A New Actigraph for Long-Term Registration of the Duration and Intensity of Tremor and Movement

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Abstract—Actigraphy, the long-term measurement of human movement with a small solid state recorder, is gaining acceptance as a useful method in many research fields. Currently available actigraphs assess or estimate the movement duration per time interval. However, the output gives no information on movement type or intensity, and cannot be used in subjects suffering from tremor. The present paper describes a new type of actigraph, that has been developed primarily for the long-term evaluation of motor symptoms in Parkinson patients. The device is the first to discriminate tremor from other movements and to assess both duration and intensity of the two types of movement. It is based on a Motorola 68HC805B6 microcontroller and contains: an accelerometer, programmable gain stages, programmable low- and highpass filters, a programmable level comparator, a peak detector, interface circuits, a real time clock, data storage, and control circuitry. The micro-controller performs a period amplitude sequence analysis (PASA) on the conditioned accelerometer signal, and stores four output variables (tremor duration, tremor amplitude, movement duration, and movement amplitude) at the end of programmable time intervals. The analysis of fluctuations in the motor symptoms of, e.g., Parkinson patients using this actigraph can be of great help in the pharmacological management of symptoms.

Index Terms—Actigraphy, activity, ambulatory monitoring, circadian rhythm, Parkinson's disease, pharmacological profile, tremor, ultradian rhythm.

I. INTRODUCTION

ACTIGRAPHY, the long-term continuous measurement of movement with a small solid-state recorder is used in an increasing number of research fields [1]. Because they are light and small, actigraphs are easy to wear. In fact, the actigraph is at present the only ambulatory system that allows long-term monitoring of otherwise extremely noncompliant patients like demented elderly people [2]. Actigraphs assess movement accelerations using an accelerometer. After amplification and

bandpass filtering the signal is fed to a threshold detector. In the currently available actigraphs "movement counts" are obtained by increasing a counter with every threshold crossing or by measuring time above threshold. Movement counts are stored in a memory at programmable time-intervals. After completion of the study the data are transferred to a computer for off-line analysis. Thus, activity levels can be assessed continuously for up to several weeks.

However, the actigraphs that are currently available have some important limitations. First, they merely give an indication of movement *duration*, causing possibly valuable information on the *intensity* (acceleration amplitude) of the movements to be lost. For example, movement counts will be of similar magnitude for either writing a text or the intense practice of sports. Second, actigraphs do not discriminate between *types* of movement. This limits the value of actigraphy in patients with tremor, e.g., due to Parkinson's disease, where it is essential to discriminate between tremor and other movements. The hallmarks of Parkinson's disease are tremor, rigidity, hypokinesia, and bradykinesia (a reduction and slowing of movements). The variability of these symptoms over the day is considerable [3] and long-term assessment of tremor would be of great help in establishing the right dose and timing of medication. However, it is very difficult to interpret measurements with the actigraphs that are currently available for this particular group of patients, as the movement counts during relatively "good" periods, when the patient is able to engage in normal activities, may be of similar magnitude as during periods with severe tremor. Other methods of long-term assessment have been proposed [4]–[7], but they have too many shortcomings to be acceptable for wide application in clinical practice [3].

For this reason a new type of actigraph has been developed, which discerns tremor from other movements and measures the duration as well as the intensity of both movement types. The output of the actigraph thus consists of four variables instead of one: movement duration, movement intensity, tremor duration and tremor intensity. The present paper describes the method of assessment and the soft- and hardware that were applied. Furthermore, a validation and some examples of registrations are given.

II. METHOD

Movement accelerations are assessed using an accelerometer. Although accelerometric movement assessment can be confounded by the effects of gravity, it has recently been

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Fig. 1. Five seconds of accelerometer signal (± 1 g) of tremor in a patient suffering from Parkinson's disease. Note that the duration of half-waves between threshold-crossings (set at ± 0.1 g), indicated in bars below the trace, is limited to a narrow range and that the series of these half-waves is not interrupted by half-waves of much shorter or longer duration, or by rest.

Fig. 2. Five seconds of accelerometer signal (± 1 g) of rest and movement in a healthy subject. Note that after a period of rest, the duration of half-waves between threshold-crossings (set at ± 0.1 g), indicated in bars below the trace, varies widely. After approximately 2.5 s the signal shows some resemblance to tremor, but a half-wave of too long a duration follows soon after a few half-waves that, in frequency, could represent tremor.

shown that this confounding influence can be minimized using a highpass filter, as has been applied in the present device [8]. A uniaxial accelerometer is used, which is sensitive in the direction perpendicular to the wrist. Only marginal improvements in movement detection can be expected from multi-axial accelerometers [9]. The new device is based on a slightly altered version of a previously described algorithm for tremor discrimination in movement acceleration signals named period amplitude sequence analysis (PASA, [3]). The tremor detection algorithm is based on the fact that tremor is a repeated movement confined to a limited frequency range (mostly 3–8 Hz), whereas other movements are less repetitive and are not limited to this frequency range. Examples are given in Figs. 1 and 2. The first step in the algorithm is a period amplitude analysis of the signal: supra-threshold movement accelerations are described as series of half waves and their amplitudes. Tremor and other movements cannot be discriminated on the basis of frequency (or period of half waves) alone, as many nontremor movements occur in the frequency range of tremor [8]. A second step in the algorithm is therefore to determine whether a series of periods should be classified as normal movement or as tremor. When the wave-lengths of a sequence of half-waves all correspond to the frequency of tremor and when this lasts for at least a critical minimum number of half-waves, e.g., 12, the signal is classified as tremor. Sequences containing half-waves of other frequencies and/or sequences that are shorter than the minimum number of half waves are classified as other movements. The average amplitude and total duration of both types of movement can be determined in successive time intervals of, e.g., minutes or

hours. Depending on the battery type and time interval, the registration can continue for a period of more than two weeks without changing batteries.

III. HARDWARE DESCRIPTION

A block diagram of the actigraph is shown in Fig. 3. An accelerometer with interface electronics, a registration unit and a battery compartment are integrated in a small ($60 \times 38 \times 19$ mm) light-weight (65 g) device that can easily be worn at the wrist for weeks continuously. A photograph of the device is shown in Fig. 11. The components are described below.

A. Accelerometer Interface

The accelerometer is an ENDEVCO Picochip model 12, measuring $4.5 \times 3.8 \times 2$ mm. The accelerometer is based on piezoelectric principles, generating a typical charge of 2 pC/g. Typical capacity is 550 pF and frequency range is linear from 1 to 2000 Hz ($\pm 5\%$). The accelerometer and interface circuitry are shown in Fig. 2. The voltage generated by the accelerometer is $U = Q/C = 1\text{E-}12/550\text{E-}12 = 1.8$ mV/g typical. A fixed gain of $100\times$ is applied to the sensor output, and a highpass filter is set at 0.16 Hz. Lowpass is determined by the amplifier gain bandwidth and is approximately 45 Hz. The interface is shown in Fig. 4.

B. Amplifier

The input amplifier consists of a gain switchable inverting amplifier. The gain is programmable between 5 and $40\times$.

Fig. 3. Block diagram of the actigraph.

Fig. 4. Accelerometer interface.

Three port lines of the micro controller serve as the holding latches for the programmed value. The lowest gain value is fixed at $5\times$. Three weighted gain settings can be added to the fixed value. The weighting factors are 5, 10, and $20\times$. By means of selecting the proper weighting factors, the gain can be programmed to eight values between 5 and $40\times$ in stages of $5\times$. See Fig. 5 for the detailed design.

C. Filters

The input amplifier is followed by a lowpass and a highpass programmable filter section, to take care of unwanted baseline shifts, *gravitational artifact* [8] and high-frequency noise. The filter section can furthermore be used to optimize the input section when the typical tremor frequency of an individual patient is known, and tremor is the only activity of interest. Both filters are Sallen–Key second-order stages with Butterworth characteristics [10]. The programming is analogous to

the programming of the input amplifier. The fixed frequency is 0.5 Hz and the weighting values are 0.5, 1, 2, and 4 Hz, resulting in a total of 16 programmable frequencies ranging from 0.5–8 Hz. The highpass filter is shown in Fig. 6. A lowpass filter of similar design [Fig. 7] has a fixed value of 8 Hz and weighted values of 0.5, 1, 2, and 4 Hz. This gives a total range of 16 programmable values between 8 and 15.5 Hz.

D. Comparator

After amplification and filtering the signal is prepared for the timer input. In order to set a threshold level and to measure half-wave lengths the signal is fed through a comparator with Schmitt-trigger characteristics. The critical trigger level for the comparator is programmable between 0.10 and 1.25 V. Because the comparator has a symmetrical switching point, the intervals for positive and negative signals are the same. This is important for measuring the interval times for positive and negative signals, as described in the PASA method. The output level of the comparator is then adjusted for proper interfacing with the micro controller. The practical realization of the comparator is given in Fig. 8.

E. Peak Detector

In order to measure movement intensity, the positive peaks of the signal are measured and held by a peak detector circuitry. After a subsequent negative threshold crossing the output of the peak detector is fed to the A/D converter of the microcontroller and subsequently the peak detector is reset. The circuitry is shown in Fig. 9.

Fig. 5. Programmable amplifier circuitry.

Fig. 6. Programmable highpass filter circuitry.

F. Microcontroller

Instead of using a microprocessor with peripheral electronics it was clear from the beginning of the design that we had to choose a micro controller in which as many functions as possible were integrated to save space, weight and current. After evaluation of several brands (Philips, Hitachi, RCA, Motorola) a Motorola 6805 type (68HC805B6) was chosen. The most important reason for our choice was the fact that these processors are completely static which means that the clock of the processor can be stopped without losing the status of the processor. In this mode the processor draws a very low current ($<1 \mu\text{A}$). When there are no signals to be measured the processor stops its own clock. The clock is started again not only when activity is detected by the comparator but also

when there is an external interrupt from the real time clock, the RS232 interface, or the marker interface. Other on chip peripherals which are used are the following.

- The eight channel, 8-b A/D converter for measuring the peak of the activity and the battery voltage for battery depletion warning.
- The flexible timer to measure the period time of the incoming signal and generation different frequencies for the sound generator.
- The parallel to serial converter for communication via the RS232 port with a host computer.
- 6-k EEPROM for storage of the main program.
- 176 bytes RAM for storage of parameters and intermediate results.

Fig. 7. Programmable lowpass filter circuitry.

Fig. 8. Programmable comparator circuitry.

G. Real Time Clock

A separate real time clock (Philips PCF 8583) with its own crystal is used to relieve the micro-controller from time keeping aspects. The real time clock can be programmed by a three-line I²C bus. It can keep track of the time, date, and year and also has a programmable alarm clock which interrupts the controller to flag the end of a storage interval.

H. Data Storage

Data are stored in two low-current serial EEPROMS (Xicor X24C16). Because of the low access rate we have chosen for

serial instead of parallel devices. This also saves current and interconnection lines. The storage capacity is 4096 bytes. After every interval, 4 bytes are used for storage of tremor duration, tremor intensity, activity duration, and activity intensity. A part of the memory (512 byte) is dedicated for storage of markers, each taking 4 bytes (month, day, hour, minute). With this capacity 128 markers and up to 37 days of data can be stored if storage intervals of 1 h are used. Given one byte for each variable, variables are stored with a resolution of 256 steps. For the time variables, autoscaling is applied. Depending on the chosen measurement interval, the eight most significant bits are read from the four-byte time value in the processor

Fig. 9. Peak detector circuitry.

and stored in memory. This results in a resolution ranging from 0.427 s for measurement intervals of 1 min up to 54.6 s for 2 h intervals. For the amplitude values, the range of 0–4 V can be utilized, resulting in a resolution of 15.6 mV. The conversion of analog-to-digital units (ADU's) to g values depends on the setting of the amplifier (see “accelerometer interface” and “amplifier”). Within the actigraph, no calibration, i.e., correction for small differences in the sensitivity of the sensor, is applied, but this could be applied off-line if necessary. After removal of the battery, data in the EEPROMS are not overwritten to prevent data loss with battery failure.

I. Interfaces

The actigraph has several interfaces to signal situations to the outside world or to communicate with external devices. The most important one is the RS232 interface for communication with a host computer. This link is used to download the programmable parameters and to uplink stored information. The baud rate for this interface is 2400. A reed switch which can be closed with a magnet forces the software in the communication mode. A second switch can be pushed by the patient to store the time and date. This marker function can be used for several applications, for example to let the patient mark the moments of medicine intake or to mark other events like a subjectively very severe tremor.

A piezoelectric beeper is used to signal several conditions to the user. At present the patient is warned in case of low battery voltage and when the limit of the storage capacity is reached. A dual LED can be used to indicate activity (green) or tremor (red) classification for checking or demonstration purposes.

J. Current Draw and Supply

The total circuitry draws approximately 400 μ A from four 1.5-V type L/S/M R44 batteries during a rest situation and

600 μ A during activity or a tremor. Registrations can continue for more than two weeks without changing batteries.

IV. SOFTWARE DESCRIPTION

An algorithm analyzing the periods of the incoming signal forms the core of the software. The implemented algorithm is a slightly altered version of the algorithm that our group described earlier [3]. A flowchart is shown in Fig. 10. Figs. 1 and 2 may be of help in visualizing how a series of half-waves loops through the algorithm. At the start of a new interval (of e.g., 15 min) interval variables are initialized. After detection of a threshold crossing the timer and peak detector are started and four variables [duration of movement (D), number of half waves in the movement (N), sum of the positive amplitudes (SPA), and number of positive amplitudes (NPA)] are initialized. The processor now acquires the subsequent maximal deflection value (A) and elapsed time (T) until a threshold crossing in the opposite direction occurs. Negative after negative or positive after positive crossings are ignored. If the next threshold crossing is within 1 s (no timer overflow) the timer and peak detector values are stored in variables T (time) and A (amplitude), and reset. If T , which is a half-wave duration, is not within the range of the programmable parameters T -high and T -low (e.g., 167 and 63 ms, corresponding to the half-wave length of 3 and 8 Hz) it is unlikely that this half-wave is part of a tremor series and the fat printed loop at the left side of Fig. 10 is exited. If T is within the range of T -high and T -low, the number (N) of half waves in the present movement sequence is increased by one and the total duration (D) of the present movement sequence is increased by T . SPA, the sum of the positive amplitudes, is increased by A , and NPA, the number of positive amplitudes, by one, but only if the amplitude A is higher than zero, in order to prevent the summation of positive and negative amplitudes which, on average, results in zero values.

Fig. 10. Flowchart of the implemented algorithm. The fat printed loop at the lower left side forms the core of the discrimination of tremor and other movements. See text for explanation.

Fig. 11. Photograph of the device.

The “fat” plotted loop aggregates the duration (D), summed amplitude (SPA), and number of half-waves (N) in a series of half-waves uninterrupted by rest. This loop is the critical part of the software for discrimination of tremor from other

(a)

(b)

Fig. 12. Scatterplot of the relation of the mean observed UPDRS score with (a) the mean assessed tremor in min/s (upper panel) and (b) the mean assessed tremor amplitude in g . Correlations are indicated in the graphs.

movements. It is exited either when half-wave durations T are out of range or when a timer overflow occurs. A timer overflow interrupt is generated if a threshold crossing is not followed by an opposite crossing within 1 s, indicating a transition from activity to rest. If, after leaving the “fat” loop in either way, the accumulated number of half-waves is by now higher than the programmable critical number of half-waves parameter (CNH), the values of D , SPA , and NPA are added to the interval variables tremor duration (TD), tremor positive amplitude sum (TA), and tremor number of half-waves (TN). If not, D , SPA , and NPA are added to the interval variables activity duration (AD), activity positive amplitude sum (AA) and activity number of half-waves (AN). The algorithm then continues at the appropriate place, depending on whether the addition of the current duration, amplitude, and half-wave number to the interval variables followed a timer overflow or an out-of-range half-wave. In the latter case this last half-wave increments the accumulated activity variables AD by T , AN by one and, if the amplitude A was positive, AA by A .

At the end of every interval (e.g., after 15 min) the ongoing looping process is interrupted. Positive amplitude sums (TA and AA) are divided by their respective number of half-waves (TN and AN), resulting in average amplitude measures. These, with TD and AD , are written to nonvolatile memory, and a new interval starts.

TABLE I
OVERVIEW OF THE VALIDATION ASSESSMENTS. SEE TEXT (VALIDATION SECTION) FOR EXPLANATION

Patient	sex	age	H&Y	minutes of observation	UPDRS mean observed	% of movement time measured as tremor	average assessed tremor: amplitude	duration	correlation of UPDRS and: amplitude
A	f	65	1	42	3.55	82%	48.74	0.25	0.52
B	f	63	3	18	3.39	85%	50.47	0.47	0.93
C	m	62	3	30	3.03	73%	43.09	0.24	0.66
D	f	64	1	49	3.02	78%	46.14	0.41	0.60
E2	m	55	1	34	3.00	64%	37.96	0.30	0.87
F	m	66	4	15	2.73	47%	24.04	0.18	0.84
G1	m	58	1	32	2.03	44%	26.27	0.23	0.71
E1	m			41	1.95	36%	20.75	0.13	0.66
G2	m			16	1.88	44%	24.51	0.12	0.62
H	m	77	2	27	1.59	32%	12.06	0.24	0.73
I	f	57	1	28	1.25	5%	2.65	0.07	0.75
J	m	41	1	19	1.05	1%	0.56	0.05	0.68
average		61	1.8	29	2.37	49%	28.10	0.22	0.71
s.d.		9	1.1	11	0.85	28%	17.38	0.13	0.12
									0.43
									0.28

Fig. 13. A seven-day actigraphic recording of the fluctuation in tremor duration in a Parkinson patient. See text for explanation.

V. VALIDATION OF THE DEVICE

For validation of the device, wrist movements were assessed in Parkinson patients and, as control subjects, in patients suffering from a neurodegenerative disease that is not marked by tremor, i.e., Alzheimer's disease. In all studies the settings of the actigraph were as follows: threshold approximately 0.05 g and half-wave length between 35 and 240 ms.

First, in order to evaluate the specificity of tremor scoring, the false positive detection rate was determined from 16 recordings of approximately five days in Alzheimer patients. The percentage of movement duration that was erroneously scored as tremor was (mean $\pm$ s.d.) $3.2\% \pm 1.3\%$, and ranged from 0.0–5.9%. Consequently, the specificity of tremor detection can be estimated to be better than 0.94. Determination of the sensitivity of tremor detection in Parkinson patients is somewhat hampered by the lack of a golden standard to which continuous tremor detection can be compared. We have approached the problem by combining an observational scale for tremor severity with simultaneous and synchronous recordings with the device. Tremor severity was scored on a

minute-by-minute basis on a 5-point rating scale following the criteria of item 20 of the Unified Parkinson's Disease Rating Scale (UPDRS) [11], i.e., varying between 0 = absent and 4 = marked in amplitude and present most of the time. Twelve recordings were assessed in ten patients (two patients were assessed on two occasions) mostly during their visit to the outpatient clinic. The average age was 61 ± 9 (mean $\pm$ s.d.) years, and their disability, as indicated by the Hoehn and Yahr scale [12], was 1.8 ± 1.1 (mean $\pm$ s.d.) and ranged from 1 to 4. The patients were simultaneously observed and measured for 29 ± 11 min (mean $\pm$ s.d.), ranging from 15 to 49 min. All patients showed varying degrees of tremor during the observation, with individual average observed severity's on the minute by minute "UPDRS-item 20" scale of 2.7 ± 0.85 (mean $\pm$ s.d.), ranging from 1.05 to 3.55. The individual values, and the results of the simultaneously assessed tremor by means of the actigraph are shown in Table I and Fig. 12. High between subject correlations were found for the mean observed UPDRS-20 scores and the mean duration (s/min, $r = 0.96$) and amplitude ($r = 0.78$) of tremor. The within