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Quantitative analysis of wrist electrodermal activity during sleep

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ABSTRACT

We present the first quantitative characterization of electrodermal activity (EDA) patterns on the wrists of healthy adults during sleep using dry electrodes. We compare the new results on the wrist to the prior findings on palmar or finger EDA by characterizing data measured from 80 nights of sleep consisting of 9 nights of wrist and palm EDA from 9 healthy adults sleeping at home, 56 nights of wrist and palm EDA from one healthy adult sleeping at home, and 15 nights of wrist EDA from 15 healthy adults in a sleep laboratory, with the latter compared to concurrent polysomnography. While high frequency patterns of EDA called "storms" were identified by eye in the 1960s, we systematically compare thresholds for automatically detecting EDA peaks and establish criteria for EDA storms. We found that more than 80% of the EDA peaks occurred in non-REM sleep, specifically during slow-wave sleep (SWS) and non-REM stage 2 sleep (NREM2). Also, EDA amplitude is higher in SWS than in other sleep stages. Longer EDA storms were more likely to occur in the first two quarters of sleep and during SWS and NREM2. We also found from the home studies (65 nights) that EDA levels were higher and the skin conductance peaks were larger and more frequent when measured on the wrist than when measured on the palm. These EDA high frequency peaks and high amplitude were sometimes associated with higher skin temperature, but more work is needed looking at neurological and other EDA elicitors in order to elucidate their complete behavior.

1. Introduction

Electrodermal activity (EDA) is widely used in psychophysiology and provides a measure of activity in the sympathetic nervous system, one of the main branches of the autonomic nervous system. Studies of EDA during sleep have shown that elevated levels of EDA, with high frequency "storm" patterns, are more common during deep, slow wave sleep (SWS) (Koumans et al., 1968), while the frequency of EDA peaks is lower in the first cycle of the night (Freixa i Baqué et al., 1983) (Table 1). Classically, EDA has been measured as skin conductance levels or skin conductance responses and involves attaching wired and gelled electrodes to the skin, usually on the fingers or palms (Boucsein, 1992; Fowles et al., 1981). However, several studies have shown a valid measurement of EDA on other locations including the forearm (Table 2). Studies using dry electrodes on the forearm have demonstrated reliable long-term measures of EDA (Poh et al., 2010) and have also led to the discovery of correlations between EDA and significant neurological events measured from EEG (Poh et al., 2012).

In this study, we used a wireless non-invasive EDA sensor worn as a wristband on the distal forearm, which made it easy for subjects to be monitored in the same manner in the sleep lab and at home. We collected and analyzed 80 nights of EDA data more than ever previously reported in a single study.

Our paper makes three main contributions. First, we compare wrist EDA (convenient for continuous long-term measurement) to palmar EDA (inconvenient). When we began this work, there was concern that the wrist measures would primarily reflect thermal sweating. Our work is the first to find significant EDA patterns in sleep from the forearm while simultaneously measuring skin temperature at the same position.

Second, we characterize EDA in natural sleep, proposing an automated method to extract features from the EDA and using these features to create a taxonomy of EDA patterns during sleep. For 15 nights where we have concurrent synchronized polysomnography (PSG), we also characterize the EDA–PSG relationships and compare the new measures with results published in the 1960–1970s. PSG is currently the gold standard to evaluate and diagnose sleep patterns; however, the use of PSG requires scalp EEG electrodes and other sensors that tend to be uncomfortable and expensive, time-consuming to apply, and arguably interfere with the sleep they are measuring. Actigraphy is a much less invasive method often used to estimate daytime and sleep activity with a wrist-worn device; however, it does not measure neural activity such as stages of sleep. In this study, we measure both EDA and actigraphy to develop a quantitative characterization of EDA in natural sleep.

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Table 1
Summary of previous sleep EDA studies.

	Description	Location
Asahina and Omura (1964), N = 20	GSR high activity in stage 4	Galvanic skin response (measurement location unknown)
Broughton et al. (1965), N = unknown	Responses are rare in stage 4 and rare in REM sleep	Electrodermal response on palm and dorsal forearm
Lester et al. (1967), N = 53	More GSR peaks in stage 4	Galvanic skin response on finger
Koumans et al. (1968), N = unknown	Electrodermal fluctuations increase during SWS and decrease during REM	Skin potential and response on palm and dorsal surface of forearm
Hori et al. (1970), N = 15	Skin potential response max: SWS, low: REM	Skin potential activity on the palmar surface of finger and the dorsal surface of hand
McDonald et al. (1976), N = 46	Storming in stages 3–4	Skin potential and resistance, unknown location
Freixa i Baqué et al. (1983), N = 8	Spontaneous skin potential responses increase during 2–4 sleep cycles	Electrodermal activity on palm and dorsal surface of hand
Ware et al. (1984), N = 12	Storming occurs during NREM sleep	Skin resistance response on hands
Burch (1965), N = unknown	GSR storms during sleep stage 4	Skin response (location unknown)
Liguori et al. (2000), N = 53	Spontaneous sympathetic skin responses were highest in stage 4 and lowest in REM sleep	Sympathetic skin response on hand
Kobayashi et al. (2003), N = 8	The GSR peaks and sweat rate were significantly less frequent during REM sleep than during NREM sleep	Galvanic skin response on the dorsal side of hand

Lastly, we also compare EDA responses with skin temperature. It has long been recognized that thermoregulatory processes are suppressed during REM, while they persist during NREM (Adam et al., 1986). In a study of five healthy men, the largest sweating, averaged across multiple sites on the body, was recorded during SWS while the lowest was recorded during REM, although sweating was not completely blocked during REM (Sagot et al., 1987). But this occurred in the absence of significant changes in skin temperature across sleep stages. We provide the first characterization of the interaction between wrist/palm EDA, skin temperature, and sleep stages.

2. Methods

2.1. Measurement

Our studies examined EDA during sleep by monitoring skin conductance on the outer or the inner wrist (dorsal or ventral forearm) or on the palmar surface, using the Affectiva Q™ sensor with 1 cm diameter Ag–AgCl dry electrodes. The sensor logged EDA, actigraphy (3-axis accelerometer) and skin surface temperature at 32 Hz. The Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects (COUHES) approved both studies.

2.1.1. EDA at home from the wrist and the palm of healthy adults (65 nights)

Nine healthy adults (two females) wore the Q sensors on the right palm and wrist for one night each. A tenth person (healthy adult female) wore the Q sensors for 56 nights. Participants put the sensor on before going to bed and took it off after waking.

Table 2
Summary of previous EDA studies.

	Location
Johnson and Lubin (1966), N = 29	Finger, GSR and SCR, sleep lab
Johns et al. (1969), N = 31	Finger, GSR, sleep lab
Liguori et al. (2000), N = 5	Hand, sympathetic skin response, sleep lab
Shiihara et al. (2000), N = 5	Finger, skin conductance, palm, skin potential, sleep lab
Kobayashi et al. (2003), N = 8	Hand, galvanic skin response, sleep lab
Poh et al. (2010), N = 26	Finger and inner wrist, electrodermal activity, physical, cognitive and emotional tasks
Poh et al. (2012), N = 80	Wrist, electrodermal activity, epilepsy patient admitted to the long-term video-EEG monitoring unit
van Dooren et al. (2012), N = 17	16 positions (fingers, distal wrist, central wrist, vertical wrist, chest, foot (instep), calf, forehead, neck, shoulders, back, buttock, abdomen, armpit, upper arm, and thighbone), skin conductance, watch emotional film clips

2.1.2. EDA with concurrent PSG (15 nights)

Fifteen healthy university students (age: 18–22, 10 males) participated in a night of measurements in a sleep laboratory, wearing the Q sensor on the wrist. Sleep was simultaneously monitored with standard PSG and scored by standard criteria (Rechtschaffen, 1968).

2.2. Definition

We define the following terms:

EDA peak: local EDA maximum that exceeds a defined threshold (see analysis below for details)

EDA-peak epoch: a 30 second section of EDA having at least one EDA peak

EDA storm: consecutive EDA peak epochs; thus, an EDA storm has a minimum duration of 1 min and has at least two peaks during that minute

Burch storm: “a minimum of 5 galvanic skin response (GSR) peaks per minute for 10 consecutive minutes of sleep” (Burch, 1965; Lester et al., 1967)

EDA event: a section of EDA data having one or more EDA peaks or storms (e.g., an EDA isolated peak, EDA peak epoch, EDA storm or Burch storm)

2.3. Analysis

In this work, we automate the processing of EDA data in order to remove noise and to extract features that are robust and meaningful for characterizing sleep and in order to provide objective measures that can be used across nights, across participants, and across studies. In PSG, it is standard practice to label sleep stages in 30-second epochs; thus, we adopt the length of 30-second segments for our comparison analyses. The EDA data were processed in four steps.

1. Detection of sleep from actigraphy: Standard zero-crossing detection and Cole's function were applied to the accelerometer data to discriminate between sleep and wake (Cole et al., 1992). Only EDA data that corresponded to the times scored as sleep were further processed. Thus, EDA data that might be associated during the night with getting out of bed and moving around were not included in the analyses below.
2. Pre-processing of EDA: All EDA data that corresponded to segments of sleep were subsequently low-pass filtered (cutoff frequency 0.4 Hz, 32nd order FIR filter).