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Estimation of skin conductance at low frequencies using measurements at higher frequencies for EDA applications

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Abstract

Using low-frequency (LF) alternating current skin conductance (SC) has recently been recommended for electrodermal activity (EDA) measurement, but the method may imply some limitations in sampling rate, which are insufficient for capturing the complete SC waveform. The aim of this study was to assess whether LF SC can be estimated based on skin admittance (SA) measurements at higher frequencies allowing higher sampling rates. SA measurements from 1 Hz to 70 kHz were gathered from 20 healthy human participants, and an interval from 500 Hz to 10 kHz was used to fit a Cole model to the measured SA by means of the nonlinear least squares method. The LF extrapolation of this fit was used to estimate the LF SC at 1, 10, 22 and 30 Hz. The method produced an overestimation of SC by approximately 20%, and the variation in LF SC was preserved by approximately 95%. The overestimation is most likely due to different frequency dependence behavior (dispersion) of SC at the lowest frequencies, which is not accounted for by a single dispersion model. In conclusion, the SA method using high frequency is unsuitable for estimation of the LF SC level, but can probably be used in EDA measurements, which are scored based on the variations in SC.

Keywords: estimation of skin conductance at low frequencies, equivalent circuit, electrodermal response

1. Introduction

Skin conductance (SC) is the most popular method for measuring electrodermal activity (EDA), reflecting primarily sudomotor activity and indirectly the sympathetic nervous system activity (Boucsein 2012). The simplicity and non-invasiveness of the method has made it attractive for several uses such as measurement of arousal (Poh *et al* 2010), sweating (Tronstad *et al* 2008), stress assessment (Setz *et al* 2010), assessment of psychiatric disorders (Iacono *et al* 1999, Nilsson *et al* 2006) and pain assessment (Hullett *et al* 2009) among others. The method for measuring SC has been subject to discussion, and a recommendation written by an expert group appointed by the Society for Psychophysiological Research was published in 2012 (Society for Psychophysiological Research 2012). One of the main topics was whether to use direct current (dc) or alternating current (ac) for the measurement. Some advantages with the ac method were highlighted such as circumventing problems of polarization and counter electromotive forces, and that the ac method permits simultaneous recording of skin susceptance and skin potential together with SC. The ac method however imposes one important limitation, which is a limit of the maximum sampling rate (f_s, number of measurements per time) depending on the frequency of the ac current used to stimulate the skin (f_e, excitation frequency) and thereby measure the ac SC. In general, acquiring an f_s above f_e is problematic because at least one whole period of the ac sine wave is needed for both the amplitude and phase response. The sensitivity depth of the ac measurement depends on f_e (Martinsen *et al* 1999) in the way that low-frequency (LF) provide a measurement sensitive to the outermost skin layers such as the stratum corneum, while measurements using higher frequencies (>1000 Hz) reflects mainly the SC of viable skin. Also with increasing frequency, the ac conductance will increase and become more dominating. Since the ac conductance is not influenced by sweating, the sensitivity to SC is reduced. Consequently, the f_e needs to be low in order to pick up sudomotor activity from the sweat ducts which provide electrical shunts through the stratum corneum when the ducts are filled with sweat. Excitation frequencies from 5–30 Hz have been recommended or used for this purpose (Montagu 1973, Society for Psychophysiological Research 2012). At the same time, sampling rates of atleast 20 Hz have been recommended in order to capture all the information in the SC signals (Venables and Christie 1980). Thus, in the worst case, a 20 Hz f_s with a 5 Hz f_e could be desired, but is problematic to realize.

Modern instrumentation allows taking a measurement of electrical admittance (containing the electrical conductance as a real part and electrical susceptance as an imaginary part) at several excitation frequencies simultaneously. When taking an electrical admittance measurement over a wide range of frequencies it is possible to compare the measurement with theoretical models of the electrical properties of the tissue. These models are based on electrically equivalent circuits and can range from a simple resistor-capacitor network in parallel to more complex models including many components and purely mathematical components such as the constant phase element (CPE) (Grimnes and Martinsen 2008). If the measured frequencies cover a large enough range, and the model correctly describes the tissue, it is possible to estimate the electrical admittance between the measured frequencies, and to a certain extent outside of the measured frequency range. In this way, it could be possible to use a multifrequency skin admittance (SA) measurement at higher frequencies (which provide a high sampling rate) in order to estimate the SC at LF (where the sensitivity to sudomotor activity is high). In 1988, Mørkrid and Qiao presented such a method in which the SA model parameters G_0 (conductance at 0 Hz), phase angle (between conductance and susceptance) and the ion relaxation time were estimated from simultaneous measurements at two different frequencies (below 500 Hz) (Mørkrid and Qiao 1988). With modern instrumentation of today, it is possible to measure at many frequencies simultaneously by using a multi frequency

time-domain excitation signal (Min *et al* 2008). This allows for much faster measurements, which means that the change in EDR per sample will be less than with traditional frequency sweep. This paper therefore investigates the possibilities for using multi-frequency measurements together with model approaches using an electrical equivalent circuit model. This equivalent circuit model is designed to mimic the tissue's electrical properties over a single dispersion. In this way we are able to measure SA at high frequencies and estimate SC at low frequencies.

The aim of this study was to assess whether SC at low frequencies can be estimated based on measurements at higher frequencies allowing higher sampling rates.

2. Methods

Generally, both the level and the variations (such as the SC response amplitude during a sudomotor response) of the SC are used in the scoring of EDA (Boucsein 2012). Thus, both the level agreement and the variation preservation between measured and estimated LF SC were assessed. Where measured LF SC is the real part of the measured LF SA, and the estimated LF SC is extrapolated from high frequency SA using the electrical equivalent model. In order to determine how accurately the LF SC levels and variations can be estimated from measured SA at high frequencies, the following general procedure was used:

(i) Gather SA and SC measurements in a selected frequency range from a number of subjects ($N = 20$)
(ii) For each measurement, use a selected high-frequency interval to estimate the parameters of an electrical equivalent model for the skin by means of mathematical curve fitting.
(iii) For each measurement, apply the electrical equivalent circuit with its estimated parameters, to estimate the LF SC, theoretically suitable for EDA measurement.
(iv) In order to determine the accuracy of the SC level estimation, calculate the estimation error by the per cent wise difference between the measured and estimated SC at the selected low frequencies.
(v) In order to determine the preservation of the SC variation, calculate the coefficient of determination (R^2) between the measured SC from all subjects and the estimated SC from all subjects.

2.1. Measurements

The SA measurements were performed on 20 healthy subjects (22–72 years old, 16 males and 4 females) using a Solartron 1260/1294 measurement system with 20 repeated measurements on each subject. For electrodes we used Kendall™ KittyCat™1050NPSM as these have been found reliable for SC measurements in previous studies (Tronstad *et al* 2010). A three electrode setup (Grimnes and Martinsen 2008), with two current carrying electrodes (M and C) and one pick-up electrode (R) (Grimnes 1983) were used for the measurements. The M electrode was placed on the hypothenar, while the C and R electrodes were placed on the underside of the forearm with 7 cm between them, as illustrated in figure 1. Five minutes before the measurement started the electrodes were affixed so that they had time to stabilize. This was also done for the subject to relax in order to obtain steady measurements of SC once the measurement started.

During the measurements the subject was sitting in an armchair. The frequency was then swept from 1 Hz to 70 kHz, for which frequency range the Solartron 1294 has a specified accuracy of 1%. Since this frequency sweep took about 50 s there would be some change in

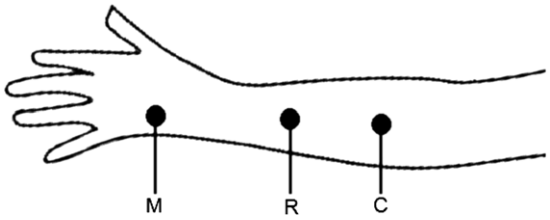

Figure 1. Electrode placement on palm and underside of forearm.

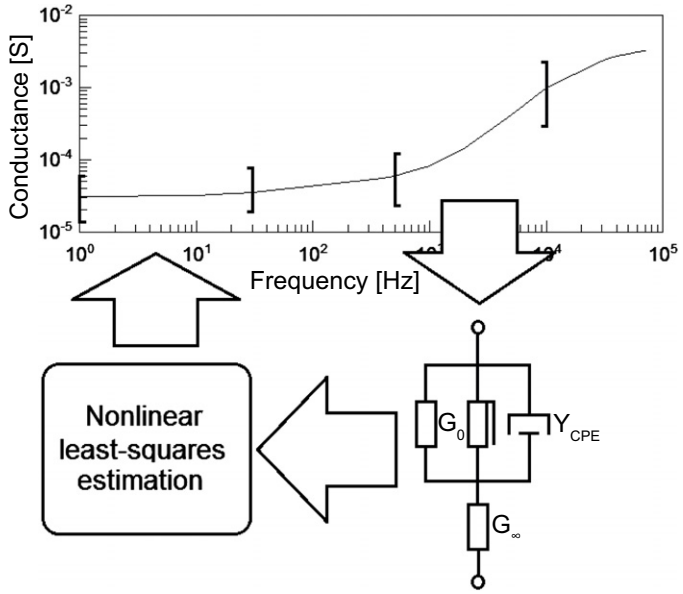

Figure 2. Approach for acquiring SC at low frequencies.

the SC over this time. To compensate for this we used the median value of these 20 repeated measurements for each subject and used these as the subject-specific SA frequency sweep for each subject. From this frequency sweep, the measurement was divided in two intervals: one LF interval with SC at selected frequencies (1, 10, 20, 22 and 30 Hz) as a target reference, and one high-frequency interval (500 Hz to 10 kHz) used for the model curve fitting.

The 500 Hz to 10 kHz was selected since this range cover most of the α-dispersion. The higher fitting limit should for best results not be above the dispersion frequency range, since this frequency range contains very little information about the conductance at low frequencies. The lower fitting limit was chosen so that in a combination with a multi-frequency measurement it would allow for a sampling rate of 50 Hz with measurements over 10 periods.

2.2. Nonlinear least squares estimation

To estimate the SC at low frequencies we have applied a nonlinear least squares estimation on the measured baseline SA between 500 Hz to 10 kHz as shown in figure 2. The model used for the nonlinear least squares estimation was a single Cole circuit. With this equivalent circuit we can then estimate the SC over a single dispersion. It is possible to add two or more Cole

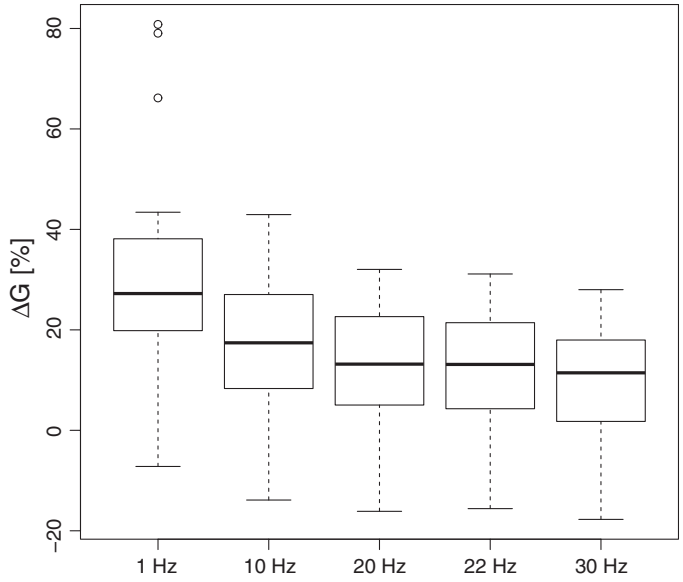

Figure 3. Box plot of the percentage difference between measured and estimated median SC.

circuits in series, but pilot testing showed little effect of this setup when it comes to level agreement between estimated and measured SC at low frequencies.

The admittance for the CPE is given as (Boukamp 1986):

$$Y_{\mathrm{CPE}} = Y_0\,(j\omega)^n \qquad 0 \leqslant n \leqslant 1. \tag{1}$$

Where ω is the angular frequency, Y_0 has the numerical value of the absolute admittance ($|Y|$) at $\omega = 1$ rad s^{-1}, and n then gives the frequency independent phase of the CPE as $-(90 * n)^\circ$. If then $n = 1$ the CPE models an ideal capacitor, while if $n = 0$ the CPE models a pure resistor. We can then make an equation of the admittance for the equivalent circuit:

$$Y = \frac{G_\infty\,(G_0 + Y_0\,(j\omega)^n)}{G_\infty + G_0 + Y_0\,(j\omega)^n}. \tag{2}$$

With this model we can then first estimate the values of G_0, G_∞, Y_0 and n using the nonlinear least squares model and the baseline SA measurements in the dispersion region. When we have estimated the values of the equivalent circuit components we can estimate the SC at the low frequencies, the approach is illustrated in figure 2. For the nonlinear estimation we used Scribner Associates software ZView®, which has a function that enables us to implement the single Cole equivalent circuit and then do the fitting and estimation to the measurement data.

3. Results

All the fittings of measured SA to the equivalent circuit had a residual sum of squares below 0.0067, which indicate a close fit between the measured and fitted SA in the frequency range 500 Hz to 10 kHz.

See figure 3 for box plots of the percentage difference between the measured and estimated median SC for each person. From figure 3 we can see that the percentage difference between measured and estimated SC at 1 Hz varies between −7–43%, with a median percentage difference of 27%. For 1 Hz we can also see three possible outliers with a percentage difference of 66%, 79% and 81%. For 10 Hz, the percentage difference varies between −14–43%, with

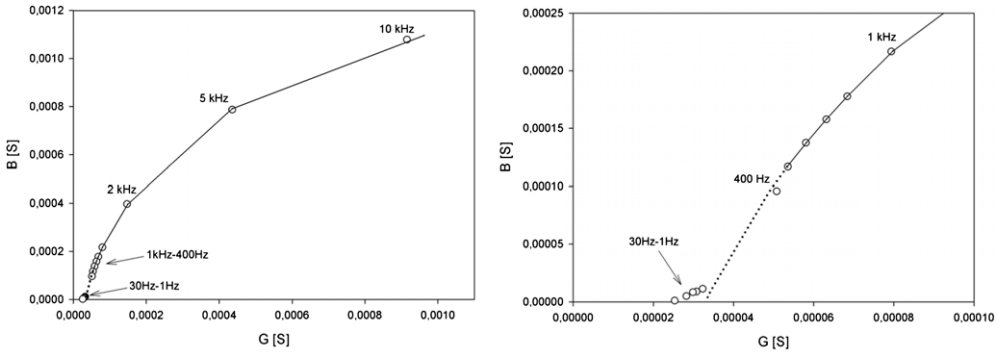

Figure 4. Measured, fitted and estimated SA represented in a Wessel-plot. The mean of all measurements from 1 Hz to 10 kHz (circles) is plotted together with the fitted SA (solid line) by the Cole model, and the estimated LF SA (dotted line). Measurements over the whole fitting and estimation range are shown in (a), and a zoom into the LF is shown in (b) in order to enhance the deviation from the model at the lowest frequencies.

Table 1. Coefficient of determination between the estimated and measured SC for both the median values and for the individual measurements.

Frequency (Hz)	R^2 for median (between subjects)	R^2 for individual (within subjects)
1	0.9461	Mean 0.8829
10	0.9604	Mean 0.9237
20	0.9655	Mean 0.9400
22	0.9668	Mean 0.9517
30	0.9709	Mean 0.9576

a median percentage difference of 17%. For 20 Hz, the percentage difference varies between −16–32%, with a median percentage difference of 13%. For 22 Hz, the percentage difference varies between −15–31%, with a median percentage difference of 13%. For 30 Hz, the percentage difference varies between −11–28%, and with a median percentage difference of 11%. The same trend visible in figure 3 can also be seen on each of the individual measurements.

The coefficient of variation for the measured SC of the 20 individual measurements for each subject varied between 26% and 31% of the mean SC at 30 Hz, while for 500 Hz it varied between 10% and 17%. Most of the changes in measured SA between the 20 measurements seemed to be random, although the measured LF SC for the first measurement was generally a bit higher than the rest of the measurements.

We also wanted to study how well this model and the estimated SC could explain the variation in the measured SC. For this we used the median of the 20 repetitive measurements and estimated SC and we calculated the coefficient of determination, R^2, as shown in table 1. From table 1 we can see that for 1 Hz the single Cole circuit model explain 94% of the variation in the measured SC. For 10 Hz this has increased to 96%. For 30 Hz this has further increased to explain 97% of the variations in the measured SC. The mean values for the individual measurements are a bit lower, most likely caused by the change in SC during the time the measurement took.

The mean of all measured, fitted and LF estimated SA is shown in figure 4, presented in a Wessel plot where the SC is plotted against the skin susceptance. The good fit in the 500 Hz–10 kHz interval is clear from the plot in figure 4(a), indicating that the model described

the tissue well in this frequency range. In figure 4(b), the disagreement between the measured and estimated LF SA clearly shows a pattern of frequency dependence which differs from that of the fitting interval (500 Hz–10 kHz).

4. Discussion

The results show that there was a substantial difference between the estimated and measured SC level at low frequencies, generally as an overestimation of approximately 20%, and decreasing as the frequency goes from 1 to 30 Hz. The variations in SC were preserved by roughly 95% according to the correlation between the estimated and measured between-subjects SC variation.

There could be several possible explanations for the estimation offset. The overestimation is in agreement with (Mørkrid and Qiao 1988) where the estimated zero-frequency SC was higher than the dc-determined zero-frequency SC. The offset could either be due to impedance frequency dependencies in the measurement at low frequencies which are not reflected in the higher frequencies, or due to an error in the fitting of the high-frequency measurements and extrapolation to low frequencies, or a combination of both. Owing to the low fitting error ($SS < 0.0067$), thus it is unlikely that the fitting error can explain the offset.

One cause of LF impedance changes could be electrode polarization, and the fact that the estimated SC was larger than the measured SC supports this explanation, as electrode polarization increases the impedance at low frequencies. If the LF SC estimation represents the SC without this undesired contribution, then this estimation method could provide a better measurement of LF SC. However, taking into account the magnitude of the overestimation in terms of impedance (as electrode polarization lies in series with the skin), the contribution from the electrode impedance of the electrode type used in this study is roughly 1% of the magnitude of the average estimation offset. Hence, the electrode polarization is negligible with respect to explaining the overestimation.

It seems very probable that there are more dispersions within the frequency range of the measurements than the single dispersion that the Cole model in the estimation takes into account. Inspection of figure 4 indicates that there was a beginning of a new dispersion at the lowest frequencies (30–1 Hz) which deviated from the extrapolation based on the Cole model. The frequency range used in these measurements (1 Hz–10 kHz) are mainly covering the α-dispersion (Grimnes and Martinsen 2008), but in some cases more than one α-dispersion may appear (Grimnes and Martinsen 2010). The overestimation of the LF SC could thus be explained by a very LF α-dispersion in the skin. It is problematic to describe this dispersion based on measurements from 500 Hz and above as used in this study, as there is no information on this dispersion at such high frequencies. In addition, the model (equation (2) and figure 2) only describes one dispersion and includes four parameters. A model describing two dispersions for also including the second alpha dispersion would require seven parameters, which greatly increases the changes of large estimation errors due to overfitting. Therefore, it seems reasonable to conclude that a complete estimation of LF SC based on measurements above 500 Hz is not feasible. However, it remains to be discussed whether or not this estimation is suitable for EDA measurements.

EDA measurements can be interpreted in different ways, and there are two main categories used in psychophysiological measurements: phasic and tonic parameters (Boucsein 2012). The phasic parameters represent characteristics of the electrodermal response associated with a reaction, such as the SC response amplitude, while the tonic parameters represent more slowly changing processes, such as the relaxed SC level. Based on the estimation results, the method leads to a considerable error in the SC level, thus the results would probably not be comparable

to studies using conventional methods. The method could however be useful in the assessment of within- or between-subjects variations in SC level, as the LF SC variations were well preserved in the estimation. The main purpose of EDA measurements with high sampling rates is to completely acquire the phasic EDA information such as the latency between a stimulus and the EDR onset or the complete EDR waveform. The SC level is not important in this regard, but the SC variation is. Although the results in this study show a preservation of SC variation between subjects, this also suggests that the variations in SC over time (i.e. phasic EDA) are preserved by the method, unless the intraindividual mechanism for SC changes is so different from the origin of the interindividual variations that they occur at different frequencies. It remains to be seen how well the phasic EDA is preserved by using a realtime implementation of the method using multi-frequency measurements.

In conclusion, we have shown that using high-frequency SA measurements for EDA recording with higher sampling rates leads to a considerable overestimation in SC level, but a good representation of the SC variations using a single-dispersion Cole model.

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