that the parameters on both axes are variable could result in different values for the correlation (Passing and Bablok 1983). Because correlation provides only relative and not absolute validity, we also included an epoch-by-epoch comparison to check for sensitivity (how well is sleep detected), specificity (how well does actigraphy detect wake) and overall accuracy or agreement. Sensitivity was defined as the ability of actigraphy to detect 'sleep' when simultaneously recorded EEG indicated any sleep stage. Specificity was defined as the ability to detect 'wake' when simultaneously recorded EEG indicated 'wake' (Ancoli-Israel *et al* 2003). The epoch-by-epoch analysis was done with MatLab and the validity of the results was tested using a test file with a predefined sleep/wake and error ratio.

Aim of the study

The aim of the study is to show that the SOMNOwatch™ actigraph is a reliable instrument to determine sleep/wake patterns as it is requested in the AASM standards of practice guideline.

Table 2. Pearson correlations for (a) actigraphy versus polysomnography, total and (b) actigraphy versus polysomnography, therapy/diagnostic.

	TST	SPT	SE	SSE	SL	TIB
(a) Actigraphy versus polysomnography, total						
r_{Pearson}	0.89	0.91	0.71	0.65	0.89	1.00
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mean actigraphy	300 min	351 min	83.3%	85.3%	14 min	357 min
Mean PSG	293 min	334 min	80.8%	87.8%	19 min	357 min
$r_{\text{Passing-Bablock}}$	0.91	0.84	0.79	0.86	1.00	1.00
(b) Actigraphy versus polysomnography, therapy/diagnostic						
r_{Pearson} therapy	0.83	0.88	0.73	0.63	0.96	1.00
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
r_{Pearson} diagnostic	0.96	0.98	0.69	0.67	0.57	1.00
P-value	<0.001	<0.001	>0.05	>0.05	>0.1	<0.001

Results

Time in bed (TIB) was identical for both devices as the markers which define TIB in the actigraphy data were transferred from SSC data to SOW data without changes. On average actigraphy overestimated the total sleep time (TST) by 7 ± 22 min, sleep period time (SPT) 18 ± 23 min and sleep efficiency (SE) as well as sustained sleep efficiency (SSE) by $2 \pm 7\%$. Start of TIB defined by the patient marker and resulting from ambient light analysis (lights off) was identical, and end of TIB (lights on) varied by 6 ± 6 min due to the setting. To find a correlation for SL a new criterion (15-epoch criterion) was introduced which yielded a strong correlation which could not be found without this criterion.

Comparison of sleeping times

Analysis revealed a strong positive correlation of 0.89 between polysomnography and actigraphy on TST (table 2(a)). Polysomnographic results and actigraphy estimations of TST were found to be equal ($t(28) = 1.67$, $P = 0.05$).

The Bland–Altman plot (figure 1) for TST shows that the polysomnographic scores are on average 7 min lower than the actigraphy score. The differences are likely to be normally distributed and thus it is fairly safe to say that 95% of all measurement differences for TST will lie between the agreement lines of -37 and 51 min.

Comparison of sleep period time

Analysis also revealed a strong positive correlation between PSG data and actigraphy data on SPT of 0.91 (table 2(a)).

The Bland–Altman plot (figure 2) shows for SPT that the polysomnography scores are on average 18 min lower than the actigraphy score. The differences are likely to be normally distributed and thus it is fairly safe to say that 95% of all measurement differences for SPT will lie between the agreement lines of -28 min and 64 min.

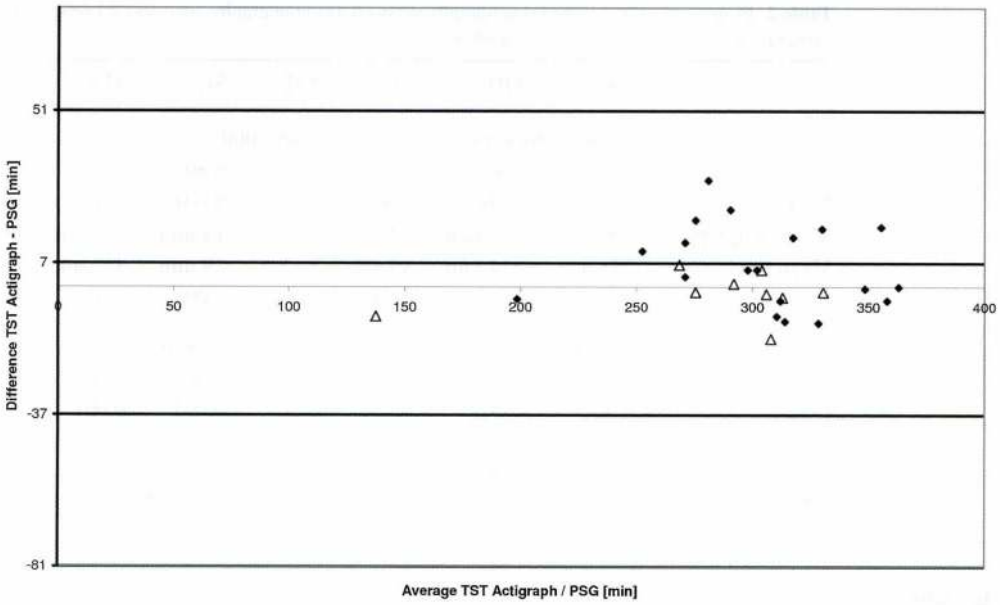

Figure 1. Bland–Altman TST. Average actigraphy from SOW and PSG from SSC versus difference in TST of both methods. There is a shift of plus 7 min, which means that on average the SOMNOwatch actigraph overestimated TST by about 7 min. Diagnostic studies are shown with Δ.

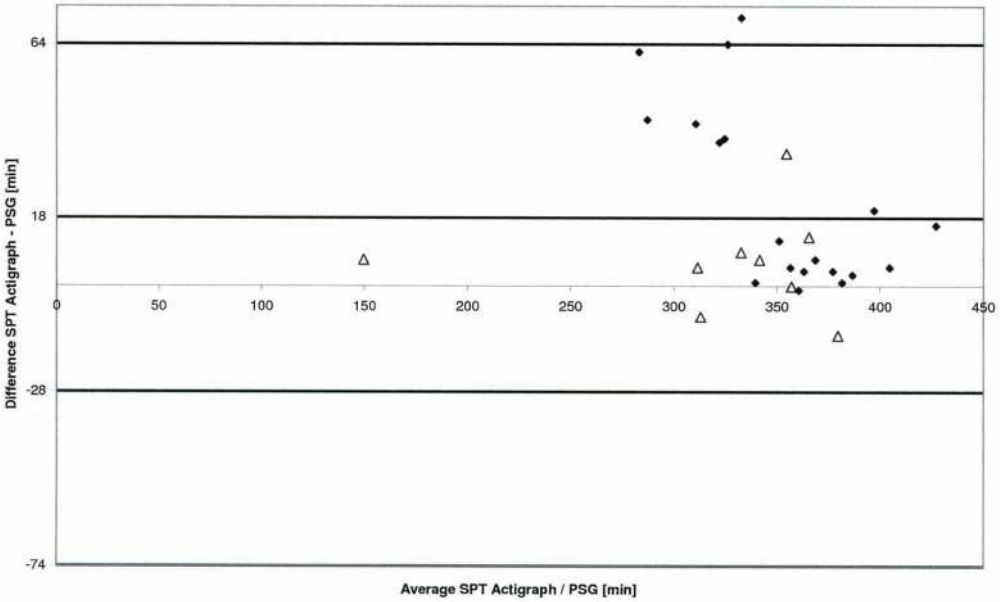

Figure 2. Bland–Altman SPT. Average actigraphy from SOW and PSG from SSC versus difference in SPT of both methods. There is a shift of plus 18 min, which means that on average the SOMNOwatch actigraph overestimated SPT by about 18 min. Diagnostic studies are shown with Δ.

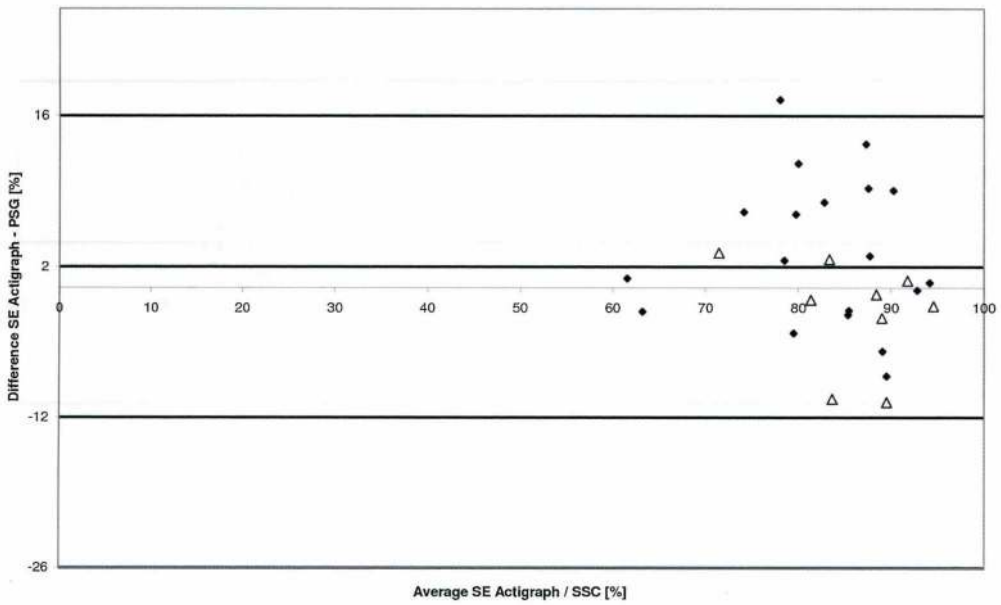

Figure 3. Bland–Altman SE. Average actigraphy from SOMNOwatch and PSG from SOMNOscreen versus difference in SE of both methods. There is a shift of plus 2%, which means that on average the SOMNOwatch actigraph overestimated SE at a level of 2%. Diagnostic studies are shown with Δ.

Comparison of sleep efficiency

Analysis revealed a positive correlation between polysomnographic data and actigraphy data on SE of 0.71 (table 2(a)). The difference between polysomnography and actigraphy estimations of SE was also found to be non-significant ($t(28) = 1.211$, $P = 0.11$)

The Bland–Altman plot (figure 3) shows that for SE the polysomnography scores are on average 2% lower than the actigraphy score. The differences are likely to be normally distributed and thus it is fairly safe to say that 95% of all measurement differences for SE will lie between the agreement lines of −12 and 16%.

Comparison of sustained sleep efficiency

Analysis revealed a positive correlation between polysomnography data and actigraphy data on SSE of 0.65 (table 2(a)). The difference between polysomnography and actigraphy estimations of SSE was also found to be non-significant ($t(28) = -1.753$, $P = 0.05$).

The Bland–Altman plot (figure 4) shows that for SSE the polysomnography scores are on average 4% higher than the actigraphy score. The differences are likely to be normally distributed and thus it is fairly safe to say that 95% of all measurement differences for SSE will lie between the agreement lines of −11 and 19%.

Sensitivity, specificity and overall accuracy

The epoch-by-epoch comparison between polysomnography and actigraphy, with the polysomnographic data as the standard, showed that 95.7% of the sleep epochs and 90.2% of

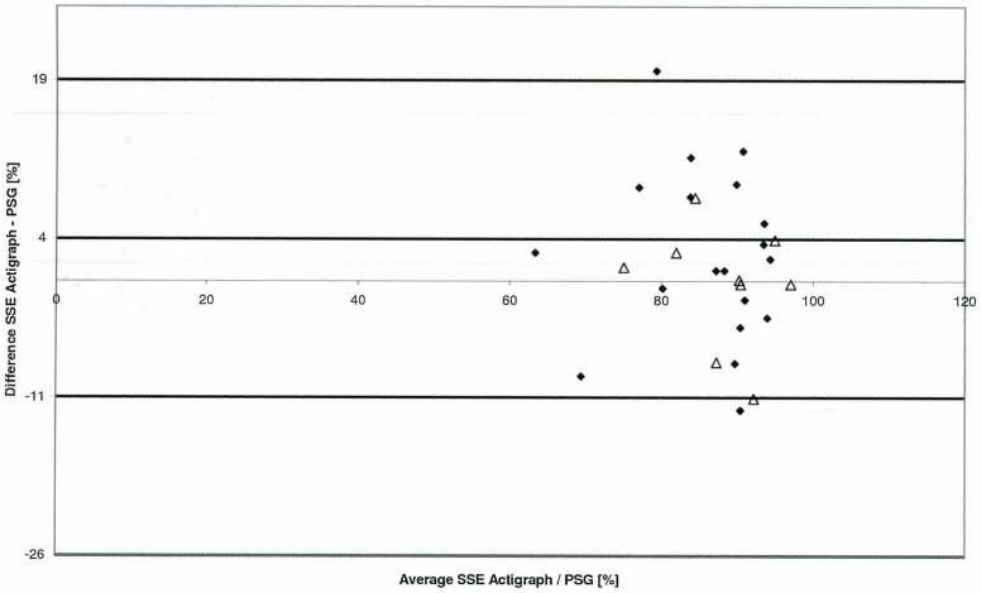

Figure 4. Bland–Altman SSE. Average actigraphy from SOMNOwatch and PSG from SOMNOscreen versus difference in SSE of both methods. There is a shift of plus 4%, which means that on average the SOMNOwatch actigraph overestimated SSE at a level of 4%. Diagnostic studies are shown with Δ.

the wake epochs were correctly identified. Overall, 85.6% of the epochs were correctly staged by actigraphy.

Comparison of sleep onset latency

For the analysis of SL, an additional criterion was introduced which was not used for the other parameters. An onset sleep stage 2 had to be at least 15 epochs or 7.5 min long to be indicated as sleep onset. This analysis revealed a strong positive correlation between PSG data and actigraphy data on Sleep SL of 0.89 (table 2(a)). The difference between polysomnography and actigraphy estimations of SL was found to be non-significant ($t(28) = -3.249$, $P = 0.001$). Thus using the 15-epoch criterion makes it possible to correlate SL stage 2 non-REM defined by polysomnography and derived from actigraphy.

The Bland–Altman plot (figure 5) shows for SL that the polysomnographic scores are on average 6 min higher than the actigraphy score. The differences are likely to be normally distributed and thus it is fairly safe to say that 95% of all measurement differences for SPT will lie between the agreement lines of −19 and 9 min.

Discussion

The current findings indicate that the actigraphic data from SOMNOwatch™ in combination with the algorithm in the DOMINO light software (SOMNOmedics, Germany) are an accurate method to determine TST, SPT, SE and SL in patients with sleep disordered breathing. Even though there is still discussion, Wang *et al* (2008) have been able to show that actigraphy is a reliable instrument for sleep/wake scoring. For this study SL was found to correlate when

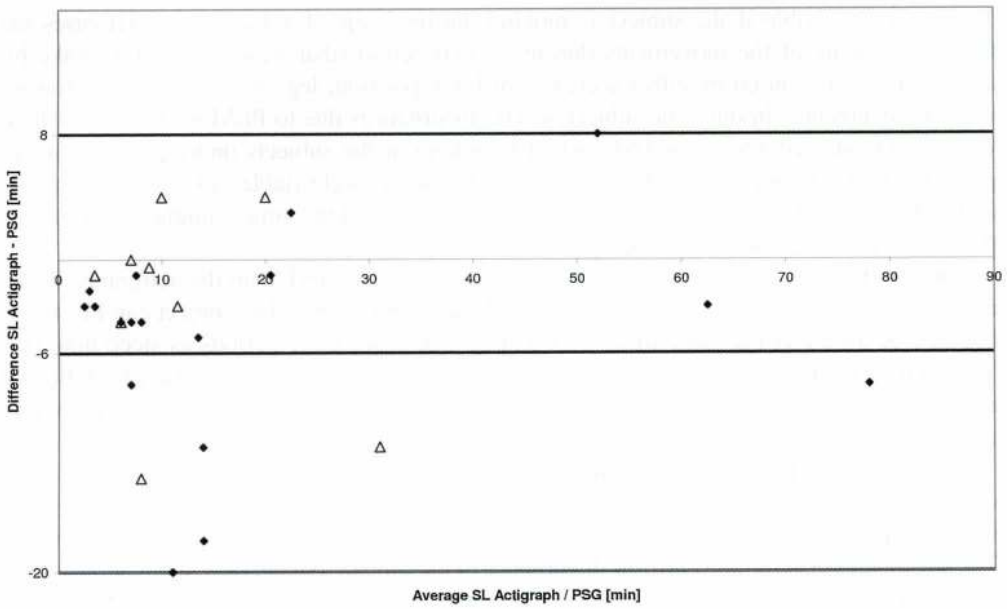

Figure 5. Bland–Altman SL. Average actigraphy from SOMNOwatch and PSG from SOMNOscreen versus difference in SL of both methods. There is a shift of minus 6 min, which means that on average the SOMNOwatch underestimated SE by 6 min. Diagnostic studies are shown with Δ.

the 15-epoch criterion is met. Sleep stage 2 onset is therefore defined at the beginning of the first period without movement for at least 7.5 min. This criterion has to be tested on a bigger population but seems valid in this study.

The epoch-to-epoch comparison gave a sensitivity value of 95.2%, a specificity value of 90.2% and an overall accuracy of 85.9%. For this analysis sleep stages 1–4 and REM were scored as asleep or non-REM sleep, whereas wake was compared only to wake.

Sustained sleep efficiency was found to be positively correlated but the correlation was lower than on the other parameters as predicted by the fact that an actigraph is not the best method to detect sleep stage 1 needed for sustained sleep efficiency. That is also a reason, why for sleep latency sleep stage 2 was chosen. Actigraphy is more likely to misplace sleep onset, as sleep onset might be detected too early when the subject is awake but lying in bed without movement. Therefore the 15-epoch criterion was introduced, which was correlated to sleep onset stage 2 by Hobson (1990).

In most cases the SPT was lower from the polysomnography data. Actigraphy might detect sleep earlier due to no movement of the subject during a wake period. In addition, the SPT depends on the detection of the first sleep stage 2. Since actigraphy does not differentiate between sleep stage 1 and 2, this parameter could not be compared effectively. Actigraphy might score sleep at the beginning of stage 1 or even before the first stage 1 epoch while the polysomnography data start the SPT only at stage 2. The correlation however was still high enough and significant. Looking at the Bland–Altman plot for SPT, the accuracy becomes greater towards a higher sustained sleep efficiency value. This confirms findings in the literature that actigraphy loses more accuracy when sleep fragmentation goes up (Ancoli-Israel *et al* 2003)

In 13 of the 28 cases, the TST in polysomnography scored data was longer than that in actigraphy scored data. Actigraphy detected more periods of wake than polysomnography.

This is only possible if the subject is moving during sleep. Looking at several cases we found that many of the movements during a sleep period (that were detected as wake by actigraphy) were caused by either a change of body position, leg movements or respiratory related movements. In only one subject severe disturbances due to PLM were found. There was no obvious difference for TST and SPT looking at the subjects under positive airway pressure versus the untreated subjects during a diagnostic night (table 2(b)). Looking at SE and SSE the correlation seems similar but is not significant at this time—might be because of the low number of subjects (9 for diagnostic).

In 15 of the 28 cases the polysomnography showed less TST than the actigraphy. This is a factor that seems to be unsolvable with only actigraphy data. The subject can lie still in bed and be awake at the same time. Actigraphy will score these periods as sleep however. The limited specificity is consistent with the findings in the literature. This was also reflected in the epoch to epoch comparison where detection of sleep epochs was more accurate than detecting wake epochs (Ancoli-Israel *et al* 2003)

Polysomnography is the standard for sleep recordings and analysis of sleep. It offers extensive information on sleep physiology, but is too cumbersome and expensive in situations where the primary focus is quantification of sleep and wake times, like in shift work conditions. The advantages of actigraphy are low disturbance of the subject's sleep, easy application as well as the opportunity to record multiple day and night periods without interruption. Actigraphy is cost effective and convenient compared to standard polysomnography (AASM 2007, Siversten *et al* 2006). This makes actigraphy especially useful to obtain objective sleep data to help in diagnosis of chronobiological rhythm disorders, and to find out average sleep/wake times over longer periods of time. It also enables data collection of large populations, to show chronic behaviours (Blackwell *et al* 2008) and to obtain data in special environmental (Cosmos, Arctic) or working conditions (shift work, etc)

The external channel of the SOMNOwatch™ provides another way to detect periods where the subject is sleeping but has some movement due to arousals by PLM, body position change or apnoeas. For future research the SOMNOwatch™ could be used together with an EEG sensor to score sleep stages from EEG data, with a nasal cannula connected to a pressure sensor to detect respiratory events or an additional acceleration sensor to detect PLM or body position.

Actigraphy seems to be valid compared to PSG measurements but loses some accuracy when a patients sleep becomes more disturbed (Ancoli-Israel *et al* 2003) However, actigraphy stays useful in situations where full PSG measurement is impossible or too cumbersome. In addition to that, actigraphy might provide better information about normal day to day sleep times than PSG in a hospital room, and thus prove a more accurate estimation of typical sleep duration.

Future research might point out that better results are gained using additional sensors e.g. for PLM during the night. Ancoli-Israel *et al* (2003) conclude in an overview study that one consistent finding is that, when compared to PSG, actigraphy is moderately valid at the moment for differentiating sleep and wake in healthy adults, but becomes less reliable as sleep becomes more disturbed (Ancoli-Israel *et al* 2003).

In conclusion, actigraphy is less accurate than polysomnography, overestimating usually the length and quality of sleep. It can, however, still give valuable and reliable information (with or without combined polygraphy) where polysomnography would be impossible or inconvenient or where limited information about sleep quality is required. Wang *et al* (2008) were able to show that the new generation of actigraphs shows reliable results in sleep/wake estimation. Actigraphy done with the SOMNOwatch™ matches these results when compared

to polysomnography data and therefore shows that the latest technique and software needs to be examined for its potential.

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