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Original Article

PLM detection by actigraphy compared to polysomnography: A validation and comparison of two actigraphs

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Abstract

Objective: To compare periodic leg movement (PLM) counts obtained with polysomnography (PSG) to those obtained from actigraphy with two devices (Actiwatch and PAM-RL).
Methods: Twenty-four patients underwent full night actigraphy with Actiwatch from both legs and simultaneous PSG. Out of these patients, 10 had additional actigraphy with PAM-RL. Bilateral and unilateral PLM indices (PLMI) for both actigraphs were calculated for time in bed and compared to polysomnographic PLMI. Additionally, a comparison between the two different actigraphs was performed.
Results: PLMI obtained with Actiwatch were significantly lower than those obtained with PSG (21.2 ± 25.6/h versus 34.4 ± 30.7/h; $p < 0.001$), whereas the PLMI from PAM-RL were significantly higher than in PSG (63.6 ± 39.3/h versus 37.0 ± 33.5/h; $p = 0.009$). In direct comparison, Actiwatch gave significantly lower PLMI than the PAM-RL ($p = 0.005$). The correlations between Actiwatch and PSG (rho $= 0.835$, $p < 0.001$), PAM-RL and PSG (rho $= 0.939$, $p < 0.001$), and Actiwatch and PAM-RL (rho $= 0.915$, $p < 0.001$) were significant. Unilateral actigraphy compared to standard PSG gave less consistent findings. When comparing different settings of the PAM-RL, manual threshold setting resulted in PLMI that were no longer different from PSG ($p = 0.074$), in contrast to the default threshold setting.
Conclusions: The Actiwatch underestimated and the PAM-RL overestimated PLMI compared to PSG. Whereas PLMI obtained with two actigraphs and PSG were highly correlated, they differed in mean values. Therefore, PSG, actigraphy and also the different actigraphs cannot be interchanged in longitudinal studies, and actigraphy should not be used for diagnostic decision making based on PLM indices. The best approximation to PSG PLMI was achieved by using manual threshold setting with the PAM-RL.

Keywords: Periodic leg movements (PLM); Restless legs syndrome (RLS); Actigraphy; Validation; Polysomnography; PAM-RL; Actiwatch

1. Introduction

Periodic leg movements (PLM) are defined as a sequence of four or more leg movements separated by at least 5 (and not more than 90) seconds with a duration between 0.5 and 5 s [1]. They appear usually as extension of the big toe and dorsiflexion of the ankle, with occasional flexion of the knee and hip [2]. The gold standard of PLM diagnosis is polysomnography (PSG) with surface electromyography (EMG) of the tibialis anterior muscles [1,3]. According to the International Classification of Sleep Disorders, a rate of periodic limb movements while awake (PLMW) per hour of waking greater than 15/h in entire nocturnal polysomnography supports the diagnosis of RLS [4]. Due to the high costs

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of PSG, actigraphy with specific software to detect PLM is increasingly used to assess efficacy of drug treatment in patients with RLS [5–10] as well as to detect PLM in larger population groups [11].

First attempts to validate actigraphy for PLM detection date back to the nineties and were performed with prototype devices (MOVOPORT; Rimkus, Germany and Swiss-type; Gaehwiler Electronics, Switzerland). A significant correlation between actigraphy and PSG was reported, but actigraphy underestimated PLM [12,13]. In recent years, more sophisticated actigraph hardware and software has been developed and evaluated [14,15]. Currently, the PAM-RL and the Actiwatch are the most frequently used actigraphs. However, previous studies have not evaluated differences between unilateral and bilateral measurements, and the influence of threshold settings.

The primary objectives of this study were (1) to validate the PLM measurements of two different actigraphs against the gold standard polysomnography and (2) to perform a direct comparison of the PLM indices (PLMI) obtained from both actigraphs. Secondary objectives were to compare the unilateral PLMI from both actigraphs against the polysomnographic PLMI (from both legs), and to study the influence of different threshold settings and PLM scoring criteria on validity and reliability of PLM detection in one of the actigraphs (PAM-RL).

2. Methods

2.1. Study design

Twenty-four patients underwent a full night (8 h) digital polysomnography (Schwarzer Brainlab, Munich, Germany, software version 3.00) with bilateral tibialis anterior (TA) surface electromyography (EMG). All patients underwent simultaneous bilateral actigraphy with Actiwatch (Cambridge Neurotechnology Ltd., UK); 10 of them (7 men and 3 women, mean age 60.9 ± 12.0 years) underwent additional simultaneous actigraphy with PAM-RL (ImSystems, Baltimore, USA). This is illustrated in Fig. 1 online supplementary material, und unilateral PLMI obtained from actigraphy were compared to the gold standard polysomnography. Moreover, a direct comparison between PLMI of both actigraphic devices was performed. In PAM-RL, we additionally analyzed alternative threshold settings (see Section 2.3.2).

2.2. Study collective

The study collective consisted of 24 consecutive patients (18 men and 6 women, mean age, 57.5 ± 12.0 years) referred to the Sleep Disorders Unit, Department of Neurology, Innsbruck Medical University. Patients were included if a PLMI above 5/h in the screening night, irrespective of the principal diagnosis, was present. For this investigation, the night after screening was used. Patients with sleep-related breathing disorders ($n = 7$) were only included when they were on effective nasal continuous positive airway pressure (nCPAP) or bilevel positive airway pressure (BiPAP) treatment in order to exclude leg movements related to periodically recurring respiratory events. Patients' diagnoses were restless legs syndrome (RLS) with PLM ($n = 12$) or periodic limb movement disorder (PLMD, $n = 12$). Five patients had additional effectively treated obstructive sleep apnea syndrome and two had upper airway resistance syndrome. These seven patients were studied while on nCPAP treatment. One patient had additional nightmares. At date of PSG recording, five patients with RLS and two patients with PLMD were treated (levodopa/benserazide 100/25 mg/d, $n = 5$; cabergoline 2 mg, $n = 1$; pergolide 0.35 mg, $n = 1$); the others were untreated. Five patients additionally took a selective serotonin reuptake inhibitor (RLS, $n = 2$; PLMD, $n = 3$), two amitriptyline (RLS, $n = 1$; PLMD, $n = 1$).

2.3. Actigraphy

2.3.1. Actiwatch

The Actiwatch actigraph records leg activity via uniaxial acceleration of mass distorts of the piezoceramic material [16]. The actigraphs were placed on the distal end of the dorsum of each foot on the base of the big toe, fixed with an elastic gauze bandage (see Fig. 1 online supplementary material). Software Version 2.36 (Cambridge Neurotechnology Ltd.) was used to detect PLM [16]. The output is amplified and filtered with passband of 3 and 11 Hz at the 3 db points and sampled with 32 Hz. The threshold setting is termed as minimum/maximum ratio limits (min/max ratio). It is defined by the company as the measure of spread in periodicity of PLM. For this study, we used the default threshold setting, which is given as 0.5. The scoring criteria according to ASDA allow a movement duration between 0.5 and 5 s and an inter-movement interval between 5 and 90 s [1], whereas the Actiwatch software system dictates a movement duration between 0.5 and 8 s and an inter-movement interval between 8 and 90 s. The recordings of the actigraph were synchronized with the "lights off" and "lights on" signals in polysomnography, and PLM were automatically scored and calculated. Each single leg movement, which is part of a PLM sequence, was displayed in a table to compare PLM detection by actigraphy to PLM in PSG on an event-by-event base.

2.3.2. PAM-RL

The PAM-RL actigraph is a three axis motion sensor designed to record leg activity and to detect PLM

with a specific software system (PAM-RL actigraph software version 7.5.3, IM Systems, USA and "Monitorlink software", SOMNOmedics, Germany). The "Monitorlink software" is designed to combine PLM counts from two PAM-RL actigraphs to a single PLM count. The PAM-RL was placed in a medioventral position on the ankle of the foot and fixed with a hook and loop fastener (see Fig. 1 online supplementary material) [17]. The filter settings of PAM-RL were 0.3–14 Hz. The sampling frequency was 10/s. Within the PAM-RL software system for PLM detection, a duration of 0.5–5 s and an inter-movement interval between 5 and 90 s was chosen. PLM were automatically scored with PAM-RL Software Version 7.5.3 (IM Systems). The default on/off threshold setting preset for PLM detection was 160 (for onset threshold) and 100 (for decay threshold). The factor to translate the on/off thresholds into acceleration units is 500 counts/g (earth gravitational acceleration). Therefore, 160 counts correspond to 0.32 g and 100 counts to 0.2 g. Additional analyses were performed with an alternative, a slightly more narrow threshold setting of 120 (for on = 0.24 g) and 80 (for off = 0.16 g), as suggested by the company SOMNOmedics which provided that software at that time. Finally, a manual on-off-threshold setting was chosen individually for each patient, since basal curves vary markedly from patient to patient. Therefore, for each patient, the recordings of the basal curve were looked through for a typical PLM sequence and the on-off-threshold settings were adapted to the basal curve according to that PLM sequence. In addition, bilateral PLMI obtained with each of the two different actigraphs using the default threshold setting were compared between each other.

2.4. Polysomnography

Digital polysomnography (Schwarzer Brainlab for Windows Version 3.30, Patch Pack 27; Munich, Germany) consisted of electroencephalography (EEG) (C3-A2, C4-A1, O1-A2, O2-A1), horizontal and vertical electrooculogram (EOG), bipolar surface EMG of mental and submental muscles and bipolar surface EMG of both tibialis anterior muscles. Respiration was monitored by nasal and buccal airflow (thermocouple) and additional nasal pressure was measured by a cannula in 10 patients, tracheal microphone, thoracic and abdominal respiratory effort (Piezo), finger oximetry and electrocardiogram. An infrared video was digitally stored and recorded during the entire night. Sleep stages were scored according to Rechtschaffen and Kales [18] using 30 s epochs.

For PLM recordings, surface EMG was recorded with bipolar electrodes, high-pass-filtered at 50 Hz and low-pass-filtered at 300 Hz, amplified 10-fold and sampled at a rate of 500 Hz. Sensitivity was set to 100 μV/cm and adjusted as needed for visual analysis. Impedance of tibialis anterior surface EMG electrodes had to be lower than 10 kΩ.

PLM during sleep (PLMS) were manually scored according to standard criteria [1]. For PLM during wakefulness (PLMW) a maximum duration of 10 s was allowed in accordance with the longer duration of EMG activation found during wakefulness [19]. Unilateral and bilateral PLMI were calculated for time in bed (TIB). Finally in the subgroup of 10 patients who underwent PAM-RL actigraphy, apart from PLM scoring according to standard criteria, PLM indices obtained from scoring without amplitude criterion (AC) were compared to PAM-RL actigraphy, since we have shown in a previous study that PLM counting without amplitude criterion gives higher PLM indices due to additional counting of low amplitude PLM [20].

2.5. Statistics

SPSS^{TM} for Windows version 12.0 (SPSS Inc., Chicago, USA) was used for data analysis. All patients were included in the analyses. PLM indices were calculated for time in bed with different methods and given as means and standard deviations. Multiple comparisons between pairs of the three methods were performed with the Wilcoxon rank sum test for paired observations. Spearman correlations between each pair of the three methods were calculated. Statistical significance was indicated by p-values smaller than 0.05. The differences between PLM indices obtained from PSG and actigraphy (Actiwatch and PAM-RL) are illustrated by Bland Altman plots [21].

3. Results

3.1. Comparison of Actiwatch and polysomnography

The PLMI obtained from bilateral Actiwatch recording was significantly lower than the PLMI obtained from polysomnography ($p < 0.001$; $n = 24$). The difference was even more pronounced for unilateral actigraphy, which gave significantly lower indices compared to standard PSG for the right ($p < 0.001$) and the left leg ($p < 0.001$). Mean values and mean differences ± standard deviations between PSG PLMI and PLMI obtained by actigraphy are given in Table 1. Individual results are presented in Table 1 online supplementary material. The differences between PLMI obtained from bilateral Actiwatch actigraphy and PSG were shown by Bland Altman plot (see Fig. 1a). Nevertheless, the correlations between standard PSG for both legs and PLMI obtained from either bilateral or unilateral actigraphy of the right leg (see Table 1) were high. This was not true if only the left leg was used.

Table 1
Correlation analyses (Spearman's rho) between polysomnography and Actiwatch actigraphy (bilateral and separately for the left and right side; $n = 24$)

	PLM index/h	Differences between PSG and Actiwatch PLMI	Spearman's correlation (Actiwatch versus PSG)	
PSG (bilateral)	34.4 ± 30.7			
Actiwatch (bilateral)	21.2 ± 25.6	13.3 ± 13.1	$r = 0.835$	$p < 0.001$
Actiwatch (right leg)	16.9 ± 20.7	12.7 ± 11.0	$r = 0.829$	$p < 0.001$
Actiwatch (left leg)	6.8 ± 14.6	27.6 ± 24.8	$r = 0.553$	$p = 0.033$

The PLM indices (PLMI) are presented as means ± standard deviations (PLM/h). Differences between PLMI obtained by polysomnography and actigraphy are given as means ± standard deviations (PLM/h).

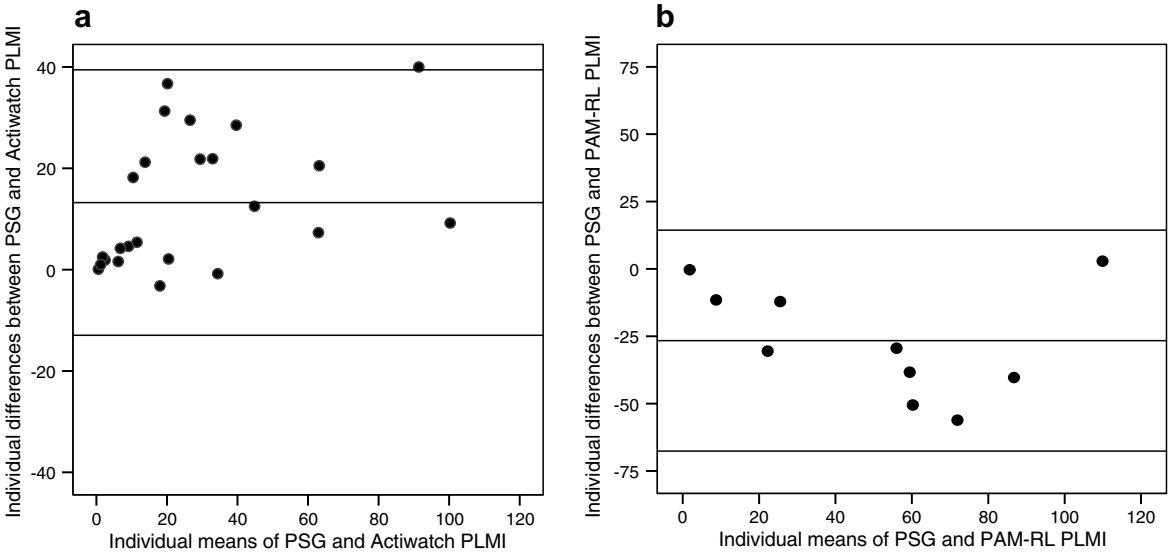

Fig. 1. Bland Altman plots of PLM indices obtained from PSG and actigraphy with the "Actiwatch" (a) and the "PAM-RL" (b). The horizontal line represents the mean of the differences (middle line) ± 2 standard deviations (upper and lower line) between polysomnographic and actigraphic PLMI.

3.2. Comparison of PAM-RL and polysomnography

In the 10 patients, who were additionally recorded with the PAM-RL, the PLMI obtained from bilateral actigraphy with the default threshold (On, 160; Off, 100) was significantly higher than the PLMI from PSG ($p = 0.009$). Comparing unilateral actigraphic PLM counts with standard bilateral PSG, we found a significant difference for the right leg ($p = 0.013$), but not for the left leg ($p = 0.169$). Mean values and mean differences ± standard deviations between PSG PLMI and PLMI obtained by actigraphy are given in Table 2. The differences between bilateral PLMI (from PAM-RL actigraphy) and polysomnography were illustrated

Table 2
Correlation analyses (Spearman's rho) between polysomnography and PAM-RL actigraphy (bilateral, unilateral, different threshold settings; $n = 10$)

	PLM index/h	Differences between PSG and PAM-RL PLMI	Spearman's correlation (PAM-RL versus PSG)	
PSG bilateral	37.0 ± 30.7			
Default threshold setting (160/100)				
PAM-RL bilateral	63.6 ± 39.3	−26.6 ± 20.5	$r = 0.939$	$p < 0.001$
PAM-RL right leg	49.7 ± 38.3	−12.7 ± 11.8	$r = 0.976$	$p < 0.001$
PAM-RL left leg	37.6 ± 24.7	−0.6 ± 26.4	$r = 0.806$	$p = 0.005$
Different threshold settings				
PAM-RL 120/80	71.0 ± 43.1	−34.0 ± 23.4	$r = 0.939$	$p < 0.001$
PAM-RL manual	44.9 ± 27.6	−8.0 ± 21.0	$r = 0.952$	$p < 0.001$

The PLMI are presented as means ± standard deviations (PLM/h). Differences between PLMI obtained by polysomnography and actigraphy are given as means ± standard deviations (PLM/h).

by Bland Altman plot (see Fig. 1b). The correlations between both bilateral and unilateral actigraphy and PSG for both legs were significant and even higher than those observed with the Actiwatch (see Table 2, Fig. 2 a–i online supplementary material). For individual data see Table 1 online supplementary material.

3.2.1. Analysis of different threshold settings of the PAM-RL

The PLMI obtained with bilateral PAM-RL using different threshold settings was highly different from PSG for the threshold setting 160/100 ($p = 0.009$) and 120/80 ($p = 0.005$). Data are given in Table 2. When the threshold was set manually and individually for each patient, a better approximation on the polysomnographic results by the PAM-RL was obtained ($p = 0.074$). Overall, the correlation between PSG and PAM-RL for all three threshold settings and PSG was very high (see Table 2).

3.2.2. Actigraphy and PSG PLMI without using the amplitude criterion

Because the PAM-RL significantly overestimated PLMI compared to PSG according to standard criteria [1] on both legs (Wilcoxon test, $p = 0.009$), we performed a different analysis by scoring the polysomnographic PLMI without amplitude criterion (AC). The PLMI without AC was 56.5 ± 39.7 PLM/h, in contrast to 37.0 ± 33.5 PLM/h according to standard criteria. PLMI in PSG scored without AC and PAM-RL actigraphy was no longer different (Wilcoxon test, $p = 0.169$).

3.3. Comparison of the two actigraphs (Actiwatch and PAM-RL)

In 10 patients bilateral PLMI obtained from Actiwatch was 19.5 ± 21.7 PLM/h, whereas bilateral PLMI obtained from PAM-RL with the default threshold setting (160/100) was 63.6 ± 39.3 PLM/h, indicating a marked difference between both methods ($p = 0.005$). PLMI obtained from Actiwatch, PAM-RL and PSG are illustrated for every single patient in Fig. 3 online supplementary material. Nevertheless, the correlation between Actiwatch and PAM-RL was also high (see Fig. 4 online supplementary material).

Individual data are given as online supplementary material (Table 1).

4. Discussion

The Actiwatch underestimated, whereas the PAM-RL significantly overestimated the periodic leg movement (PLM) counts compared to polysomnography (PSG). In consequence, also PLMI assessments with both actigraphs differed. Nevertheless, PLM indices (PLMI) detected with both devices correlated significantly with PLMI obtained from polysomnography which indicates a fairly constant shift in PLMI level by the two actigraphs. However, it might be advisable to evaluate PLM on both sides.

In the earliest validation study of actigraphy for PLM detection (Movoport, Rimkus, Germany) Kazenwadel et al. reported a high correlation between unilateral actigraphy and polysomnographic PLM measurements, but a significant underestimation of PLM compared to PSG [12]. Similar findings were reported by Sforza et al. using another actigraph (Swiss-type, Gaehwiler electronics, Switzerland) [13]. In a recent study, Sforza et al. reported a high sensitivity and specificity of the PAM-RL to detect patients with a polysomnographic PLMI higher than 10/h [14]. At the same time, King et al. reported similar results for the Actiwatch actigraph (Cambridge Neurotechnology Ltd.) showing that the Actiwatch had a sensitivity of 90.6% and a specificity of 83.3% to detect a polysomnographic PLMI $\geqslant 5$ [15]. However, direct comparison between PSG and actigraphy was only given for 199 30-s epochs [15].

The divergent results between PSG and actigraphy (underestimation with Actiwatch, overestimation with PAM-RL) may relate to the fact that PLM in PSG are identified by surface EMG and generated by activation of the tibialis anterior muscles (with and without movements), whereas in actigraphy the manifest lower limb movements are measured. Therefore PSG and actigraphy cannot replace each other since both represent different measures.

One possible reason for the difference between the two actigraphic devices could be due to technical considerations. The Actiwatch records leg activity only via uniaxial acceleration of mass distorts of the piezoceramic material, whereas the PAM-RL uses a three axis motion sensor for PLM detection. Even in the same actigraphic device (PAM-RL) results varied remarkably according to the chosen threshold setting. According to our results, the best approximation to PSG PLMI was achieved by using a manual threshold setting gained by visual inspection of actigraphic data and individual adjustment of settings. Therefore, similar to polysomnographic PLM scoring according to classic criteria [1] which require a visual amplitude evaluation, a visually adjusted manual threshold setting of actigraphy is preferable to the factory presets. The differences between PSG and actigraphy are of main interest since a cut-off value > 15/h during polysomnography is supportive of the diagnosis of RLS [4]. Our findings indicate that actigraphy cannot replace polysomnography in the diagnostic assessment of PLM using cut-off values. For PLM screening the device should error on the side of overestimation and not underestimation.

Another interesting finding was that unilateral actigraphy gave worse results than bilateral actigraphy compared to uni- and bilateral PSG. In clinical routine,

however, unilateral actigraphy is still frequently used. According to our findings, this practice might be discouraged.

Furthermore, PLM counting in PSG according to standard criteria gives clearly lower indices than PLM scoring without amplitude criterion, as recently shown by our group [20]. Whereas the difference between PAM-RL actigraphy and PSG differed in statistical terms when using standard criteria for PLM counting (lower in PSG) [1], this was no longer true when PLM were counted without amplitude criterion. This might indicate that the PAM-RL is sensitive to detect very small movements or PLM originating from other muscles than the tibialis anterior muscle and might therefore be even more sensitive for movement detection than standard polysomnography.

A potential limitation of our study is that the number of patients undergoing actigraphy with both devices was small ($n = 10$) and heterogeneous since we included patients with PLM > 5/h, irrespective of the principal diagnosis.

To summarize, our data suggest that both the PAM-RL and the Actiwatch are reliable devices for PLM detection, but cannot replace polysomnography. The absolute numbers of PLMI may deviate considerably from PSG, which limits the suitability to use for cutoff, e.g., when selecting patients for trials on the basis of PLMI. Attention has to be paid to the choice of threshold setting since PLMI were highly variable when using different thresholds in the PAM-RL. The best approximation was achieved by using a manual threshold setting. Our data suggest that actigraphy should be used in that way. Moreover, our data indicate that unilateral actigraphy is not an adequate approximation because deviation from PSG becomes too large.

The underestimation of Actiwatch and overestimation of PAM-RL compared to PSG, as well as the marked difference between the two devices, suggest that PSG and actigraphy, but also the different actigraphic devices, cannot be interchanged. This must be taken into account when actigraphy is used in longitudinal studies or in follow-up studies to assess the therapeutic efficiency in clinical trials or research.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.sleep.2008.03.015.

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