Investigation of the Influence of the Moisture Content of Clothes on Capacitive Electrocardiography

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Abstract

For vital sign monitoring in private spaces, the usage of unobtrusive measurement techniques is desirable to avoid restrictions with respect to free movement of the users. One of these techniques is capacitive electrocardiography (cECG) which instead of adhesive electrodes uses metal electrodes so that a capacitive coupling with the body is achieved through the clothes which reduces the signal-to-noise ratio (SNR). It is known that the relative humidity and thus the moisture content of the worn clothes has a strong influence on the cECG. However, to the best knowledge of the authors, the effects have not been modelled in detail, yet. In this paper, models for the change of permittivity and resistance of textiles with moisture content are used to obtain a range of values for them. Furthermore, a model for the commonly used active electrode is used for simulations with Simscape, such that the influence of the changing properties on the obtained cECG signal can be quantified by means of the SNR. It can be shown that the resistance of the texiles changes from several giga-ohms to several kilo-ohms. Furthermore, it can be seen that while the permittivity of cotton changes over roughly one magnitude (approx. $10\,\mathrm{pF}$ *to* $140\,\mathrm{pF}$*), the permittivity of polyester does not significantly change. From the simulations, it can be seen that the SNR for cotton is generally higher than for polyester and that the SNR rises for higher moisture contents.*

1. Introduction

Capacitive electrocardiography (cECG) refers to an unobtrusive measurement technique that measures the electrocardiogram via a capacitive coupling with the body. For that, instead of adhesive electrodes, simple metal electrodes are brought into contact with the body. For the cECG, no direct skin contact is necessary so that it is usually measured through layers of clothes [1]. Since the coupling with the body is not fixed, movements can lead to motion artifacts. Moreover, since the contact is not conductive, special instrumentation in form of a so-called active electrode is necessary which reduces the signal-to-noise ratio (SNR) [2]. In the past, many systems for cECG were invented trying to overcome the shortcomings of the active electrodes [1]. Besides the electrical circuit design, the textile as well as the weather, i.e. the relative humidity, and the moisture created by transpiration were identified as influencing factors for the signal quality [3] leading to the development of cECG systems with active humidification [3, 4]. However, a detailed model of the change of electrical properties of the textiles with respect to cECG quality were, to the best knowledge of the authors, not researched yet. This knowledge could give crucial insights for the design of cECG systems and may help to make cECG more reliable with respect to its diagnostic value. In this paper, existing models for the active electrode as well as the change of electrical properties of cotton and polyester with respect to their moisture content are combined to investigate the influence on the cECG signal using the Simscape library of Matlab/Simulink. The paper is structured as follows. First, the electrical circuit model for active electrodes is revised. Second, models for permittivity and resistance of textiles with respect to their moisture content are presented. Finally, the models are parametrised and used in simulations to investigate the influence of different moisture contents of the textile on the SNR of a cECG.

2. Method

2.1. Electrical circuit model for cECG

To measure an ECG with a capacitive coupling, a trans-impedance amplifier with very high input impedance is necessary since there is no direct conductive contact to the electrode surface leading to a high coupling impedance. In [2], a model for the active capacitive electrode including triboelectric effects was introduced. An adaptation of the model is shown in Fig. 1 omitting an isolation layer on the electrode surface. U_{in} describes the heart's electrical signal, R_c and C_c are the coupling resistor and capacitor

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due to the clothing, R_{in} and C_{in} describe the input resistor and capacitor of the amplifier and R_g and C_g are the resistor and capacitor from the body to ground. The current source parallel to R_c models triboelectric effects. While designing systems for cECG, usually a trade-off between the cut-off frequency of the high-pass formed by C_c and R_{in} and its time constant need to be made to avoid strong distortion of the cECG morphology while leaving a "fast" discharging path for static charges on the electrode. Thereby, R_c and C_c are dependent on the clothes. C_c can be calculated by

$$C_c = \epsilon_0 \epsilon_r \frac{A}{l}, \tag{1}$$

with ϵ_0 and ϵ_r being the permittivity of air and the clothes, A being the area of the electrode and l being the thickness of the textile.

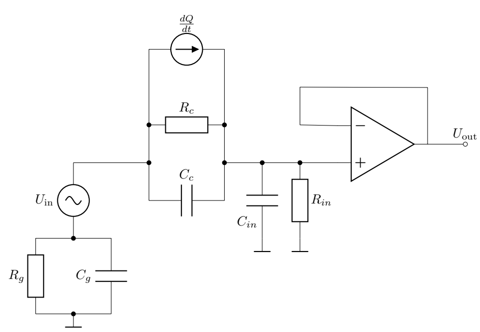

Figure 1. Model for an active electrode adapted from [2].

2.2. Model for the permittivity of textiles

In [5], a model for the electrical permittivity of textile materials with respect to temperature T, angular frequency ω and moisture content M was derived using Landau theory. For the real part of the permittivity it follows

$$\epsilon_r(\omega, T, M) = \epsilon_1 + \frac{1}{u(1 + \frac{\omega^2 v^2}{u^2})} \tag{2}$$

$$u = z - \frac{C_1^2}{A_1^2 + \frac{\omega^2}{\Gamma_1^2}} \tag{3}$$

$$v = \frac{1}{\Gamma_2} + \frac{C_1^2}{\Gamma_1[A_1^2 + \frac{\omega^2}{\Gamma_1^2}]} \tag{4}$$

$$z = \frac{1}{2\chi_0} - \frac{1}{2}\gamma\psi_0 \tag{5}$$

$$A_1 = A - B\psi_0 + \frac{3}{2}C\psi_0^2 \tag{6}$$

$$C_1 = \gamma P_0 \tag{7}$$

$$A = a(T - M - T^*), \tag{8}$$

where a, B, C and γ are Landau coefficients, Γ_1 and Γ_2 are kinetic coefficients, χ_0 is the dielectric susceptibility, ϵ_1 is the electronic permittivity and P_0 and ψ_0 are the polarisation and crystal order parameter at equilibrium respectively. The authors [5] further introduced a similar model for a mixture of water and polyester using the volume fraction of water $1 - \Phi$ and polyester Φ

$$\epsilon_r^p(\omega, T, \Phi) = \frac{1}{u_1(1 + \frac{\omega^2 v_1^2}{u_1^2})} \tag{9}$$

$$u_1 = z_1 - \frac{c_1^2}{a_1^2 + \frac{\omega^2}{\Gamma_1^2}} \tag{10}$$

$$v_1 = \frac{1}{\Gamma_2} + \frac{c_1^2}{\Gamma_1[a_1^2 + \frac{\omega^2}{\Gamma_1^2}]} \tag{11}$$

$$z_1 = \frac{1}{2\chi_0} - \frac{1}{2}\gamma\Phi\psi_0 \tag{12}$$

$$a_1 = a(T - (1 - \Phi)T^*) - B\psi_0 + \frac{3}{2}C\psi_0 \tag{13}$$

$$c_1 = \gamma\Phi P_0. \tag{14}$$

2.3. Model for the electrical resistance of textiles

According to Morton et al. [6], the resistance R of textiles with respect to the moisture content or relative humidity can be modelled by

$$\log_{10}\mathrm{R_s} = -n \cdot \log_{10}\mathrm{M} + \log_{10}\mathrm{K} \tag{15}$$

$$\log_{10}\mathrm{R_s} = -a \cdot RH + b \tag{16}$$

$$R = \rho \cdot \frac{l}{A} = \frac{R_s}{d} \cdot \frac{l}{A}, \tag{17}$$

with R_s being the mass-specific resistance in $[\frac{\Omega g}{\text{cm}^2}]$, n, K, a and b being constants, ρ being the electrical resistivity and d being the density of the material.

2.4. Parameter fitting

2.4.1. Permittivity

The model of [5] was validated using various recorded data of the permittivity with respect moisture content, temperature and frequency in [7] . Fig. 5 and Fig. 9 of [7] were reproduced to determine the unpublished parameters (temperature and supercooled temperature). The complete parameter list can be found in Tab. 1.

2.4.2. Resistance

In [6], the parameters n and $\log_{10} K$ for cotton were already determined to be 11.4 and 16.7 respectively. For (terylene) polyester the curve from Fig. 29 of [8] had to be

Table 1. Fitted parameters for permittivity models.

Fibre	C_1/c_1	z/z_1	ϵ_1	Γ_1 [Hz^{-1}]	Γ_2 [Hz^{-1}]	a	$B\psi_0 - \frac{3}{2}C\psi_0^2$	f [Hz]	T [°C]	$T*$ [°C]
cotton	23.36	2.01	0.02	2210.07e3	2286.69e3	0.1	-14.7	1000	21	-6
polyester	0.74	0.72	-	3350.05e9	4372.14e9	0.005	0.831	9.8e9	-35	0.5

used to determine a and b graphically, so that it followed $a \approx \frac{27}{400}$ and $b \approx 12.7$. Furthermore, the dependency between the relative humidity and the regain RG and the regain and moisture content was used to determine the resistance with respect to the moisture content. For that a graph (RG to RH) from [9] was used. Furthermore, the regain and moisture content depend on each other with

$$M = \frac{100RG}{RG + 100}. \tag{18}$$

2.5. Simulation of electrode model

The model of Fig. 1 was implemented in Matlab/ Simulinks' Simscape library without the current source. The input ECG signal is simulated using the synthesiser of [10] using a controlled voltage source. C_{in} and R_{in} as well as the voltage noise of the amplifier were modelled using a standard precision amplifier (OPA140, Texas Instruments), i.e. $C_{\text{in}} = 10pF$ $R_{\text{in}} = 10G\Omega$ and $V_{\text{noise}} = 5.1\frac{nV}{\sqrt{Hz}}$. For R_g and C_g, $10\,\mathrm{M\Omega}$ and $200\,\mathrm{pF}$ were chosen, respectively [2].

3. Results

To investigate the influence of the moisture content of the textiles cotton and polyester with respect to the signal quality of the measured cECG three steps were performed. First, meaningful moisture contents for the fibres with respect to the relative humidity were obtained. Second, the resulting permittivity, capacity and resistance were calculated using the previously described models. Finally, the simulations with Simscape were performed for different relative humidities. According to [11], the relative humidity in Europe inside and outside the house lies between $30\,\%$ and $90\,\%$. Using the data of [12] for cotton and [9] for polyester, this leads to moisture contents between $3\,\%$ to $15\,\%$ and $0.24\,\%$ and $0.92\,\%$ for cotton and polyester respectively using linear interpolation. The resulting ϵ_r and R_s are shown in Tab. 2. The fabrics were assumed to be $2\,\mathrm{mm}$ thick. The density of cotton and polyester were assumed to be $d_{\text{cotton}} = 1.535\mathrm{g\,cm^{-3}}$ and $d_{\text{polyester}} = 1.39\mathrm{g\,cm^{-3}}$ [6]. It is visible that the permittivity of polyester does not change significantly with higher moisture contents which is in line with the literature [13]. In contrast, the permittivity of cotton changes roughly one magnitude. Furthermore, it is visible that the $R_{S,\text{cotton}}$ is roughly one magnitude lower than $R_{S,\text{polyester}}$. The resulting resistance changes over several magnitudes from several giga-ohms to several kilo-ohms. For the simulations, three different sizes (small: $3.14\,\mathrm{cm^2}$, medium: $16\,\mathrm{cm^2}$, large: $44.89\,\mathrm{cm^2}$) for the electrode surface area were selected from the literature [14–16] and the resulting capacity and resistance were calculated using Eq. 1 and Eq. 17. The signals are compared using a measure analogue to the SNR

Table 2. ϵ_r and R_s for cotton and polyester w.r.t. the relative humidity. The values of R_s are given in [$\frac{\Omega g}{cm^2}$].

RH [%]	30	50	70	90
M_{cotton} [%]	3.56	5.07	6.97	8.49
$M_{\text{polyester}}$ [%]	0.22	0.35	0.48	0.58
$\epsilon_{r,\text{cotton}}$	7.58	10.16	18.11	139.7
$\epsilon_{r,\text{polyester}}$	5.42	5.43	5.45	5.48
$R_{s,\text{cotton}}$	2.1e10	3.7e8	9.7e6	4.9e4
$R_{s,\text{polyester}}$	4.7e10	2.1e9	9.4e7	4.2e6

$$\text{SNR} = \frac{\sum \text{ECG}_{\text{in}}^2}{\sum(\text{ECG}_{\text{in}} - \text{ECG}_{\text{out}})^2}. \tag{19}$$

In Tab. 3 and Tab. 4, the SNR for the simulations for cotton and polyester are shown. It is visible that the SNR improves with rising relative humidity and thus with rising moisture content. Furthermore, it can be seen that the SNR for cotton is generally higher than the SNR for polyester with respect to the same area and same relative humidity. The highest SNRs were achieved with the largest size electrode at $90\,\%$ relative humidity. A proper ECG morphology was only visible for SNRs approx. larger than $7\,\mathrm{dB}$, while R-peak were visible already for SNRs larger than $2\,\mathrm{dB}$ and $0\,\mathrm{dB}$ for cotton and polyester respectively.

Table 3. SNR in [dB] for simulation for cotton.

Area [cm^2]/RH [%]	30	50	70	90
3.14	-5.64	1.34	9.05	9.76
16	2.47	7.94	9.67	17.95
44.89	7.28	9.27	9.73	18.14

Table 4. SNR in $[\mathrm{dB}]$ for simulation for polyester.

Area $[\mathrm{cm}^2]$/RH [%]	30	50	70	90
3.14	-6.91	-4.61	4.03	9.42
16	0.37	3.69	8.66	9.31
44.89	5.83	7.79	9.46	12.36

4. Discussion and conclusion

Even though the model exhibits the expected behaviour which are in line with the literature, some limitations of the results exist. First, as can be seen by the models for the permittivity, it is not only dependent on the moisture content but also on the frequency and temperature. Especially for the permittivity of polyester, the frequency for which it was measured was rather high ($9.8\,\mathrm{GHz}$). However, other publications [13] have shown that the values do not differ by much. Second, the resistance of textile fibres is usually measured along the fibre so that slight differences with respect to a patch of woven textile is conceivable. However, it is assumed that the fibres are sufficiently isotropic. Finally, the effect of transpiration could not be investigated, especially for polyester, since the measurement data is missing. Therefore, measurements in a cECG mock-up should be performed in the future to further validate the model and collect the missing data. First investigations in a lab setting with humans was performed in [17] confirming the general range of resistance values. Nonetheless, in this paper it could be shown that it is possible to model the influence on the cECG quality with respect to changes of the permittivity and resistance of textile due to changing moisture contents and that insights important for the design of cECG systems for different environments can be gained.

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