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Optimizing electrode sites for segmental bioimpedance measurements

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Abstract. Recent advances in the application of bioelectrical impedance analysis (BIA) have indicated that a more accurate approach to the estimation of total body water is to consider the impedance of the various body segments rather than simply that of the whole body. The segmental approach necessitates defining and locating the physical demarcation between both the trunk and leg and the trunk and arm. Despite the use of anatomical markers, these points of demarcation are difficult to locate with precision between subjects. There are also technical problems associated with the regional dispersion of the current distribution from one segment (cylinder) to another of different cross-sectional area. The concept of equipotentials in line with the proximal aspects of the upper (and lower) limbs along the contralateral limbs was investigated and, in particular, the utility of this concept in the measurement of segmental bioimpedance. The variation of measured segmental impedance using electrode sites along these equipotentials was less than 2.0% for all of the commonly used impedance parameters. This variation is approximately equal to that expected from biological variation over the measurement time. It is recommended that the electrode sites, for the measurement of segmental bioelectrical impedance in humans, described herein are adopted in accordance with the proposals of the NIH Technology Assessment Conference Statement.

Keywords: bioelectrical impedance analysis, segmental bioimpedance, human body composition measurement, electrode sites

1. Introduction

Bioelectrical impedance analysis (BIA) has become popular as a noninvasive technique to estimate body composition. The technique of BIA is based on the principle that the impedance, Z, (at a given current frequency) of a cylindrical conducting body is related to the conductor length, L, resistivity, ρ, and conducting volume, V, *viz.*

$$V = \frac{\rho L^2}{Z}. \tag{1}$$

However the measured impedance is frequency dependent and the nature of this dependence is discussed in depth by such authors as Cole and Cole (1941), Schanne and Ruiz P-Ceretti (1978) and Ackmann and Seitz (1984). The theoretical impedance spectrum, between 1 kHz and 1 MHz, when plotted in the complex plane (magnitude of reactance against resistance) yields a circular shaped locus with a centre depressed below the resistance axis (figure 1) (Cole and Cole 1941). The peak of this locus (i.e. point of maximum reactance) occurs at the

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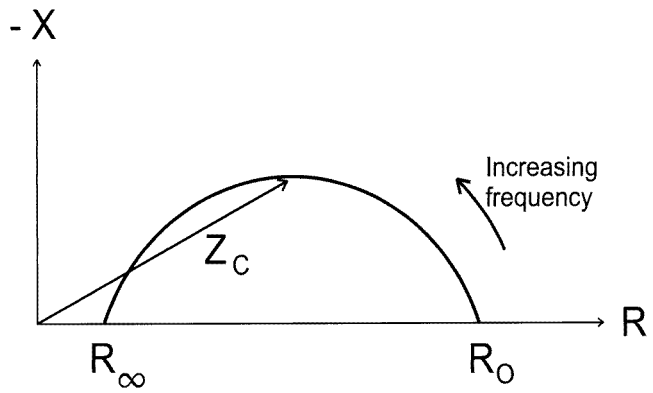

Figure 1. Theoretical impedance spectrum from biological tissue (magnitude of reactance plotted against resistance).

characteristic frequency ω_C and the measured impedance at this frequency is the characteristic impedance Z_C.

The theoretical relationship to this locus is

$$Z = R_{\text{inf}} + \frac{R_0 - R_{\text{inf}}}{1 + (\text{j}\omega\tau)^{\alpha}} \tag{2}$$

where Z is the complex impedance, R_{inf} and R_0 are the resistances at infinite and zero frequency respectively, ω is the angular frequency, τ is the time constant and α represents the degree of depression below the resistance axis (Cole and Cole 1941, Schanne and Ruiz P-Ceretti 1978, Ackmann and Seitz 1984).

The application of the BIA technique in human subjects uses a tetrapolar surface electrode arrangement, consisting of two measurement electrodes and two distally positioned drive electrodes. This electrode configuration has been used with humans by essentially all investigators since Hoffer *et al* (1969). The tetrapolar arrangement eliminates the skin–electrode contact impedance and ensures that the measured impedance is essentially that of the underlying body tissues (Ackmann and Seitz 1984, Cornish *et al* 1998). For the measurement of whole body impedance the measurement electrodes are typically positioned on the dorsal surface of the right wrist at the level of the process of the radial and ulnar bones; and on the anterior surface of the right ankle between protruding portions of the tibial and fibular bones. The drive electrodes are positioned 5 cm distal to the measurement electrodes; on the dorsal surface of the third metacarpal bone of the right hand and the dorsal surface of the third metatarsal bone of the right foot (Lukaski *et al* 1985, Scheltinga 1992).

The technique of multiple frequency bioelectrical impedance analysis (MFBIA) is based on the theory that at low frequency the current preferentially passes through the extracellular water space (ECW) whilst at high frequency an electrical current penetrates the cell membrane and thus is conducted through both the extra- and intra-cellular (ICW) water spaces. The body's impedance to the applied AC current is then measured over a range of frequencies and from the resulting impedance spectrum the resistance of the extra- and intra-cellular fluid compartments can be determined. This determination of the subcompartment water volumes has been shown to significantly improve the estimation of total body water (TBW) compared with that of single frequency BIA (Cornish *et al* 1993, Thomas *et al* 1992).

Numerous empirical algorithms relating whole body impedance measurements to total body water (TBW) or fat-free mass (FFM) have been published in the literature

(e.g. Houtkooper *et al* 1996). These algorithms use subject height as a surrogate measure of conducting path length. In many of these algorithms other subject parameters (such as weight, age, sex etc) have been included to improve the predictive power of the numerical relationship. While the correlation coefficients and standard errors have been significantly improved with the inclusion of these added parameters, there is no theoretical basis for their inclusion and there are still conflicting opinions as to what parameters (other than ht^2/R) should be included in the prediction equations and the degree of enhancement caused by their inclusion (Diaz *et al* 1989, Kushner 1992).

Several research groups have found that empirical algorithms, using whole body impedance for estimating total body water, developed and validated from measurements recorded in one particular group of subjects are inaccurate when applied in different subject groups. The types of subject group which have highlighted this lack of portability (in application of algorithms) include variations in age, ethnicity and conditions such as obesity, anorexia and various pathologies such as HIV and cirrhosis (Baumgartner *et al* 1990, Roche and Guo 1993). Several researchers (Fuller and Elia 1989, Organ *et al* 1994, Thomas *et al* 1998) have suggested that the reason for this lack of portability of algorithms between subject groups may be due to the assumption of representing the human body by a conducting cylinder with uniform cross-sectional area as in equation (1).

This assumption is clearly invalid when applied to the human body. The geometrical shape of the human body more closely approximates five cylinders (two arms, two legs and a trunk), excluding the head. As resistance is inversely proportional to cross-sectional area the arms have the greatest influence on whole body impedance but the smallest contribution to body volume, whereas the impedance of the trunk has the least impedance of the body segments but the greatest volume. Secondly, isotropic conduction dictates that current density is uniformly distributed along axes in all directions. This does not occur throughout the human body. Due to organs such as the lungs, intramuscular fat and numerous tissue interfaces which all act as dielectric conductors, electrical conduction is anisotropic through certain body segments.

The present authors (Thomas *et al* 1998) have previously reported investigations detecting significant shifts in the extracellular water volume between body segments of subjects becoming supine after standing. These extracellular shifts were generally from the limbs into the trunk region. However there were no significant shifts between the intracellular water volumes of body segments. This segmental approach to estimating total body fluid volumes minimizes the effect of variation in cross-sectional area within any body segment and hence minimizes the uncertainty associated with the overall estimate of TBW and ECW.

Several research groups (notably Fuller and Elia 1989 and Organ *et al* 1994), have investigated the bioelectrical impedance of body segments, in particular the upper and lower limbs and the trunk. One problem encountered by these studies was accurately determining the measurement electrode sites defining the distinction between the trunk and the upper limb, and the trunk and lower limb. This is particularly troublesome when measuring the impedance of obese subjects where anatomical landmarks are difficult to identify. As the measured impedance is proportional to the square of the length of the conducting path, the precise placement of these measurement electrodes is critical to the final precision of the result.

The BIA technique uses a constant current source and detects the impedance of body tissues by measuring the potential difference (i.e. voltage) between the measurement sites. Equipotentials are loci of points with the same potential and are perpendicular to the flow of current. When the flow of the electric current is in a longitudinal direction through the body, in very narrow sections, these equipotentials are in a transverse direction. Hence measurement electrode sites on anterior, posterior and lateral surfaces of these narrow sections should yield

Table 1. Anatomical descriptions of the measurement electrode sites.

Position	Anatomical description
1	dorsal surface of the right wrist at the process of the radial and ulna bones
2[a]	acromion process of the right humerus
3	midway between the clavicular notches
4	acromion process of the left humerus
5	left elbow
6	left wrist
7	anterior surface of the right ankle between the tibial and fibular bones
8[a]	lateral side of the right thigh in line with the midpoint of the inguinal crease
9	lateral side of the left thigh in line with the midpoint of the inguinal crease
10	left knee
11	left ankle

[a] Standard measurement electrode position for the measurement of segmental bioimpedance.

the same measured value. However, in regions of the body where the current distribution is not parallel to the longitudinal axis the equipotentials are not linear and are difficult to accurately determine in an individual. This situation is exacerbated when the current is transmitted from one body segment to another with a large difference in cross-sectional area (e.g. thigh to trunk or arm to trunk), or around significantly large nonconductors such as the bony joints of the elbow, knee and shoulder.

Organ *et al* (1994) suggested a six electrode arrangement for the measurement of the impedance of the three major body segments and whole body impedance. They compared group results of these measured values with the group results of whole body (i.e. wrist to ankle). This paper extends the work of Organ *et al* (1994) and investigates the variation in measured impedance as the electrode site is progressively moved along what are believed to be equipotential lines across the human body.

2. Methods

The bioelectrical impedance of 20 healthy subjects was measured using a standard protocol (Cornish *et al* 1996), and a SEAC SFB3 swept frequency bioimpedance monitor (Brisbane, Australia). This instrument measures the impedance and phase at 496 frequencies logarithmically spaced between 4 kHz and 1 MHz. The software supplied determines the best fitting theoretical locus and from the fitted plot the following values were determined: the resistance at zero frequency R_0, the resistance at infinite frequency R_∞, the resistance at 50 kHz R_{50} and the impedance at the characteristic frequency Z_c. The resistance at zero frequency is used to predict ECW; the resistance at infinite frequency (in conjunction with R_0) can be used to predict ICW; while R_{50} and Z_c are both used to predict TBW (Cornish *et al* 1993, Thomas *et al* 1998).

A tetrapolar electrode arrangement was used with the drive electrodes positioned on the dorsal surface of the third metacarpal bone of the right hand and the dorsal surface of the third metatarsal bone of the right foot. The positions of the drive electrodes were fixed while the positions of the measurement electrodes were moved along what were believed to be equipotentials across the body. The precise positions of these sites are described in table 1 and shown in figure 2. The positions labelled as 2 and 8 are the 'standard' measurement electrode positions commonly used for the measurement of segmental bioimpedance (Fuller and Elia 1989, Thomas *et al* 1998).

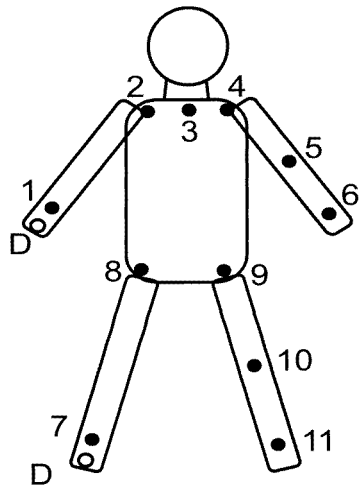

Figure 2. Schematic representation of the measurement electrode sites (solid circles; numbered 1 to 11), and drive electrode sites (open circles; labelled D).

Table 2. Measurement electrode sites used to record body segment impedance.

Body segment	Standard[a] electrode sites	Alternative measurement electrode sites			
arm (upper limb)	1 & 2[a]	1 & 3	1 & 4	1 & 5	1 & 6
arm plus trunk	1 & 8[a]	1 & 9	1 & 10	1 & 11	
leg (lower limb)	7 & 8[a]	7 & 9	7 & 10	7 & 11	
leg plus trunk	7 & 2[a]	7 & 3	7 & 4	7 & 5	7 & 6

[a] These electrode pairs represent the standard electrode sites for the measurement of the relevant body segment.

The hypothesis tested was that when the current is passed between the right wrist and right ankle, the entire left arm and points along the line joining the acromion process of the left and right humerus are all at the same equipotential and hence all should record the same bioimpedance value when used as a measurement electrode site. Similarly, for the same drive electrode sites, the entire left leg and points along the line joining the mid-inguinal crease of the left and right sides of the body are also on an equipotential and hence all should record the same bioimpedance value when used as a measurement electrode site.

For each of the 20 volunteers the bioelectrical impedance of four body segments (arm, arm plus trunk, leg and leg plus trunk) was measured using measurement electrode sites along these proposed equipotential lines. The positions of the measurement electrodes used to record the impedance of the various body segments are listed in table 2.

In all cases, measurements were performed with the subject lying supine on a nonconducting surface. Electrode sites were cleaned with an alcohol swab before the application of standard EKG electrodes. The electrodes used were 3M 'Red Dot' EKG single use electrodes (manufacturers code 2330). They are Ag/AgCl hydro-gel based electrodes with a measured gel area (i.e. electrical contact area) of 120 mm^2. Subjects did not move between measurements and all electrodes remained in place. Measurements were made in a random order to minimize any trend effects of time and were all completed within 5 minutes.

3. Data analysis

Data files recorded by the bioimpedance monitor were analysed using the manufacturer's software and the values of four commonly used impedance parameters extracted. These parameters were the resistances at zero frequency, infinite frequency and at 50 kHz, and the impedance at the characteristic frequency (*viz*. R_0, R_∞, R_{50} and Z_c respectively). The standard error of the fitted theoretical locus in each case was less than 1%. Since absolute impedance varies between individuals, data were normalized by expressing the impedance at each of the alternative sites as a percentage of the value obtained at the standard site for each body segment. The significance of difference between the mean results at the different sites was assessed by analysis of variance (ANOVA) on the group results for each body segment and each impedance parameter.

4. Results

The variation in impedance at the different alternative sites compared to the standard sites are presented for each body segment in tables 3 to 6. Statistical evaluation of these data showed that in the measurement of the impedance of the arm (table 3), the mean value obtained using site 3 (midway between the clavicular notches) was slightly less than (1.8%), and significantly different ($p < 0.01$) from, the values obtained for R_∞, R_{50} and Z_c at the remaining alternative electrode sites. Similarly, in the measurement of the impedance of the leg plus trunk (table 6) the mean value obtained using site 3 (midway between the clavicular notches) was slightly greater than (1.5%), and significantly different ($p < 0.05$) from, the values obtained for R_0, R_{50} and Z_c at the remaining alternative electrode sites. No other significant differences for any given impedance parameter were found for any of the body segments.

Table 3. Impedance of the arm measured at the alternative measurement electrode sites. Values expressed as a percentage of the value obtained from the standard electrode site and averaged over the subject group ($n = 20$).

	Impedance (% of the value obtained from the standard site) mean (SD)			
Parameter	sites 1 & 3	sites 1 & 4	sites 1 & 5	sites 1 & 6
R_0	105.8 (1.9)	107.0 (2.0)	107.4 (1.9)	107.8 (1.8)
R_∞	104.9 (1.4)	107.1 (1.9)	107.1 (2.0)	106.5 (2.0)
R_{50}	106.5 (1.2)	108.1 (1.3)	108.4 (1.5)	108.6 (1.4)
Z_c	105.7 (1.6)	107.0 (1.9)	107.3 (1.7)	107.4 (1.7)

Table 4. Impedance of the arm plus trunk measured at the alternative measurement electrode sites. Values expressed as a percentage of the value obtained from the standard electrode site and averaged over the subject group ($n = 20$).

	Impedance (% of the value obtained from the standard site) mean (SD)		
Parameter	sites 1 & 9	sites 1 & 10	sites 1 & 11
R_0	96.2 (1.8)	97.2 (1.4)	97.3 (1.6)
R_∞	98.8 (1.7)	99.5 (2.0)	99.4 (2.0)
R_{50}	96.8 (1.3)	97.7 (1.2)	97.8 (1.6)
Z_c	96.6 (1.9)	97.5 (1.9)	97.5 (2.0)

Table 5. Impedance of the leg measured at the alternative measurement electrode sites. Values expressed as a percentage of the value obtained from the standard electrode site and averaged over the subject group ($n = 20$).

	Impedance (% of the value obtained from the standard site) mean (SD)		
Parameter	sites 7 & 9	sites 7 & 10	sites 7 & 11
R_0	103.5 (1.6)	103.4 (1.4)	103.9 (1.3)
R_∞	104.5 (1.6)	103.7 (1.7)	103.6 (1.9)
R_{50}	104.5 (1.3)	103.7 (1.6)	103.8 (1.6)
Z_c	103.6 (1.5)	103.4 (1.4)	103.6 (1.4)

Table 6. Impedance of the leg plus trunk measured at the alternative measurement electrode sites. Values expressed as a percentage of the value obtained from the standard electrode site and averaged over the subject group ($n = 20$).

	Impedance (% of the value obtained from the standard site) mean (SD)			
Parameter	sites 7 & 3	sites 7 & 4	sites 7 & 5	sites 7 & 6
R_0	94.4 (1.6)	92.5 (1.8)	92.8 (1.4)	92.8 (1.6)
R_∞	95.8 (1.5)	94.8 (1.9)	94.6 (2.0)	94.8 (2.0)
R_{50}	94.2 (1.4)	93.0 (1.4)	92.7 (1.3)	92.8 (1.4)
Z_c	94.9 (1.3)	93.6 (1.8)	93.6 (1.7)	93.6 (1.9)

4.1. Equipotential between the arm and the trunk (the contralateral upper limb)

All values of the impedance parameters derived from measurements obtained using the alternative electrode sites 3, 4, 5 and 6 were slightly but significantly different from those values using the standard electrode site at the acromion process of the right humerus. The values for the upper part of the body (arm) were greater than 100%, while those for the lower body (trunk plus leg) were less than 100%. This suggests one of two possibilities:

(a) the equipotential line on which these points are located is slightly below the effective 'top' of the 'arm cylinder', resulting in an overestimation of the arm impedance and an accompanying underestimation of the trunk plus leg impedance or
(b) the site, at the acromion process of the right humerus, chosen on the right side of the body as being equivalent to the 'top' of the arm is in fact slightly above the true effective 'top' of the arm.

The ANOVA analysis identified site 3 (midway between the clavicular notches) as being slightly but significantly different from the other sites on the proposed equipotential. This may well be true as the criterion for choosing this site was the reproducibility of physically locating the same site using anatomical landmarks. The statistical differences identified suggest that this site is slightly higher on the body than the equipotential along the contralateral arm.

4.2. Equipotential between the leg and the trunk (the contralateral lower limb)

All values of the impedance parameters derived from measurements obtained using the alternative electrode sites 9, 10 and 11 were slightly but significantly different from those values using the standard electrode site (8) at the lateral side of the body in line with the mid-inguinal crease (except the values of R_∞, for the arm plus trunk, which were not significantly different

from zero). The values for the upper body (arm plus trunk) were less than 100%, while those for the lower body (leg) were greater than 100%.

Similarly, this suggests one of two possibilities:

(a) the equipotential line on which these points are located is slightly above the effective 'top' of the 'leg cylinder', resulting in an overestimation of the leg impedance and an accompanying underestimation of the trunk plus arm impedance or
(b) the site, on the lateral side of the thigh in line with the mid-inguinal crease, chosen on the right side of the body as being equivalent to the 'top' of the leg is in fact slightly below the true effective 'top' of the leg.

A third possibility which may explain this apparent, slight deviation from 100% of the measured value from the standard site (of both the upper and lower contralateral limbs) is the right to left asymmetry of the human body. Conventional whole body, and segmental (limb), BIA consistently shows a bilateral asymmetry (Kushner 1992, Ward *et al* 1992). This has been attributed to a variation in the cross-sectional areas of contralateral limbs due to limb dominance and may well contribute to slight perturbations in the transverse equipotentials.

5. Discussion

Bioelectrical impedance analysis has numerous advantages as an analytical technique for assessing body composition. It is noninvasive, portable, inexpensive and able to be frequently repeated on any subject. However the accuracy of the technique across different population groups is severely limited by the availability of appropriate empirical relationships specific to the group of subjects being measured. It has been suggested that this inadequacy is a result of an invalid assumption in the application of the underlying theory; in particular—the human body cannot be accurately represented by one conducting cylinder of uniform cross-section. Some researchers (Organ *et al* 1994, Thomas *et al* 1998) have suggested that this inadequacy may be rectified by considering an electrical analogue of the human body to be three cylinders connected in series, (arm, trunk and leg). They suggest that an algorithm incorporating three impedance predictors derived from these three segments should better estimate body composition than one derived from whole body impedance.

The accuracy of any estimation from a BIA measurement is very much contingent upon accurately and reliably locating the precise electrode sites to record the appropriate impedance measurements. A 1 cm displacement of the electrode can result in a 2% change in measured impedance (NIH 1996). The wrist and ankle locations (required for whole body BIA measurements) are easily identifiable on virtually all subjects. They are also easy to access regardless of subject clothing and present no personal embarrassment in their location. However the standard thigh and shoulder electrode sites needed for segmental measures of BIA can be quite difficult to accurately locate particularly in obese subjects, a group for whom the measurement of body composition is of particular interest.

This study has demonstrated that the distal extremity of both the upper and lower limb is at the same equipotential as all parts of the upper and lower contralateral limb respectively. We have also demonstrated that accurate and reliable measurements of relevant body segments can be recorded using this equipotential line. These options for measuring the bioimpedance of body segments not only improve the accuracy of the resulting measurements but also remove much of the inter-operator variability created by the necessity of locating specific anatomical landmarks.

The variation in the relative values of the measured impedance parameters along the proposed equipotential lines was less than 1% and the maximum standard deviation of any

measured relative impedance parameter in this study was 2%. However this variation includes both an instrumental variation of up to 1% and a biological variation (Ward *et al* 1997). The biological variation, particularly in ECW segmental volumes, over a period of 5 to 10 minutes upon becoming supine is significant and of the order of 2 to 4% (Thomas *et al* 1998). Hence the variation, along the equipotentials, in the measured impedance values detected in this study (albeit very small) may be *solely* due to real biological changes in the subject.

In conclusion, on the basis of the data obtained in the present study, it is recommended that measurement of segmental bioimpedance be standardized according to the protocol used here, i.e. the contralateral wrist and ankle as the electrode sites for the arm/trunk and trunk/leg demarcations respectively. Such standardization will enable more accurate assessment of impedance and facilitate comparison of data between different research groups. This will make considerable progress in meeting the challenge of optimizing BIA analysis set forth in the NIH Technology Assessment Conference Statement in which standardization of technique was deemed essential to provide meaningful estimates of TBW or fatness (NIH 1996).

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