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Waveform difference between skin conductance and skin potential responses in relation to electrical and evaporative properties of skin

CHRISTIAN TRONSTAD,[a] HÅVARD KALVØY,[a] SVERRE GRIMNES,[a,b] AND ØRJAN G. MARTINSEN[a,b]

[a]Department of Clinical and Biomedical Engineering, Oslo University Hospital, Oslo, Norway
[b]Department of Physics, University of Oslo, Oslo, Norway

Abstract

The shapes of skin conductance (SC) and skin potential (SP) responses are often similar, but can also be very different due to an unexplained cause. Using a new method to measure SC and SP simultaneously at the same electrode, this difference was investigated in a new way by comparing their temporal peak differences. SC, SP, skin susceptance (SS), and transepidermal water loss (TEWL) were recorded from 40 participants during relaxation and stress. The SP response could peak anywhere between the onset of an SC response to some time after the peak of an SC response. This peak time difference was associated with the magnitude of the SCR, the hydration of the skin, and the filling of the sweat ducts. Interpretation of the results in light of existing biophysical theories suggests that this peak difference may indicate the hydraulic capacity state of the sweat ducts at the time of a response.

Descriptors: Electrodermal activity, EDA, Skin potential, Skin conductance, SCR, SPR

Electrodermal activity (EDA) originates from the activity of the sweat glands and is widely used in physiological measurements due to a strong link with the sympathetic nervous system activity. Sweating leads to rapid changes in the skin conductance (SC) by creating ionic current paths through the highly resistive dry stratum corneum (the outer layer of skin consisting of dead cells). The secretion and movement of electrolytes also leads to swift changes in the electrical potential of the skin (SP) relative to a nonactive skin potential—especially an initial increase in negativity that likely is secondary to sodium reabsorption across the duct wall at the level of the germinating layer (below the corneum). Recovery from these responses is at least in part attributable to emptying of the sweat duct due to diffusion of sweat into the dry peritubular corneum and probably also to a slow reabsorption of sweat from the duct. In addition, even slower changes in SC and SP also follow sweating as the corneum hydrates and dehydrates, with the hydration especially arising from the aforesaid diffusion of sweat from the ducts into the corneum.

SC is most commonly used for psychophysiological measurements (Boucsein, 2012). SP recordings are not as much in use, as the SP response (SPR) is composed of two underlying processes that drive the SP in opposite directions, making the evaluation of SPR amplitudes problematic (Venables & Christie, 1980). SP measurements are more frequently used within neurology for assessment of the autonomous nervous system functionality (Kucera, Goldenberg, & Kurca, 2004), where the term sympathetic skin response is used. The current study involves two novel methodologies. First, skin susceptance or SS (the contribution to ionic current transport from the capacitance of the skin when AC measurement is used; Grimnes, 1982), which primarily reflects hydration of the corneum.[1] Second, the difference between the SC response (SCR) and the more complex SPR waveforms suggests that there could be additional physiological information to gain by measuring both simultaneously. To that end, recently, Grimnes, Jabbari, Martinsen, and Tronstad (2011) developed a solution for simultaneous recording of SP and skin AC conductance at the same electrode, which has enabled investigation of the temporal relationship between the two EDA measures from the same ducts. Comparisons previously have been done between SP and skin resistance recordings by correlation analysis of classic characteristics, such as

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Address correspondence to: Christian Tronstad, Department of Clinical and Biomedical Engineering, Oslo University Hospital, Rikshospitalet, Sognsvannsveien 20, 0027 Oslo, Norway. E-mail: chrton@ous-hf.no

1. SS has rarely been used previously, but it follows sweating as the corneum hydrates and dehydrates. More specifically, low frequency SC is mainly due to the free ions in the sweat duct, while SS is due to the ions bound to the corneum proteins so that they can only move very short distances back and forth (vibration). The SC and SS contributions can be measured separately by modern electronic circuitry. The SS or electrical capacitance of the skin is proportional to the moisture content or hydration of the corneum (Martinsen et al., 2008). Thus, SS, measured by the quadrature component (90° ahead in phase) of the AC current through the skin, serves as a relatively direct index of corneal hydration in a way not provided by SC or SP measurements. In the traditional DC measurement of electrodermal activity, resistance or its reciprocal conductance are the variables of interest. When alternating current is used, the reciprocal terms are impedance and admittance. With AC measurements, current flow is also influenced by capacitance. The capacitance contribution to impedance is called reactance and the contribution to admittance is called susceptance. Thus, impedance consists of an AC resistance component and an AC reactance component, whereas admittance consists of an AC conductance component and an AC susceptance component.

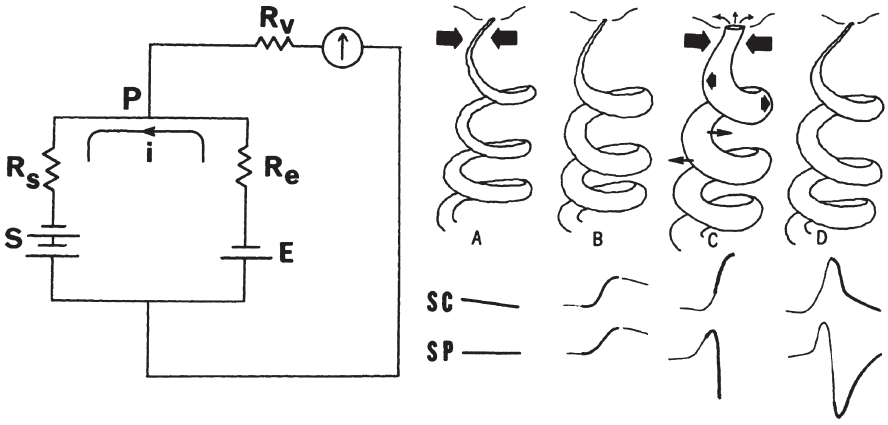

Figure 1. The Edelberg voltage-divider (1968) and poral valve (1993) models. Left: Voltage-divider circuit in the skin. Rs = resistance of sweat duct; Re = resistance of extraductal epidermis or stratum corneum; S = standing potential in sweat duct; E = standing potential in epidermis or corneum; Rv = input resistance of voltage amplifier. From Edelberg (1968) with permission from John Wiley & Sons Ltd. Right: Diagram of the sequence in a sweat response at a hydrated site. A: Unfilled ducts with high hydraulic capacity and collapsed poral segment. B: Secretion has partially filled ducts. C: Secretion has filled ducts to limit of capacity (now having low hydraulic capacity) and has generated sufficient intraductal pressure to open poral "valve." D: Escape of sweat has reduced intraductal pressure to collapse point. The associated SCR and SPR are shown at the bottom. From Edelberg (1993) with permission from Springer-Verlag GmbH.

initial levels and response amplitudes (Gaviria, Coyne, & Thetford, 1969) and between SP and skin impedance as a function of room temperature and skin abrasion (Shirai, Yamamoto, Nakamura, & Kusuhara, 2010). However, these comparisons from different sites did not permit the precision obtained from comparisons of SP and SC at the same site.

To better understand the value of the contributions of these two innovative methodologies, it is necessary to review the complex features of electrodermal measures and theories concerning the mechanisms.

While the SCR is always monophasic, the SPR appears either as monophasic negative responses, as biphasic responses (where an initial negative component is followed by a positive deflection), as triphasic responses, where the positive limb of the biphasic response achieves a greater negativity than the initial negative wave, or as monophasic positive in which no negative component is seen (Boucsein, 2012). A two-effector hypothesis was initially proposed with the negative and positive components being mediated by different systems (Forbes & Bolles, 1936; Takagi & Nakayama, 1959; Wilcott, 1958). However, the hypothesis was later criticized and lost ground due to new explanations.

Edelberg (1968) proposed a voltage-divider model, in which the (measured) surface potential is governed by the relative magnitude of a sweat duct resistor and an epidermal (stratum corneum) resistor, connected to voltage sources of higher and lower negative potentials, respectively (see Figure 1 left). Key assumptions are that the ductal resistance decreases when sweat fills the duct and the corneal resistance decreases when hydrated—especially by diffusion of sweat from the duct into the peritubular corneum, but also by diffusion from the usually wet electrode gel at the surface. This model can be more easily understood by ignoring the small negative potential in the stratum corneum and envisioning a simple circuit with a large negative potential in the sweat gland duct driving current across the two resistors, whose relative magnitude determines the portion of the voltage drop across each resistor and with the surface electrode measuring the voltage at the point between the two resistors. If the ductal resistance is high relative to the corneal resistance, most of the negative potential is lost across the ductal resistor and the surface measured potential will be low. Thus, by this model, filling of the sweat duct decreases the ductal resistor (decreasing the voltage drop across the ductal resistor) and generates a negative SP swing at the surface electrode. On the other hand, as sweat diffuses into the corneum and reduces the corneal resistance, the surface potential is driven in a positive (actually, less negative) direction, generating a positive deflection and thereby a biphasic waveform in total.

Based on reports of hydration of the epidermis leading to swelling of the corneum at the surface and blockage of sweat duct poral openings onto the skin surface (Peiss, Randall, & Hertzman, 1956; Randall & Peiss, 1957; Sarkany, Shuster, & Stammers, 1965), Fowles and Rosenberry (1973) assumed this model and investigated the SP with respect to hydration from a wet surface electrode gel. They found that hydration virtually eliminated positive SPRs. Fowles (1986) later concluded that most of the existing findings could be explained by an effector system with the negative sweat gland potential operating in conjunction with the voltage-divider model (Fowles, 1986).

Edelberg (1993) developed his model further into a poral valve model as shown in Figure 1 (right), based on the aforesaid blocking of the duct at the skin surface when hydration of the corneum causes the sweat gland pore at the surface to close. In this model, partial filling of the duct will cause an increase in SC and a negative SP, as noted above. As the duct is filled to the limits of its limp capacity and secretion continues, intraductal pressure increases and forces an opening of the poral valve, increasing conductance further. Additionally, the high pressure promotes diffusion of sweat into the deeper levels of the corneum and thus hydration of the peritubular corneum. According to the voltage-divider model, this corneal hydration produces a positive SP deflection. Thus, the increased pressure initiates a positive component at the same time that it initiates an SCR—that is, the onset of the positive component precedes the peak of the SCR. As the sweat escapes from the duct, the rapid reduction of pressure allows the pore to close and the sweat duct component of the SC decreases quickly. In the voltage-divider model, this rapid increase in resistance of the sweat gland pathway causes a further positive SP deflection (in addition to the

positive deflection due to corneal hydration). Finally, Edelberg proposed that diffusion of sweat from the periductal area into the broader surrounding the corneum reduced the corneal hydration effect (i.e., reversed the decrease in resistance in the corneum in the voltage-divider model), causing recovery of both the SCR and the positive component of the SPR (i.e., a decrease in SC and an increase in SP).

If the pores are not fully closed by hydration, strong secretion still may exceed the emptying capacity of the pores, producing increased intraductal pressure with the subsequent positive SP deflections as a result of pressure-induced diffusion of sweat into the peritubular corneum. According to this model, the turning point of an SPR from the negative to the positive direction, occurring before the SCR peak, should represent the time at which the corneum begins to become hydrated before the pore has completely opened. Further, by this model, biphasic SPRs should only occur when ducts become completely filled while there is still pressure from the gland, which should lead to sweat emergence and an increase in evaporation. Thus, there should be a relation between occurrence of biphasic SPRs and increases in evaporation (sweating) from the skin surface.

The key components of this model are an increase in ductal pressure due to hydration-induced poral closure, a parallel forced opening of the duct (onset of increased SC) and diffusion of sweat into the corneum (decreased corneal resistance and a positive SPR) as a result of the pressure, a rapid reduction in pressure as the sweat escapes to the surface (recovery of the SCR), and a dissipation of peritubular corneal hydration with further diffusion of the sweat into the corneum that produces a recovery of the positive SPR component.

A feature of EDA, which to the authors' knowledge has never been studied before, is the time difference between the turning points or peaks of the SPR and SCR waveforms. In this study, we have investigated the temporal distance of the SPR turning point (from negative to positive voltage direction) relative to the peak of the corresponding SCR, which we have called "skin potential relative early turn" (SPRET). In general, the onset of the positive SPR component is expected to precede the peak of the SCR and to follow the onset of the negative component of the SPR. However, in the case of a monophasic negative SPR similar to the SCR, it has a zero SPRET (because there is no positive component before its recovery), while a monophasic positive SPR has a SPRET of 100% (because there is no onset of the negative SPR). Thus, this feature is a continuous parameter of the SPR waveform, which could be of physiological interest and be used to investigate the electrodermal processes in detail.

The general aim of this study was to gain a better understanding of the electrodermal system by finding out why and when the SCR and SPR waveforms are different, including an explanation in context with the existing models of EDA. Existing models include intraductal pressure, pore opening, and hydration as the most important factors influencing the SPR shape, and these factors can be approached by measuring the transepidermal water loss (TEWL, surface sweating) and the SS. Employing the SPRET as a quantitative measure of the SP and SC waveform difference, we wanted to test whether these factors, or typical parameters of EDA (i.e., SCR amplitude), can explain the variations in the SPR shape. According to the poral valve model, an increase in sweating sufficient to reach and fill the pores (i.e., pore filling) should cause an increase in SPRET due to higher intraductal pressure. Also, more hydrated skin should have lower SPRET according to the elimination of positive SPRs by hydration as reported by Fowles and Rosenberry (1973). In addition to these two hypotheses, there may be features of the SC or SP such as the SCR amplitude or rise time, which relate to or affect the SPRET during the electrodermal response. Hence, the specific aim was to acquire SPRET variations within- and between-subjects and to find its correlation to TEWL, SS, and other EDA parameters, using the following procedure:

- Record SC, SP, SS, and TEWL (surface sweating) simultaneously during provoked sweating and relaxation.
- Extract electrodermal responses and calculate SPRET for each response, reflecting the onset of the SPR positive component before the peak of the SCR.
- Test whether SPRET is higher during stress-induced sweating (i.e., with ducts filled) compared to during relaxation (i.e., with ducts empty).
- Assess correlations between SPRET and within-subject variations in phasic EDA parameters and TEWL, and between-subjects variations in TEWL and tonic EDA parameters (including SS).
- Discussion of the results in view of the existing models of EDA.

Materials and Method

Skin Admittance and Potential Measurement

Based on the solution described in Grimnes et al. (2011), a PC-based EDA measuring system for simultaneous recording of skin admittance (SY) and SP at the same electrode was developed. It consists of a matchbox-sized front-end electronics box connected via a National Instruments DAQ card to a laptop running software written in LabVIEW, v. 8.5, similar to Tronstad, Grimnes, Martinsen, Amundsen, and Wojniusz (2010). The saline bath immersion of the underarm as a reference electrode was replaced by a more practical three-electrode system. This electrode system consists of a measuring electrode, one reference electrode, and a current-sink electrode. The reference electrode together with the current-sink electrode serves to provide a monopolar AC SC measurement below the measuring electrode without needing to use different electrode sizes as with the two-electrode system. At the same time, SP measurement is provided by the DC voltage between the measuring electrode and the reference electrode (which has to be placed at an electrodermally inactive skin site). The constant current control from the previous (Grimnes et al., 2011) system was replaced by a Howland current source giving a 10 Hz AC current of 14 μA to the skin. In addition to SC and SP measurements, the quadrature component of the SY signal was used to also measure SS (skin susceptance related to corneum electrical capacitance). The differential amplifier in the previous system was replaced by voltage sensing with analog-to-digital conversion at both terminals and software differencing. This enables detection of variations in the reference site potential, thereby checking to which extent the reference site is electrodermally inactive, which is a requirement for accurate SP recording (Boucsein, 2012). Although abrasion (Edelberg, 1967) or skin drilling (Venables & Christie, 1980) is a recommended pretreatment for the inactive site, no pretreatment of the skin was used in this study because relatively small bias potentials are not influencing the parameter of investigation (SPRET), and there is also no risk of contamination, and therefore no need for associated procedures. The measuring electrode was attached at the hypothenar site of the palm, the SP reference electrode was attached to the apex of the elbow, and a current-sink electrode was placed on the underarm. In order to

avoid wetting of the skin from the electrode gel, a solid hydrogel electrode type (Arbo KittyCat) was used for the recordings. This gel type was known to cause no or minimal wetting of the skin according to Tronstad, Johnsen, Grimnes, and Martinsen, 2010. Given the presumed importance of having a dry corneum in order to facilitate the process associated with the positive component of the SPR (diffusion of sweat into peritubular corneum), the use of this gel was critical to the success of the study.

TEWL Measurement

TEWL was measured using the QSweat (WR Medical Electronics Co., Stillwater, USA). The QSweat uses dry air (room air, drawn across a desiccant) to pick up moisture from a measurement capsule (5.06 cm^2 circular measurement area) placed on the skin. Constant airflow of 60 cm^3/min through the capsule transports the captured moisture to the temperature and humidity sensors in the device. The airflow back and forth from the capsule to the QSweat passes through two 2.4-m air hoses, causing a temporal delay in the measured response.

The skin capsule was attached on the hypothenar eminence on the palm of one of the hands of the participant (the opposite hand of the placement for the EDA electrodes). The capsule comes with a silicone band and two mounting spikes on the back side for strapping to the skin. The silicone band was mounted on the spikes and wrapped around the hand and wrist in such way that the silicon band could be tightened and adjusted in four directions. The capsule position was then adjusted by varying the tension in the different silicone bands to even out the pressure between the capsule and the skin. This was done until a tight fit was obtained and no leakage could be detected by the QSweat software (WR-TestWorks 2.0.1). To further prevent air leakage, the participant was asked to find a comfortable position for the hand, and to move it as little as possible during the measurements.

A step-response test of the QSweat system was done before the experiments started to test its responsiveness. By sliding a probe from a dry to a wet surface, a response delay of 8 s and a time constant of 19.2 s were found for the TEWL measurement. The 8-s delay was due to the time required to pass through the 2.4-m air hoses.

Experimental Protocol

Forty healthy participants (31 male, 9 female, age 17–64), were recruited from Oslo University Hospital and University of Oslo and gave informed consent before participation. The study was approved by the regional ethics committee (REK #2010/1927a).

The experiments were carried out in silent laboratory or meeting rooms with only the participant and two operators present. Room temperature was 22.5 ± 1°C. After bilateral fixation of EDA and TEWL sensors to the hypothenar areas of opposite hands, assigned randomly to the left and right sides, the TEWL measurement was monitored until stable levels were attained. The experiment was aborted if the TEWL stabilized above the maximum of the QSweat measuring range (1,000 nL/min). In parallel with TEWL stabilization, at least 5 min were allowed for stabilization of EDA electrodes before the recording started. In order to produce variations in sweating and thereby duct filling over time, intervals of relaxation and mental stress were alternated. The participants were sitting comfortably in a chair during the relaxation and were not allowed to speak with the operators unnecessarily. Mental stress was induced by asking the participant to repeatedly subtract seven from a starting number of 1,000. This was repeated in three 2-min intervals, with 5 min for relaxation before and after (5-2-5-2-5-2-5), giving a total recording session of 26 min.

Data Analysis

Signal conditioning. Due to noisy TEWL recordings, the time series were digitally low-pass filtered with a third-order zero-phase Butterworth filter with a 0.025 Hz cutoff frequency in order to dampen all noisy fluctuations sufficiently. The response delay and time constant found from the step test was used to correct the phase of the signal and the responsiveness by backwards-filtering digitally through an inverted resistor-capacitor filter with the measured time constant.

The TEWL recordings, with a sampling frequency of $fs = 4$ Hz, were aligned with the EDA recordings with $fs = 10$ Hz by resampling to 10 Hz by linear interpolation using the time-series tools in MATLAB.

In order to assess similarity between SCR and SPR, all SP recordings were multiplied by −1 before analysis (in order to convert the negative potentials to positive).

Parameterization of EDA time series. In order to extract all EDR events, the SCR onsets and peaks were identified by computation of the minima and maxima of the EDA using the Ledalab v. 3.4.0 MATLAB package (Benedek & Kaernbach, 2010) with the standard peak detection method (trough-to-peak). SCRs with an amplitude above 0.05 μS and the corresponding SPR segments were extracted from the time intervals between the SCR onset and the onset of the next SCR. In order to examine the characteristic SPR waveform, it is important that its recovery not be disrupted by another response. In order to preclude such disruption, only the segment from the onset of the SCR to either its complete recovery or to the onset of the next SCR was extracted for each SCR and its corresponding SPR segment.

Within this SCR interval, the SCR and SPR peaks were located by the findpeaks() function in MATLAB, and the SPRET was calculated from the time of the SCR peak minus the time of the SPR peak, divided by the time from SCR onset to SCR peak, and multiplied by 100 for a percent. An illustration of this parameter is given in Figure 2. Responses that did not contain any SPR peak (as determined by the findpeaks() function) were not included in the analysis.

In order to test whether the SPRET was related to surface sweating, the TEWL level at the onset of the SCR, and its rate of change (first derivative), were extracted during each EDR for comparison with every SPRET within each subject. The same extraction was done with a range of selected EDR parameters in order to examine other factors that could be related to the SPRET. As little was previously known about the cause of SPRET variation from response to response, all the traditional phasic EDA parameters (Boucsein, 2012, Chapter 2.3), also called scores, were calculated for each EDR for intraindividual correlation analysis. Table 1 gives a complete list of all the parameters included in the analysis. The SCR_amp, or amplitude of the skin conductance response, represents the magnitude of the EDR, which is presumably related to the strength of sweat secretion in the duct and the number of active sweat ducts below the electrode, and is also dependent on the level of the SC or SP just prior to the onset of a response. The levels of both the SC and SP (SCL and SPL in Table 1) were also extracted as they may be related to the filling state of the duct or the corneum hydration preceding the EDR, which could be related to the

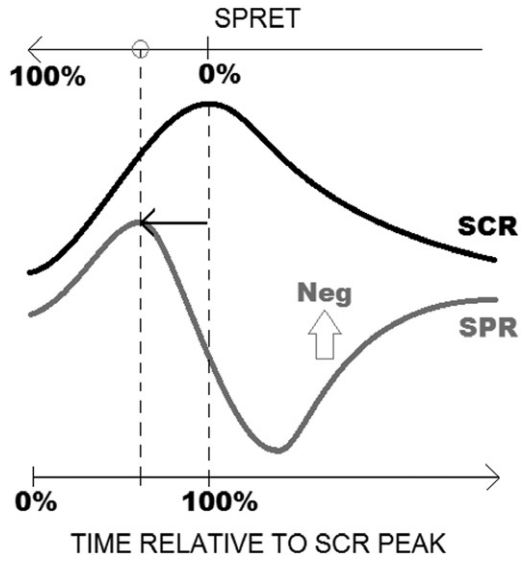

Figure 2. Illustration of the skin potential relative early turn (SPRET) parameter. Based on an SCR, its onset and peak defines the 0% and 100% time relative to the SCR peak (bottom axis). The peak (in negative voltage direction) of the corresponding SPR determines the SPRET (upper axis) by the relative time at which the SPR turns in the positive voltage direction before the SCR turns in the negative conductance direction. This example shows an SPR that peaks at approximately 60% relative to the SCR peak, which gives a SPRET of 100% − 60% = 40%.

SPRET. In order to extract the magnitude of SCRs in a way that is less influenced by the level prior to the response or overlapping responses, the maxima of the SCR slope (maximum of the first derivative) and the SCR curvature (the rate of change of the slope or the maximum of the second derivative) were calculated in addition to the SCR amplitude. The SPRET, being a timing parameter, could presumably very well be related to the timing of the SCR, traditionally represented by the rise time (the time between the onset and peak of the SCR) and the 50% recovery time (time from the SCR peak until the SC has recovered by 50% of the amplitude). Hence, these timing parameters (SCR_ris and SCR_rec/2) were also calculated for each individual response.

In order to examine how between-subjects skin factors are related to the SPRET, the baselines of TEWL, SC, SS, and SP for each participant were used for comparison with the participant's median SPRET. The baselines were computed by taking the mean of the three measurements that came directly before the onset of the mental stress intervals (at 5 min, 12 min, and 19 min), thus representing relaxed levels of SC, SP, SS, and TEWL with minimal influence from sweating. In other words, parameters that vary in time, along with each EDR, were used for the within-subject analysis while parameters representing the participant-specific baseline levels were used in the between-subjects analysis.

All the parameters were calculated based on the raw data and not the data that were later transformed for standardized waveform comparison (see Construction of typical SPR waveforms). All signal conditioning and parameterization was done in MATLAB R2011a.

Statistics

In order to quantify the relation between SPRET and the selected parameters listed in Table 1, correlation coefficients and their p values were calculated for each parameter versus SPRET. For each participant, the SPRET for each individual response was compared to the phasic parameters (SCR_amp, SCR_ris, SCR rec/2, SCL, SPL, SCR_slope, SCR_curv, TEWL, and TEWL_TD) by the Spearman rank-order correlation coefficient. In order to quantify the association between SPRET and participant-specific factors, the median SPRET of each participant was compared to the participants' baselines of TEWL, SC, SP, and SS by the Pearson product-moment correlation coefficient. To assess the temporal relation between changes in TEWL and SPRET, the mean of all TEWL time series was compared to the distribution of SPRET for all responses from all participants. The median SPRET within each minute interval of the recording was compared to the mean TEWL by the Pearson product-moment correlation coefficient.

All statistics were done in MATLAB R2011a using the statistics toolbox.

Table 1. *Description, Function, and Unit for All Parameters Extracted from the Measurements and Used in the Statistical Analysis*

Parameter	Description	Data source	Function	Unit
SPRET	Turning point of the SPR relative to the SCR peak	Individual response	Dependent variable	%
SCR_amp	Amplitude of the skin conductance response	Individual response	Within-subject covariate	µS
SCR_ris	Time from onset of SCR to peak SCR	Individual response	Within-subject covariate	s
SCR_rec/2	Time from SCR peak to 50% recovery of the SCR.	Individual response	Within-subject covariate	s
SCR_slope	Maximum first derivative during SCR	Individual response	Within-subject covariate	µS/s
SCR_curv	Maximum second derivative during SCR	Individual response	Within-subject covariate	$\mu S/s^2$
SCL	Skin conductance level	Individual response	Within-subject covariate	µS
SPL	Skin potential level	Individual response	Within-subject covariate	mV
TEWL	Transepidermal water loss	Individual response	Within-subject covariate	nL/min
TEWL_TD	First derivative of TEWL	Individual response	Within-subject covariate	nL/min^2
TEWL_BL	TEWL baseline before mental stress onset	Total time series	Between-subjects covariate	µL
SC_BL	Skin conductance baseline before mental stress onset	Total time series	Between-subjects covariate	µS
SP_BL	Skin potential baseline before mental stress onset	Total time series	Between-subjects covariate	mV
SS_BL	Skin susceptance baseline before mental stress onset	Total time series	Between-subjects covariate	µS

Note. The data source column explains whether the parameter was computed based on individual EDRs or based on the total time-series data for the whole recording for each participant.

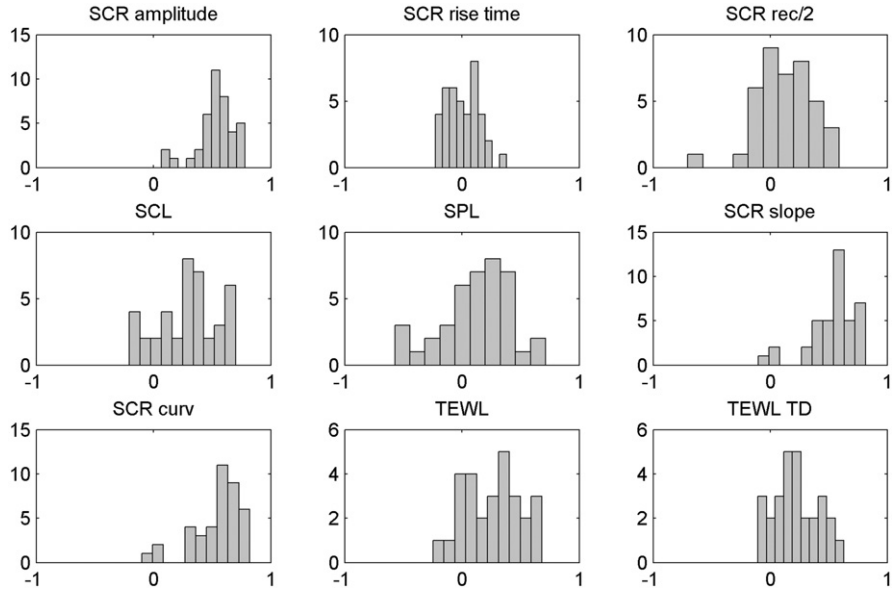

Figure 3. Within-subject Spearman rank order correlations ($N = 40$) between SPRET and SCR_amp, SCR_ris, SCR_rec/2, SCL, SPL, SCR slope, SCR curvature, TEWL ($N = 28$), and TEWL_TD ($N = 28$). All rho > 0.2 are significant at the 95% level.

Construction of Typical SPR Waveforms

Based on the extracted SPR segments, a set of typical SPR waveforms was constructed according to different values of SPRET. First, all the SPR segments were resampled in time by linear interpolation so that the SCR peak time of each SPR was aligned at sample number 100. This allowed a temporal comparison between all SPR waveforms with a standardized time scale according to the SCR peak belonging to each SPR. These resampled SPR segments were then standardized in magnitude by transforming the voltage values into z scores. All the standardized segments were then binned into SPRET categories in 10% intervals, and the median curve was determined for each bin in order to represent the typical SPR waveform. This analysis permitted the portrayal of typical SPR waveforms as a function of how early the positive component began in relation to the peak of the SCR.

Results

Within-Subject Results

As seen in the histograms in Figure 3, which plots the distribution of rho values for the correlation between the parameters indicated versus SPRET values, significant positive correlations were found between the SPRET and most of the phasic EDA parameters. The strongest correlations were found for the magnitude of the SCR: The SPR peaked earlier (higher SPRET) for SCRs with higher slopes, curvatures, or ampitude (median rho = 0.58, 0.60, and 0.53, respectively, $p < .001$). This association was also found for the SCL and SPL, with higher prestimulus levels related to earlier SPR peaks in most of the participants (SCL vs. SPRET median rho = 0.33, $p < .01$, and SPL vs. SPRET median rho = 0.17, $p < .05$, respectively). The TEWL and the time derivative of the TEWL were also positively correlated to the SPRET, meaning that more surface sweating, or increases in the rate of sweat production, were associated with earlier SPR peaks (TEWL vs. SPRET median rho = 0.28, $p < .05$, and TEWL_TD vs. SPRET median rho = 0.22, $p = .06$). There was a random association between the SPRET and the timing parameters of the EDR (SCR_ris vs. SPRET median rho = 0.004, $p = .32$, and SCR_rec/2 vs. SPRET median rho = 0.11, $p = .19$).

Between-Subjects Results

The median SPRETs for all participants were normally distributed (confirmed by the Lillie test) with a range from 0% to 64%. As shown in Table 2, the SPRET had a negative correlation to the participant-specific baseline levels of TEWL, SC, and SS. In other words, participants with higher baseline levels of these parameters had SPRs that peaked later on average. There was no significant association between the median SPRET and the SP baseline of the participants.

General Results

Figure 4 shows the SPRET for all responses from all participants and how a shift in SPRET coincides with increases in TEWL provoked by arithmetic problems. As seen in the lower part of the plot, earlier SPR peaks were associated with more surface sweating (mean TEWL vs. median SPRET, $r = .88$, $p < .001$). The SPRET seems to decrease earlier than the fall in TEWL by approximately 1 min when the curves relax.

Table 2. *Between-Subjects Correlations Between SPRET and the TEWL, Skin Conductance, Skin Potential, and Skin Susceptance Baselines*

	Correlation coefficients between SPRET and:			
	TEWL_BL	SC_BL	SP_BL	SS_BL
Pearson's r	–0.36*	–0.55*	–0.13	–0.48*

*$p < .05$.

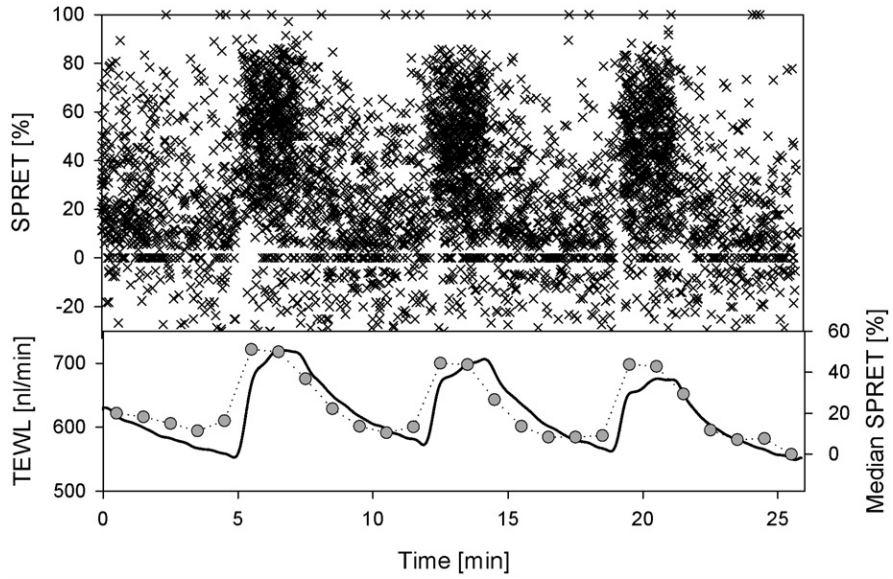

Figure 4. SPRET for all responses from all participants vs. time (above) for comparison with mean TEWL (solid line below). The gray circles represent the median SPRET during each minute interval. The participants were given arithmetic problems during minutes 5–7, 12–14, and 19–21.

The construction of typical SCR and SPR waveforms resulted in the shapes presented in Figure 5 (left). The SPR is very similar to the SCR when SPRET is close to 0, but the total shape changes with a positive voltage component as SPRET increases towards 100. The SCR shape was independent of the SPRET. Not all SPRs seem to have recovered completely during the SCR. As seen in the upper dashed curves in the plot, there were a significant number of cases where the SPR would peak later than the SCR, giving a negative SPRET. These SPRs seem to have slower rise and recovery segments, which give them a different shape than the other

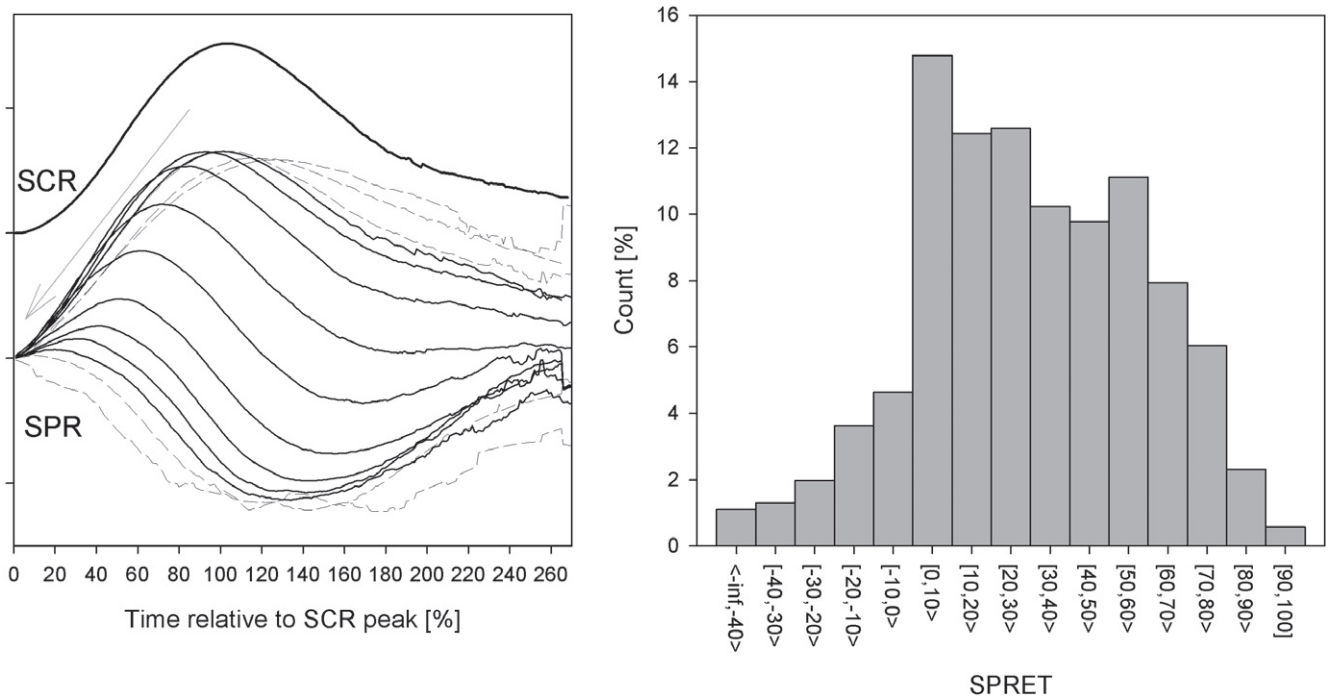

Figure 5. Left: Typical SCR (above) and SPRs (below) based on standardized responses, categorized according to the SPRET in 10% intervals. Each SPR curve represents the median of SPRs (standardized in both time and magnitude) for each category of the 10% interval SPRET bins ranging from -infinity to 100% SPRET. Categories with less than 5% representation are marked with a dashed line. The arrow indicates how the SPR waveform changes from monophasic to biphasic as the SPRET increases towards 100% (or towards 0% time relative to the SCR peak). The vertical axis represents normalized amplitudes in positive conductance direction and in negative voltage direction. Right: Histogram of the SPRET for each category.

SPRs. As seen in the histogram in Figure 5, the SPRs in this study could peak anywhere between 50% later to 100% earlier than the SCR, with most SPRs peaking between 0% to 80% earlier.

Discussion

In this study, the SPRET was found to lie between −50% to +100%, with most of the SPRs having a SPRET between 0–80%. The results point to several factors significantly related to the SPRET, which means that these factors are also related to the SPR waveform and whether it is monophasic or biphasic. EDRs with large magnitudes (slope, curvature, amplitude) were related to earlier SPR peaks. Participants with higher baseline levels of SC, SS, and TEWL had EDRs with later SPR peaks on average. For the pooled data from all participants, there was a strong positive correlation between the degree of surface sweating and how early the SPR would peak.

The SPRET Distribution

Based on the range of the SPRET distribution as shown in Figure 5, the SPRs in this study could peak (in the negative voltage direction) any time between the onset of the SCR to the peak of the SCR (100% to 0% SPRET), but unexpectedly the SPR could also peak at a later time than the SCR peak (negative SPRET). Most of the SPRs peaked at the same time or slightly earlier than the SCR peak, with an equal waveform. Inspecting the typical waveforms in Figure 5, it is clear that SPRs with a SPRET lower than about 30%, including all negative SPRETs, would normally be regarded as monophasic with no positive voltage component. This means that the SPRET provides a continuous parameter that quantifies the degree of influence from the mechanism and drives the SPR in the positive direction, which cannot be found from inspecting the SPR waveform alone. The SPRs with SPRET > 90% could be regarded as monophasic responses in the positive voltage direction. The rest of this discussion concerns the factors that determine the variation in SPRET.

Within-Subject Factors

Interpretation of the within-subject correlations (Figure 3) means that the SPR peaks earlier when the SCR is stronger (larger slope, curvature, and amplitude). It is reasonable to assume that the stronger SCRs could come from stronger pumping of sweat from the sweat gland, which also gives a larger hydrostatic pressure elicited on the ductal walls. According to the voltage-divider model, it is this ductal wall pressure that causes an augmentation of the movement of sweat into the peritubular corneum, which lowers the corneal resistance and produces a positive SP turn. Given the helical structure of the ducts, it is likely that this pressure may act on the walls earlier than on the pore opening (SPRET > 0%), and that the ductal pressure may occur even earlier relative to the pore opening for stronger responses (increased SPRET), which gives one possible explanation for the positive correlation between SPRET and the amplitude, slope, and curvature of the SCR. It was expected based on the poral valve model that the parameters that represented pore filling (i.e., TEWL and SCL) would have a correlation to SPRET in the direction that more filled ducts at the start of the response were associated with earlier peaks of the SPR.

Between-Subjects Factors

Between participants, the SPRET had a negative correlation to the baseline SC, SS, and TEWL, which means that participants with lower baseline levels of these three measures were associated with earlier SPR peaks. The SC baseline, when sweating is not present, is mainly dependent on the thickness of the stratum corneum and especially its hydration. The skin susceptance is known to be correlated with skin hydration without influence from the sweat gland activity (Martinsen et al., 2008). Because the TEWL, which is a measure of moisture loss, was correlated to SPRET in the same direction as SC and SS, it is most likely that the SC variation between participants also reflected the variation in skin hydration. Thus, all the between-subjects correlations indicate that participants with drier skin have SPRs that peak earlier. Based on the range in median SPRET between participants (0–64%) and the SPR waveform type according to the SPRET distribution (Figure 5), which shows that SPRs go from monophasic to biphasic at around 30% SPRET, this means that individuals with drier skin have more biphasic SPRs. This is in agreement with Fowles and Rosenberry (1973) who found that the positive SPR amplitudes (high SPRET) were virtually eliminated by applied skin hydration with 0.5% KCl. Because hydration of the skin affects the SPRET and the poral closure of the ducts, it was important to avoid external influences on the hydration such as wetting electrode gels. In this study, a solid hydrogel type known to give no or minimal wetting of the skin was used for the recordings, and it is likely that using different electrode gels will give different SPR waveforms.

SPRET and the State of the Sweat Ducts

Based on the temporal comparison between the SPRET distribution and the TEWL (Figure 4), a relatively large shift in SPRET coincides with the periods of increased evaporation. The ducts are presumably filled with sweat early in these periods, and subsequent glandular sweat secretions increase the intraductal hydrostatic pressure, which leads to positive SPR deflections in agreement with the voltage-divider model. The early fall of SPRET compared to the TEWL decay could be attributed to hydration of the corneum following sweating, which reduces the positive SPR deflection either due to swelling and pore blocking or an increased admittance to the corneum potential.

In light of the poral valve model, sweat secretion in a duct that is filled to the limits of its limp capacity causes an SCR peak, which represents the pore valve opening. The SPR peak (from the negative to positive direction) is determined by pressure-induced hydration of the peritubular corneum. The results from this study clearly show that these two peaks do not always occur simultaneously. During sweating (while ducts are filled), the SPR peak occurs earlier than the SCR peak (SPRET is higher) when the hydraulic capacity is low. By the poral valve model, this would mean that the corneal hydration process occurs earlier relative to the pore opening when the duct is already filled and its hydraulic capacity is low. A monophasic positive SPR would come from a duct that is already filled to its limp capacity before secretion, and the SPRET will be 100%. A monophasic negative SPR would come from an empty duct that is filled without increasing intraductal pressure unduly, reducing the ductal resistor in the voltage-divider model while the stratum corneum resistor is relatively constant, producing a synchronous SCR and SPR (0% SPRET). For biphasic SPRs, the SPRET increases as the duct capacity decreases. Hence, the SPRET may indicate the hydraulic capacity of the duct at the time of the response (the higher the SPRET, the lower the hydraulic capacity of the duct).

Assuming that the SCR slope or curvature is proportional to the secretion pressure (which forces the pore opening), the positive

correlation between these SCR parameters and the SPRET supports this theory, as the pressure will most likely act on the ductal walls before the pore opening, with a positive SP deflection proportional to the pressure. However, the skin hydration seems to affect the SPRET in a different way that is not directly related to the sweat duct capacity. In view of the voltage-divider model, increased skin hydration reduces the corneal resistor, which diminishes the effect on this resistor when sweat diffuses into the peritubular corneum and thereby also diminishes the positive SPR component and causes a negative shift in the SPRET, independent of the hydraulic capacity.

Limits of the Study

In order to provoke sufficient sweating to assume complete duct filling and to record a relatively equal number of EDRs during filled and emptier ducts, a continuous stimulus was used, although point stimuli with sufficient interstimulus time would be preferable for characterizing the complete SPR waveform. Therefore, little analysis was done on the part of the SPR during SCR recovery due to incomplete recovery, and the complete SPR tail is thus not presented due to lack of such data (Figure 5).

Due to a large number of noisy TEWL recordings, the time series had to be aggressively filtered, which reduced the responsiveness. This may have affected the within-subject correlation between SPRET and the TEWL parameters, suggesting that the comparison of averages as presented in Figure 4 gives a more accurate picture of this relation.

Because the SPRET calculation was based on finding peaks, SPR waveforms that did not contain any peaks, such as responses that continuously decreased or increased from start to end, were not included in the analysis because the SPRET would be ambiguous in these cases. Therefore, the case of 100% SPRET could possibly be underrepresented in this analysis.

Conclusion

The findings in this study suggest that the SPR may turn from negative to positive voltage direction anywhere between the time of the onset of an SCR to some time after the peak of an SCR. This waveform difference between the SCR and the SPR, assessed by the SPRET, is related to the magnitude of the SCR, the hydration state of the skin, and the filling of the sweat ducts. However, these factors do not explain all the SPRET variation, which suggests that either some important EDA factors were not accounted for in this study, or that the SPRET parameter may contain additional physiological information from the skin. The following conclusions are drawn from the findings in this study:

- The SPR may peak (turn from the negative to the positive voltage direction) anywhere between the time of the onset of an SCR to some time after the peak of an SCR.
- SPRs that peak less than 30% earlier than the SCR have a monophasic waveform.
- Stronger SCRs are associated with earlier SPR peaks.
- Drier skin is associated with earlier SPR peaks and more biphasic waveforms.
- Filled sweat ducts, or low hydraulic capacity of the duct, is associated with earlier SPR peaks.
- The findings are in agreement with the voltage-divider and poral-valve models of the electrodermal system.

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