Use of electrocardiogram (ECG) electrodes for Bioelectrical Impedance Analysis (BIA)

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Abstract: BIA is a safe, noninvasive, portable and relatively inexpensive method of estimating body composition that is practical and suitable for individual use and large-scale studies. However, the cost of the electrodes recommended by some BIA manufacturers is too high for developing countries; where very often the long and complicated process of importation reduces the time they can be used. The purpose of this study was to evaluate the use of two types of ECG electrodes (2290 and 2228 by 3M®) in BIA measurements to decrease the costs of the test. The results showed that the 2228 ECG electrodes can be used in BIA measurements for adult’s body composition assessment. These electrodes are available in the domestic market and their costs are 92% lower than the electrodes recommended by manufacturer. The results show a new cost-benefit relation for BIA method and make this a more accessible tool for individual tests, large-scale researches and studies in the community.

1. Introduction
According to WHO, the global prevalence of overweight and obesity in adults in 2008 was 30%, with a projection of reaching 43% by 2015 [1]. Colombia's situation is even worse as 51% of adults are overweight or obese [2]. There are several methods to determine body composition but greater precision and accuracy require a greater complexity and higher costs. Total body water by isotope dilution, hydrodensitometry, magnetic resonance imaging (MRI) and computerized tomography (CT) provide precise and reliable measurements of body composition and can be considered as reference methods for in vivo measurements. However, cost, accessibility, complexity and the radiation exposure with MRI and CT limit the use of these techniques [3,4]. Recently, dual-energy X-ray absorptiometry (DEXA) has become an attractive alternative method; nevertheless, all methods described above are poorly accessible for large-scale research in the community [4]. BIA is based on measuring tissue conductivity and the relation between the volume of conductor and its electrical impedance applied in the study of human body composition [5]. BIA is a simple, safe, noninvasive, relatively inexpensive method that is practical and suitable for individual use, large-scale researches and field studies in the community. [6]. However, the cost of the electrodes recommended by some manufacturers of bioimpedance analyzers is high to disseminate the use of BIA in developing countries, where usually the long and complicated process of importation reduces the time they can be used. The purpose of this study was to evaluate the use of two types of ECG electrodes in BIA measurements to reduce the costs of the test.
2. Materials and methods

2.1. Subjects

The methods, classified as minimum risk by the Colombian Ministry of Health, were approved by the Bioethics Committee of the University of Caldas. Variations in body composition related to gender, age, ethnicity and genetic influence that affect BIA measurements [7] were minimized by using an adequate measurement protocol and selecting a homogeneous group of young adult females from a specific region in Colombia [1,8]. A sample of 12 young adult females of the University of Caldas (Colombia) was evaluated. The purpose and procedures of the study were explained to the volunteers and the inclusion/exclusion criteria were verified after completing a questionnaire. Afterwards, the volunteers signed an informed written consent. Inclusion criteria were to be female, aged between 18 and 24 years, with body mass index (BMI) between 18.5 and 29.9 kg/m$^2$ and without co-morbidities. Exclusion criteria were smoking, having any metal implant (including copper T) or a cardiac pacemaker, be pregnant, using diuretics, had undergone surgery for weight reduction or had silicone implants in the breasts. Subject’s characteristics are shown in table 1.

| Variables                  | Mean | SD  |
|----------------------------|------|-----|
| Age (years)                | 21.7 | 4.05|
| Height (cm)                | 157.5| 6.06|
| Weight (kg)                | 56.9 | 7.45|
| BMI (kg/m$^2$)             | 23.5 | 4.87|
| Hand electrodes distance (cm)| 8.5  | 0.78|
| Foot electrodes distance (cm)| 12.7 | 1.09|

2.2. Data acquisition

Measurements were performed in one session early in the morning to minimize environmental [9] and biological [7] variations. Relative humidity and environment temperature were controlled with an electric heater (BFH416 by Bionaire$^{TM}$) and a dehumidifier (BMD100 by Bionaire$^{TM}$). Relative humidity (RH) (73.5 ± 1.9%) and environmental temperature (18.8 ± 0.7 °C) were measured with a thermo-hygrometer (13307 by DeltaTrak$^{®}$, ±0.1 °C / ±1% RH) and atmospheric pressure (787.4 ± 0.6 mmHg) was measured with a barometer (K4 by Konustar$^{®}$, ±0.1 mmHg). Volunteers were asked to comply with the following requirements before the test: 48 hours of not drink alcohol, 12 hours of not exercising vigorously and 12 hours of fasting but keeping normal water hydration. All were asked to evacuate her bladder and colon 30 minutes before the test and all wore underwear and a hospital gown during the test. All volunteers were evaluated out of menstrual cycle [8,10,11]. Other possible sources of error like hydration status, subject position, limb abduction, electrode position, wearing jewellery and skin alcohol use, were also controlled in this study [8,10,11,12].

2.3. Anthropometric measurements

Height (S) (Heightronic-235 by Seca$^{®}$, ±0.01 cm) and weight (W) (PP2000 by Icob-Detecto$^{®}$, ±0.1 kg) were measured twice, and a third measurement was taken if it was found a difference greater than 0.5 cm or 0.1 kg respectively [13].

2.4. BIA measurements

Bioelectrical impedance was measured (Hydra 4200 by Xitron Technologies$^{®}$) on the dominant side of body for three times at the end of an exhalation on a nonconductive surface. Raw resistance (R), capacitive reactance (Xc) and impedance (Z) data were stored in a computer [14,15]. Subjects remained in a supine position by 5 minutes and BIA measurements were made between minutes 6 to 10, with the arms comfortably separated from the body 15 degrees, and the legs comfortably separated about 45 degrees (Figure 1) [8,16]. Dorsal hand and anterior foot surfaces were cleaned with alcohol
and dried with a paper towel [8]. For reproducible measurements, four landmarks were made for the placement of the electrodes: midline between prominent ends of radius and ulna of wrist, midline of third metacarpal-phalangeal joint on dorsal hand surface, midline between the medial and lateral malleolus of ankle and midline of third metatarsal-phalangeal joint on anterior surface of foot [8,16]. Current was applied at distal electrodes and voltage was measured at proximal electrodes (Figure 2) [8,16]. Minimum distance between current and voltage electrodes must be 5 cm [8]; and this condition was met with all participants in this study. A blanket was used for comfort and homogeneous skin temperature [8,17].

Results obtained with two types of ECG electrodes (2290 and 2228 by 3M®) were compared to the results obtained with the electrodes (292-STE by Impedimed®) recommended by manufacturer. The 292-STE electrodes were used as the reference BIA measurement. Table 2 shows some characteristics of the three different types of electrodes tested in this study.

| Electrode | Image | Use  | Backing       | Gel         | Skin sensor contact area (cm²) | Cost (c) (US$) |
|-----------|-------|------|---------------|-------------|-------------------------------|----------------|
| 292-STE   | BIA   | Printed film<sup>a</sup> | Solid adhesive<sup>b</sup> | 5.75 | 6.0                      |
| 2290      | ECG   | Micropore | Dried      | 2.55 | 0.75                     |
| 2228      | ECG   | Foam sticky | Wet       | 3.14 | 0.50                     |

<sup>a</sup>Latex free  <sup>b</sup>Impedimed® proprietary  <sup>c</sup>Cost for testing in one person (four electrodes)

The 12 subjects were divided into three groups (A, B and C) of 4 individuals each. The measurement protocol used for each type of electrode is shown in figure 3 [8, 16]. A variation in the order of using the reference electrodes was made to evaluate BIA variations generated by test time and change in position of subjects (figure 4) [8]. Biological BIA variation by change of subject position and time of the tests was controlled adopting a stand position to restore the distribution of the body liquids between measurements with different types of electrodes [6,8].
2.5. Statistical methods

The mean and the standard deviation (SD) were used to evaluate the characteristics of subjects and laboratory conditions. The paired Student’s t-test ($p<0.01$) and the graphical method of Bland and Altman were used to evaluate the significant differences in all measurements [18].

Low and high frequencies were represented by 5 and 500 kHz respectively. Raw data (R, Xc and Z) at 5 and 500 kHz were analyzed to determine the effect of changing the order of using the reference electrodes. Raw data, model data (extracellular resistance $R_{ec}$, intracellular resistance $R_{ic}$, capacitance $C$ and infinite resistance $R_{inf}$), volume data (extracellular water $ECW$ and intracellular water $ICW$) and body composition data (fat-free mass $FFM$, body fat $BF$ and percent body fat $\%BF$) were analyzed to determine significant differences between electrodes. The 292-STE Impedimed© electrodes were used as the reference BIA measurement. Fat-free mass (FFM) was calculated with the equation (1) [16]. Body fat (BF) was obtained by subtracting FFM from total body mass (W). Percent body fat ($\%BF$) was calculated with $(BF/W)\times100$.

$$FFM = d_{ECW} V_{ECW} + d_{ICW} V_{ICW}$$
$$d_{ECW} = 1.106, d_{ICW} = 1.521$$

$$d : \text{density}, V : \text{volume}$$

The Hydra_S_Acquisition Utility© Version 1.0 (2003) was used to capture the raw data and the Hydra_Data_Model_Vol Utility© Version 2.2 (1997) was used to obtain the model data and volumes. Body composition data were calculated with Microsoft© Excel© Version 2007 and the statistical analysis was made with XLSTAT© Trial version (2010). Also, the standard error of estimate (SEE) was use to evaluate if the body composition data were acceptable (table 3) [19].

| Table 3. Acceptable SEE. |
|---------------------------|
| ECW, ICW | FFM, BF | %BF |
| (lt)     | (kg)    | (%) |
| 1.0 to 1.5 | 2.0 a 3.5 | 3.5 a 5 |
3. Results
Comparison of results of raw data (R, Xc and Z at 5 and 500 kHz) obtained with the reference electrodes (292-STE) in the three groups A, B and C (4 subjects each) showed that all \( p \) values were greater than 0.01, then the paired Student’s t-test found no significant differences when using the strategy of changing the order of using the reference electrodes (Table 4). The Bland and Altman analysis [18] showed similar results.

| Raw data | A vs. B | A vs. C | B vs. C |
|----------|---------|---------|---------|
| \( R_5 (\Omega) \) | 0.4 | Not | 0.6 | Not | 0.5 | Not |
| \( Xc_5 (\Omega) \) | 0.5 | Not | 0.9 | Not | 0.3 | Not |
| \( Z_5 (\Omega) \) | 0.4 | Not | 0.6 | Not | 0.5 | Not |
| \( R_{500} (\Omega) \) | 0.4 | Not | 0.6 | Not | 0.5 | Not |
| \( Xc_{500} (\Omega) \) | 0.5 | Not | 0.8 | Not | 0.4 | Not |
| \( Z_{500} (\Omega) \) | 0.4 | Not | 0.6 | Not | 0.5 | Not |

\( p_t \): \( p \) value by paired Student’s t-test (Significant difference if \( p_t < 0.01 \))

B&A: significant difference by Bland & Altman method (Yes or Not)

Comparison of results of raw data (R, Xc and Z at 5 and 500 kHz) obtained in 12 subjects with the ECG electrodes (2290 and 2228) against results obtained with the reference electrodes (292-STE), showed significant differences in most cases with 2290 electrodes; while 2228 electrodes showed a significant difference only in Xc at 500 kHz (Table 5).

| Raw data | 2290 | 2228 |
|----------|------|------|
| \( R_5 (\Omega) \) | 0.451 | Not | 0.023 | Not |
| \( Xc_5 (\Omega) \) | 0.000 | Yes | 0.168 | Not |
| \( Z_5 (\Omega) \) | <0.0001 | Yes | 0.023 | Not |
| \( R_{500} (\Omega) \) | 0.001 | Yes | 0.026 | Not |
| \( Xc_{500} (\Omega) \) | <0.0001 | Yes | <0.0001 | Yes |
| \( Z_{500} (\Omega) \) | 0.015 | Not | 0.085 | Not |

\( pt \): \( p \) value by paired Student’s t-test (Significant difference if \( pt < 0.01 \))

B&A: significant difference by Bland & Altman method (Yes or Not)

Comparison of results of model data (Rec, Ric, C and Rinf) obtained in 12 subjects with the ECG electrodes (2290 and 2228) against results obtained with the reference electrodes (292-STE) showed significant differences in Ric and Rinf with 2290 electrodes and none significant difference with 2228 electrodes (Table 6). Volume (ECW and ICW) and body composition (FFM, BF and %BF) data showed significant differences in most cases with 2290 electrodes and none significant difference with 2228 electrodes.
Table 6. Comparison of model data with ECG electrodes against reference electrodes (n=12).

| Model data | 2290 | 2288 |
|------------|------|------|
|             | \( p_t \) | B&A | \( p_t \) | B&A |
| Rec (\( \Omega \)) | 0.130 | Not | 0.029 | Not |
| Ric (\( \Omega \)) | 0.024 | Yes | 0.274 | Not |
| C (\( \mu F \)) | 0.403 | Not | 0.076 | Not |
| Rinf (\( \Omega \)) | 0.632 | Yes | 0.098 | Not |

\( p_t \): \( p \) value by paired Student’s t-test (Significant difference if \( p_t < 0.01 \))

B&A: significant difference by Bland & Altman method (Yes or Not)

The SEE values obtained for volume and body composition data with ECG electrodes (2290 and 2228) showed acceptable SEE in all cases with 2228 electrodes (Table 7). Percentages of error for FFM and BF with the 2228 ECG electrodes were 0.3% and 0.0%; while the 2290 ECG electrodes produced errors of 3.6% and 6.7% respectively.

Table 7. SEE obtained for volume and body composition data.

| Volume and body composition data | 2290 | 2228 |
|---------------------------------|------|------|
| ECW (lt)                        | 0.2  | 0.2* |
| ICW (lt)                        | 1.6* | 0.3  |
| FFM (kg)                        | 2.3* | 0.4  |
| BF (kg)                         | 2.3  | 0.4* |
| %BF (%)                         | 3.8  | 0.7* |

* underestimation

Bland & Altman plots for volume and body composition data obtained in 12 subjects with the ECG electrodes (2290 and 2228) against the reference electrodes (292-STE), showed that 2228 ECG electrodes had a good response to the prediction of ECW, ICW, FFM, BF and %BF because the average is at zero or very close to it and the scatter data were ever within ±2SD (Figure 5).

Figure 5. Bland & Altman plots of FFM (kg) with ECG electrodes against the reference electrodes (292-STE), (n=12). (a) 2290 ECG electrodes, (b) 2228 ECG electrodes.

4. Discussion and conclusion

Electrodes are critical for the accuracy of BIA measurements and researchers have studied the skin–electrode impedance, type of gel (dried or wet gel), shape and size electrode, inter-electrode distance, electrode material, electrode construction, electrode placement and material of the interface [20,21]. Additionally, there have been significant efforts for developing systems to characterize and compare
textile electrodes against conductors [22] and compare different textile electrodes against standardized electrolyte electrodes [23]. Some authors have showed that ECG electrodes can be useful for reducing costs when monitoring anesthetic depth with bispectral index [24]. For BIA measurements, foam sticky, wet gel and Ag/AgCl ECG electrodes have been used [25], however, there has been no validation of the ECG electrodes in BIA measurements. The purpose of this study was to fill this gap.

A good system of electrodes for bio-potential measurements should have low coupling electrode-gel-skin impedance, high adhesion, good physical stability, large effective area and high flexibility [26]. Three types of electrodes used in this study met these characteristics. Although dried gel electrodes have more advantages over wet gel electrodes, dried gel electrodes have a weakness: they are less conductive and less humid than wet gel electrodes. Wet gel is able to get into the pores of the skin which ensures better interface gel-electrode-skin and it is easier to clean. For this reason wet electrodes are the most commercial ones [20]. In this study it was found that 2228 wet-gel electrodes are more suitable for BIA measurements than the 2290 dried-gel electrodes.

Recommended area for electrodes for measuring BIA is greater than 4 cm$^2$ [8] since a smaller area decreases the capacitance, increases the impedance [21] and deteriorates the coupling of the gel-electrode and skin interface. However, area of 3.14 cm$^2$ was apparently enough in this case. Some authors have shown that this variable only plays a minor role [27]. We suggest use standardized techniques for BIA measurements to minimize environmental and biological variations [28]. Other ECG electrodes with foam backing, wet gel and a minimum skin sensor contact area of 3.14 cm$^2$ could be used in BIA measurements but they should be validated with a similar process as in this study.

This study suggests that the 2228 ECG electrodes can be used in BIA measurements with the bioimpedance analyzer Hydra 4200 for adult’s body composition assessment. The 2228 ECG electrodes are available in the domestic market and their costs are 92% lower than the electrodes recommended by manufacturer of this bioimpedance analyzer. The results show a new cost-benefit relation for BIA method and make this a more accessible tool for individual tests, large-scale researches and studies in the community.

5. References

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6. Conflict of interest
The authors declare that there is no conflict of interest for this work and that any sponsorship from the manufacturers or brands mentioned in this study was received.

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