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A FAST METHOD TO ESTIMATE BODY CAPACITANCE TO GROUND

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Abstract: This paper describes a method to estimate the capacitance between the human body and earth ground that is based on an impedance analyzer intended to measure ungrounded impedances. The method does not need any external components other than two common resistors, works in the 10 kHz to 1 MHz frequency range, and can be applied to other grounded impedances.

Keywords: Body capacitance, bioimpedance, impedance analyzer.

1. INTRODUCTION

The capacitance between the human body and earth ground plays an important role in several measurement systems. When measuring bioelectric signals, for example, the capacitance between the body and ground has a major effect on power-line interference [1]-[3]. The mutual capacitance of electric wiring and humans has also been studied for proximity sensing systems based on existing electrical infrastructure in buildings [4], through the variation of the output frequency of *RC* oscillators. Artifacts due to the stray capacitance between the body and ground have long been suspected to affect bioimpedance measurements above 100 kHz [5], [6]. This effect has been recently confirmed by suitable models and measurements [7]. Stray capacitance to ground must also be considered when measuring body impedance in the context of electromagnetic hazard analysis [8] [9].

To assess the value of the body capacitance to ground, and also that between the body and the electrical wiring in a building, a simple method based on a (grounded) oscilloscope and a voltage divider probe was proposed in [1] and applied to subjects lying on a bed with an earth-grounded frame, and to standing people in different scenarios [2]. An alternative method based on the same principle but using a variable resistor, an amplifier, and a (grounded) digital multimeter produced similar values for those capacitances [3]. The coupling between power lines and the body provided the "input" 50/60 Hz signal, and the two capacitances were calculated by solving the system equation that describes the output voltage for two different resistor values connected between the body and earth ground. These methods, however, cannot be easily applied to measuring the capacitance between the body and ground at higher frequencies, such as those used in bioimpedance measurement (10 kHz-1MHz). Here we propose a method that only needs a commercial impedance analyzer and two known resistors.

2. MEASUREMENT METHOD

Most common commercial impedance analyzers cannot measure grounded impedances [10]. Hence, we propose the network in Fig. 1 as a "measurement fixture" that consists of two series-connected known resistors R_1 and R_2 to whose common node the body is connected by an electrode (impedance Z_e). The impedance analyzer measures the impedance between nodes H and L. The body is assumed to have impedance Z_b and its capacitance to ground is C_b.

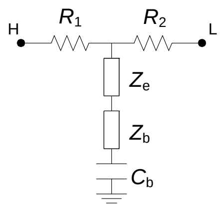

Fig. 1 Measurement fixture to measure a grounded impedance

Using a wye-delta transformation, the equivalent impedance Z_{HL} between the measurement terminals is

$$Z_{\mathrm{HL}} = R_1 + R_2 + \frac{R_1 R_2}{Z_{\mathrm{e}} + Z_{\mathrm{b}} + \dfrac{1}{j\omega C_{\mathrm{b}}}} \tag{1}$$

Hence, the measured impedance includes C_b, but also electrode and body impedance. These two impedances can be modeled as $Z_e + Z_b \approx R_0 + 1/j\omega C_0$, with both R_0 and C_0 dependent on the frequency, so we have

$$Z_{\mathrm{HL}} = R_1 + R_2 + \frac{R_1 R_2}{R_0 + \dfrac{1}{j\omega C_0} + \dfrac{1}{j\omega C_{\mathrm{b}}}} \tag{2}$$

If C_b (60 pF-500 pF) [8] is much smaller than C_0, we can rearrange (2) to obtain the real and imaginary parts of Z_{HL},

$$Z_{\mathrm{HL}} = R_1 + R_2 + \frac{\omega^2 R_0 R_1 R_2 C_{\mathrm{g}}^2}{1+\left(\omega R_0 C_{\mathrm{b}}\right)^2} + j\frac{\omega R_1 R_2 C_{\mathrm{g}}}{1+\left(\omega R_0 C_{\mathrm{b}}\right)^2} \tag{3}$$

At frequencies below 1 MHz, and because R_0 can be less than 1 kΩ, R_1 and R_2 can be selected to fulfill the conditions

$$\left(\omega C_{\mathrm{b}} R_0\right)^2 << 1 \tag{4}$$

$$\left(\omega C_{\mathrm{b}}\right)^2 R_0 \frac{R_1 R_2}{R_1 + R_2} << 1 \tag{5}$$

so that the measured impedance reduces to

$$Z_{\mathrm{HL}} \approx R_1 + R_2 + j\omega R_1 R_2 C_{\mathrm{b}} \tag{6}$$

Hence it depends only on R_1, R_2, and C_{b}. These approximations are valid whenever the impedance of the capacitance to ground is much larger than that of the electrode plus that of the body. In this case, C_{b} can be calculated from the imaginary part of Z_{HL} as

$$C_{\mathrm{b}} \approx \frac{\operatorname{Im} Z_{\mathrm{HL}}}{\omega R_1 R_2} \tag{7}$$

The fact that, when the approximations hold true, the real part of Z_{HL} depends only on the two known resistors permits us to check to what extent the assumptions that lead from (2) to (6) are acceptable.

3. EXPERIMENTAL DESIGN

We have measured the capacitance to ground from 10 kHz to 1 MHz for two subjects (#1: 1.90 m, 130 kg; #2: 1.80 m, 80 kg). R_1 and R_2 were first two commercial 1 kΩ resistors, 1 % tolerance, whose measured values at 100 kHz were $R_1 = 997.6\ \Omega \pm 1.0\ \Omega$ and $R_2 = 998.4\ \Omega \pm 1.0\ \Omega$. In a second set of measurements, R_1 was the same but R_2 was $99.7\ \Omega \pm 0.1\ \Omega$. The impedance analyzer was model 4294A from Agilent. To assess the effect of electrode-skin impedance, two types of electrodes and sites were tested. First, a brass electrode (area 4.9 cm^2) with conductive ECB gel was attached to the inner side of the right forearm, as shown in figure 2. A braided tinned copper strap connected the electrode to the node common to R_1 and R_2. The overall connection was 14 cm long. Second, a pre-gelled electrode (Skintact R-34, AquaTac gel) was connected to the back of the right hand. A spring clip and a braided tinned copper strap connected the electrode to the node common to R_1 and R_2. The overall connection was 9.5 cm long.

Fig. 2 Measurement of the impedance to ground for subject #1 when connected by a metal electrode and conductive ECB gel

Subjects were seated on an office chair built from reinforced plastic and without any major metallic parts. The arm with the electrode rested on the wooden bench where the impedance analyzer was placed. Nearby electronic equipment were grounded but other metallic objects such as filing cabinets were not grounded. Two measurement series were performed for each subject: first with their feet (with shoes) resting on the floor, and then with their feet raised about 10 cm from ground. It was expected that the distance from feet to ground largely affected the value of *Cb*.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Solid lines in Fig. 3 show the real part of Z_{HL} from 10 kHz to 1 MHz for subject #1, metal electrode and 1 kΩ resistors. From (6), the result should be about 2000 Ω and independent from the frequency. However, the measured real part increases with increasing frequency: at 100 kHz, it increases from 2000 Ω (raised feet) to 2005 Ω when the feet rest on ground; at 1 MHz, the change is from 2075 Ω to 2214 Ω. This means that perhaps the condition in (5) is not fulfilled above 100 kHz for $R_1 = R_2 = 1$ kΩ. In fact, when C_{b} increases (feet on ground) the real part starts to increase at frequencies smaller than those when C_{b} is smaller; this is agreement with the condition in (5), which is more difficult to fulfill when C_{b} is larger.

For subject #1, the body capacitance to ground calculated from (7) and when using the same electrode and R_1 and R_2 values, is shown in Fig. 4 (solid lines). When the feet are at 10 cm above ground, C_{b} is about 100 pF. When the feet rest on ground, hence C_{b} is larger, the calculated value decreases from 152 pF at 100 kHz to 139 pF at 1 MHz. These values are similar to those measured at 50 Hz [2] [3]. This dependency of C_{b} on the frequency suggests that perhaps the approximations leading to (7) are not valid. First, to move from (2) to (3), it has been assumed that $C_0 >> C_{\mathrm{b}}$; later, to simplify (3) into (6), it has been assumed that condition (4) was fulfilled. Hence we need an estimate of R_0 and C_0 to assess the validity of the approximations and to properly select R_1 and R_2.

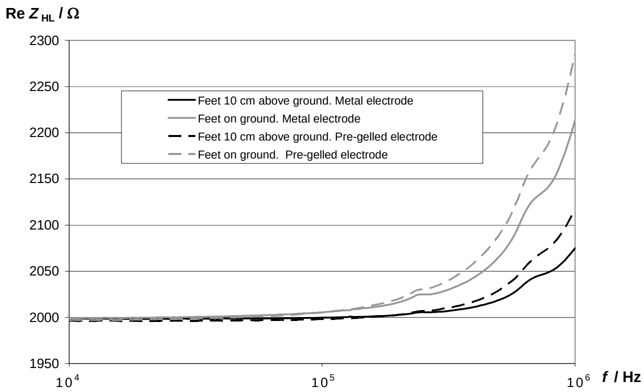

Fig. 3 Real part of the impedance for subject #1 with $R_1 = R_2 = 1$ kΩ and a metal electrode (solid lines), as shown in Fig. 2, or a pre-gelled electrode (dashed lines)

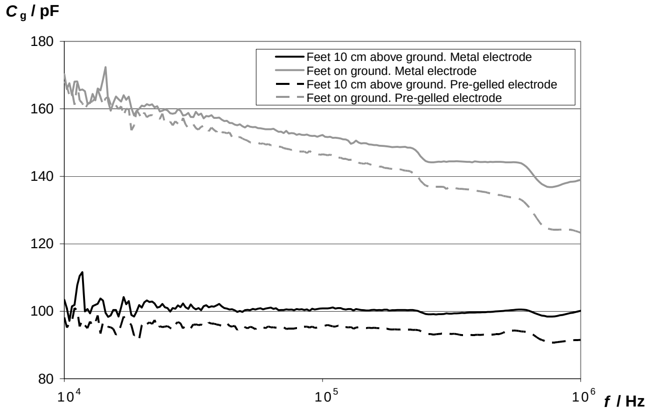

Fig. 4 Body to ground capacitance for subject #1, calculated from (7) with $R_1 = R_2 = 1$ kΩ and a metal electrode (solid lines), as shown in Fig. 2, or a pre-gelled electrode (dashed lines)

To corroborate the results above, subject #1 was measured again but with a pre-gelled ECB electrode connected to the back of the right hand, and the arm was perpendicular to the front panel of the spectrum analyzer. The results, shown as dashed lines in Figs. 3 and 4, were worse in the sense that the real part of Z_{HL} starts to increase below 100 kHz, and the larger C_b, the earlier the increase. As for the C_b value calculated from (7), the same frequency dependence found when using a (dry) metal electrode is observed.

Measurements on subject #2 with a pre-gelled ECB electrode and the same connection to the same R_1 and R_2 resistors confirmed the frequency dependencies shown in Figs. 3 and 4. However, as expected from the smaller body size of this subject, C_b values were smaller: 81 pF (raised feet) and 116 pF (feet on ground) at 100 kHz, and 78 pF and 100 pF respectively, at 1 MHz.

To estimate R_0 and C_0, the same approach in Fig. 1 can be used, but connecting the body also to ground ($C_b \rightarrow \infty$). This condition can be achieved by touching earth ground with the hand that is not connected to the R_1-R_2 node. The measured impedance is then

$$Z_{HL0} = R_1 + R_2 + \frac{j\omega R_1 R_2 C_0}{1 + j\omega C_0 R_0} \qquad (8)$$

and R_0 and C_0 can be calculated from the real and imaginary parts of the measured impedance.

Using this approach, the respective values at 10 kHz, 100 kHz and 1 MHz were 499 Ω, 363 Ω, and 308 Ω for R_0, and 62 nF, 20 nF, and 3.8 nF for C_0. Therefore, both R_0 and C_0 depend on frequency. Nevertheless, for the larger C_b value (150 pF) and 1 MHz, which are worst-case conditions, the assumption $C_b << C_0$ was correct. However, for $R_0 = 500\ \Omega$ and $R_1||R_2 = 500\ \Omega$, $(\omega C_b R_0)^2 = (\omega C_b)^2 R_0 (R_1||R_2)$ equals 0.002 at 100 kHz and 0.22 at 1 MHz. Therefore, conditions (4) and (5) are fulfilled at 100 kHz but not at 1 MHz, as suspected from the frequency dependence of the measured real part of Z_{HL}.

Condition (4) is independent from R_1 and R_2 but condition (5) can be fulfilled by reducing $R_1||R_2$. If, for example, we select $R_2 = 100\ \Omega$ and keep R_1 =1 kΩ, then $R_1||R_2 = 91\ \Omega$ and condition (5) is fulfilled even at 1 MHz. Measuring subject #1 when using the new R_2 value yielded the results in Figs. 5 and 6. The real part of Z_{HL} is less dependent on frequency: at 100 kHz it increases from 1098 Ω to 1099 Ω when C_b increases by placing the feet on ground, whereas at 1 MHz it increases from 1106 Ω to 1119 Ω. This is in contrast with the 5 Ω and 139 Ω increments at the same frequencies when $R_2 = 1$ kΩ (Fig. 3).

Fig. 6 shows that when the feet rest on ground, the calculated C_b value increases from 102 pF to 150 pF at 100 kHz and from 101 pF to 138 pF at 1 MHz. Hence, for $C_b \approx 100$ pF, the calculated value is the same regardless of whether R_2 is 1 kΩ or 100 Ω. However, when C_b is larger, the dependency of the calculated value on the frequency is far smaller for $R_2 = 100\ \Omega$ (Fig. 6) than for 1 kΩ (Fig. 4). Nevertheless, this dependence of C_b on de frequency cannot be easily explained from the circuit model used.

Results for subject #2, connected with a metal electrode, and $R_2 = 100\ \Omega$ showed similar trends. The real part of Z_{HL} remained constant (1098 Ω) at 100 kHz when the feet were on ground, whereas at 1 MHz it increased from 1105 Ω to 1113 Ω. The C_b value calculated from (7) increased from 89 pF to 120 pF at 100 kHz, and from 87 pF to 115 pF at 1 MHz. The smaller C_b value as compared to that of subject #1 resulted in similar increments at 100 kHz and 1 MHz.

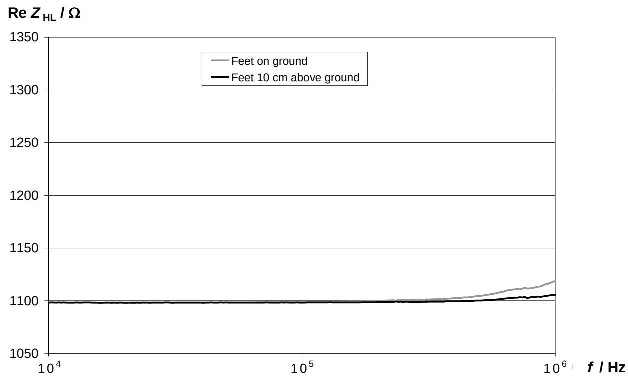

Fig. 5 Real part of the impedance for subject #1 with $R_1 = 1$ kΩ and $R_2 = 100\ \Omega$, and a metal electrode

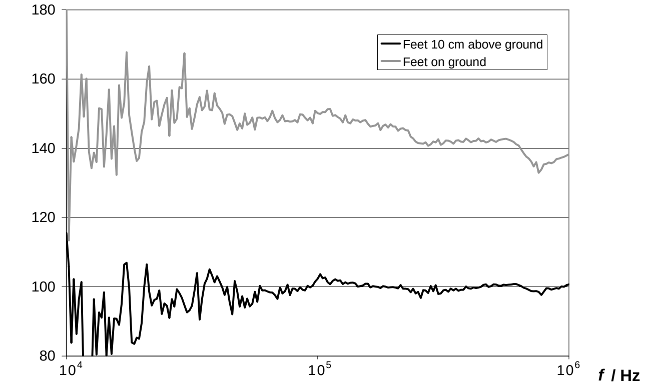

Fig. 6 Body to ground capacitance for subject #1, calculated from (7), with $R_1 = 1$ kΩ and $R_2 = 100\ \Omega$, and a metal electrode

These results indicate that the proposed measurement method works better for capacitances whose impedance is much smaller than that of the body plus the electrode (R_0, C_0) used to connect it. This can be further corroborated by gently pressing the electrode: the real part of Z_{HL} decreases and becomes almost constant from 10 kHz to 1 MHz. Because the impedance of the body plus the electrode is less dependent on the frequency than C_b, the method would not work above 1 MHz. In addition, above 1 MHz there are resonances, probably because of stray inductance of connecting straps.

On the other hand, calculated C_b values when R_2 = 100 Ω are noisier than those obtained when R_2 = 1 kΩ. This is a consequence of the measurement method. The impedance analyzer applies a voltage between node H and signal ground and somehow measures the current exiting from node L. The arrangement in Fig. 1 implies that the higher the frequency, the larger is the intensity of the current that flows to earth ground through the body, and therefore does not reach node L. The reduced current in L is interpreted as impedance that increases with frequency, i.e. the stray inductance term in (6). In [7], this effect was demonstrated to be one source of unexpected inductive terms and positive phases in bioimpedance measurements. Here we use it to estimate that parasitic "inductance". But the limited ability of the instrument to distinguish small reactive components in front of large resistive components, limits the amount of "disappearing" current that can be detected. At low frequency, the impedance of C_b is larger and only a relatively small amount of current will flow through it, which cannot be perceived as "missing" current at L. Because of the same reason, R_1 and R_2 are not interchangeable. In fact, attempts to use R_1 = 100 Ω and R_2 = 1 kΩ yielded erratic results.

Another factor that influences the results is the closeness of conductive objects, grounded or not. For example, when using a metal electrode, the subject's arm was parallel to the front panel of the impedance analyzer (Fig. 2), whereas when a pre-gelled electrode was connected to the hand, the arm was almost perpendicular to that front panel. In Fig. 4, C_b is smaller in this second case. In addition, any movement during the measurement is reflected in the result; for example, in Fig. 4, the larger peaks for C_b close to 10 kHz reflect the pressing of a key of the keyboard used to control the instruments. Further, any movement of an assistant close to the subject being measured also reflected in a slightly different C_b value.

Finally, in spite of the limited bandwidth where this method can be applied, the simultaneous measurement of the real part helps to assess whether the approximations assumed in the calculation procedure are valid or not.

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