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Alternate electrode placement for whole body and segmental bioimpedance spectroscopy

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Abstract

Bioimpedance spectroscopy (BIS) is frequently used to monitor body fluid and body composition in healthy and clinical populations. BIS guidelines state that there should be no skin lesions at the site of electrodes, and if lesions are present, electrode positions should be changed. However, alternate electrode positions are yet to be reported. This study aimed to determine if ventral electrode placements were suitable alternatives for whole body and segmental BIS measurements. Three alternate electrode placements were assessed for whole body BIS using a combination of ventral hand and foot electrode placements. An alternate position was assessed for upper and lower body segmental BIS. The results demonstrated that for whole body BIS, if drive and sense electrodes on the hand are moved to ventral positions, but foot electrodes remain in standard positions, then whole body BIS variables were comparable to standard electrode positioning (percentage difference range = 0.01 to 1.65%, $p = 0.211$–0.937). The alternate electrode placement for upper limb segmental BIS, results in BIS variables that are comparable to that of the standard positioning (percentage difference range = 0.24–3.51%,

$p = 0.393–0.604$). The alternate lower limb electrode position significantly altered all resistance and predicted BIS variables for whole body and lower limb segmental BIS (percentage difference range = 1.06–12.09%, $p < 0.001$). If wounds are present on the hands and/or wrist, then the alternate electrode position described in this study is valid, for whole body and upper limb segmental BIS.

Keywords: bioelectrical impedance analysis, electrode sites, body composition, body fluid distribution, wounds

(Some figures may appear in colour only in the online journal)

1. Introduction

The use of bioimpedance spectroscopy (BIS) to monitor changes in physiological parameters such as total body water (TBW), fat free mass and nutritional status in healthy and clinical populations is well established. By delivering electrical impulses across a range of frequencies, cellular level architecture and function can be assessed through adhesive electrodes attached to intact skin. The standard tetrapolar placement of electrodes for whole body BIS, requires that four individual electrodes are placed on standardised locations on the dorsal surface of the hands and feet (Lukaski *et al* 1985, Kyle *et al* 2004a). This tetrapolar arrangement consists of two sense (or measurement) electrodes and two distally positioned drive (or current delivery) electrodes (Cornish *et al* 1999). The 2004 European Society for Clinical Nutrition and Metabolism (ESPEN) guidelines for the clinical utilisation of BIS state that in regards to electrode position; there should be a minimum of 5 cm between drive and sense electrodes, and that electrodes should always be placed on the same side of the body for repeated assessments (Kyle *et al* 2004b). The guidelines also state that there should be no skin lesions at the site of the electrodes, and if skin lesions are present, the electrode position should be changed (Kyle *et al* 2004b). While placement of electrodes on the contralateral side of the body is an option if unilateral skin lesions, or wounds are present, there appear to be few recommendations as to any alternate electrode positions in the literature for use in situations where bilateral lesions/injuries prevent standard electrode placement. This is concerning given that accuracy and reproducibility of BIS is reliant upon accurate and reliable, repeatable electrode positioning.

Whilst standardised protocols have attempted to reduce such measurement errors, even slight changes in electrode placement can result in unreliable BIS results (National Institute of Health 1996). As each electrode is individually placed, there is potential that each electrode could contribute to reproducibility errors (Moon *et al* 2009). There is conflicting evidence in the literature as to the impact alternate electrode placements have on BIS variables. It has been reported that if electrodes are moved proximally by 1 cm, this results in a 2% change in mean resistance values, where a 2 cm shift in electrode position results in a 4% change in resistance values (Elsen *et al* 1987). Significant changes in resistance have also been reported when wrist or ankle electrodes were moved centrally by 1 cm (Schell and Gross 1987). Dunbar *et al* (1994) reported on a small sample of nine participants, that moving electrodes laterally, medially or proximally by 1 cm, generally had no effect on percent body fat, calculated via prediction models utilising bioimpedance variables, whereas moving electrodes distally by 1 cm resulted in significantly overestimated percent body fat when compared to the standard electrode placement. The effect of altered electrode placement on impedance values was not reported in their investigation (Dunbar *et al* 1994). Additionally, while investigating modelling of upper and lower limb muscle volume using BIS, Stahn *et al* (2007) demonstrated that resistance values were unchanged when anterior (standard) and the average between anterior and posterior (alternate) electrode placements were compared (Stahn *et al* 2007). Therefore the ESPEN recommendations to change electrode position if skin lesions are present, could result in unreliable measurements, given that small 1 cm shifts in electrode position, in various directions, can greatly affect BIS measurements. However some researchers have demonstrated that alternate electrode placements have limited effect on some BIS variables, therefore further investigation is required.

It is evident that moving electrodes proximally and distally results in unreliable BIS measurements, but moving electrodes medially and laterally may not affect BIS reliability. Little is known about moving electrodes further than 1 cm laterally; from dorsal to ventral positions, for example. Lingwood *et al* (2000) compared the standard tetrapolar placement of electrodes with an alternate position in neonates in the attempt to increase the distance between the drive and sense electrodes. The alternate position required that the sense electrodes were placed on the ventral (instead of dorsal) surface of the hand and foot. They found that there were no significant differences in impedance values obtained using dorsal versus ventral positioning of the sense electrodes (Lingwood *et al* 2000). This is encouraging as ventral placement of electrodes may be an option, when wounds or dressings inhibit the standard placement of electrodes over intact skin in adults. Further research is required to address this in adults and to determine if both sense and drive electrodes can be moved ventrally when standard dorsal placement is not possible due to skin lesions or other extraneous variables.

While ventral positioning of electrodes could potentially offer a solution as an alternative electrode placement for whole body impedance measurements, it has not been established whether the same ventral positioning of electrodes could be applied in segmental impedance analysis. Cornish *et al* (1999) examined various electrode positions for segmental BIS measurements in order to provide optimal electrode placements for both upper and lower limb segments. Whether or not the optimal electrode placements for segmental BIS described by Cornish *et al* are valid when electrodes are placed on ventral rather than dorsal surfaces remains unknown.

Therefore the aims of this study were to determine if ventral electrode placements were a suitable alternative for whole body and segmental BIS measurements, for use in circumstances where standard electrode placement is impeded by skin lesions or dressings. Based on the literature it is hypothesised that the ventral alternate positions would result in comparable measured resistance parameters and predicted body fluid and composition values, in comparison to values obtained using the standard electrode placement.

2. Methods

2.1. Subjects

To be included in the study, participants had to be between the ages of 18 to 65 years and have a body mass index (BMI) of between 15–40 kg m^{-2}. Subjects were excluded if they were unable to lie supine for the duration of the testing or had a recent history of renal disease including the use of diuretic within four weeks of testing. Contradictions according to manufacturer's specifications also excluded pregnant or breast-feeding subjects, subjects with surgical implants, cardiac pacemakers and/or electronic life support devices. This study was approved by the hospital's human research ethics committee (2011/028) and all subjects provided written informed consent prior to participation.

2.2. Instrumentation

The ImpediMed SFB7 (ImpediMed, Brisbane, Queensland, Australia) was used to assess whole body and segmental BIS measurements. The SFB7 applies 256 discrete current frequencies from 4–1000 Hz. The instrument outputs both raw impedance values and derived variables such as body water and fat free mass which are calculated using manufacturer's algorithms. The electrodes used were Kendall CA610 diagnostic tab electrodes (reference code 31447793, Covidien, Mansfield, MA, USA)

2.3. Procedures

Prior to data collection, subject's height, body mass, age and gender were recorded and input into the SFB7. All measures were taken with the subject lying on an examination bed, in a supine position, with arms abducted by approximately 30 degrees and legs separated. Subjects were required to lay supine for 5–10 min prior to BIS being measured. Before application of the electrodes the appropriate skin surfaces were cleansed using alcohol swabs. Whole body BIS was measured on the right side of the body using four different electrode placements; WB1: standard tetrapolar placement (figures 1(A) and (B)), WB2: ventral hand and ventral foot placement (figures 1(C) and (D)), WB3: ventral hand placement with standard foot placement (figures 1(A) and (D)) and WB4: standard hand placement with ventral foot placement (figures 1(B) and (C)). For the ventral hand placement, both sense and drive electrodes mirrored the standard/dorsal electrode placement, on the ventral (palmer) surface of the wrist (at the level of the midpoint between the styloid process of radial and ulnar) and hand (1 cm proximal to the metacarpal phalangeal joint of the middle finger) respectively. For the ventral foot placement, the drive electrode mirrored the standard/dorsal electrode placement, on the ventral (sole) surface of the foot (1 cm proximal to the metatarsal phalangeal joint of the second toe). The sense electrode was placed laterally, in line with the standard position, slightly anterior to the Achilles tendon.

Segmental measures of the right upper and lower limbs were performed using the protocol suggested by Cornish *et al* (1999), whereby sense electrodes are placed on the dorsal surface of the contralateral wrist and ankle for upper (UL1) and lower limb (LL1) segments respectively (Cornish *et al* 1999) (figures 2 and 3). An alternate electrode position was also assessed in which all electrodes were moved to the ventral surface, with the exception of the contralateral electrode which remained on the dorsal surface (UL2 and LL2).

The SFB7 was set to collect all measurements in triplicate, with 1 s intervals between each measure, and all electrodes remained in place during the measurements. Whole body impedance was measured first followed by segmental impedance, however the order of presentation of standard or alternate electrode placements within each of these conditions (whole body and segmental impedance) were randomised. All measurements were completed within 10 min and subjects abstained from drinking, eating and toileting during that time.

2.4. Data analysis

All analyses were performed using Stata Statistical Software, release 13 (StataCorp LP, 2013, College Station, TX). Descriptive analyses were completed and are presented using means and standard deviations (SD). Percentage difference values were also calculated, whereby each BIS variable from the alternate electrode positions were expressed as a percentage change of the value obtained from the standard site (WB1, UL1 and LL1). All further statistical analyses were performed using the raw (not percentage difference) variables. All triplicate measures

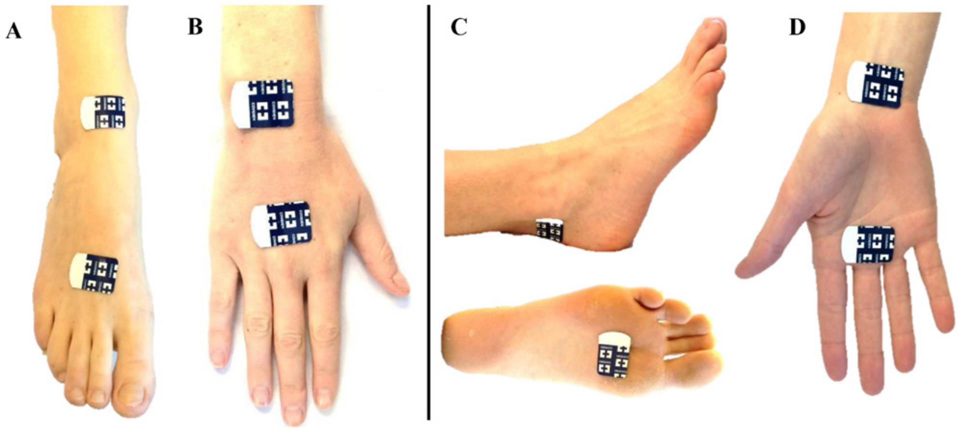

Figure 1. Standard (A and B) and alternate (C and D) electrode placements used for whole body BIS.

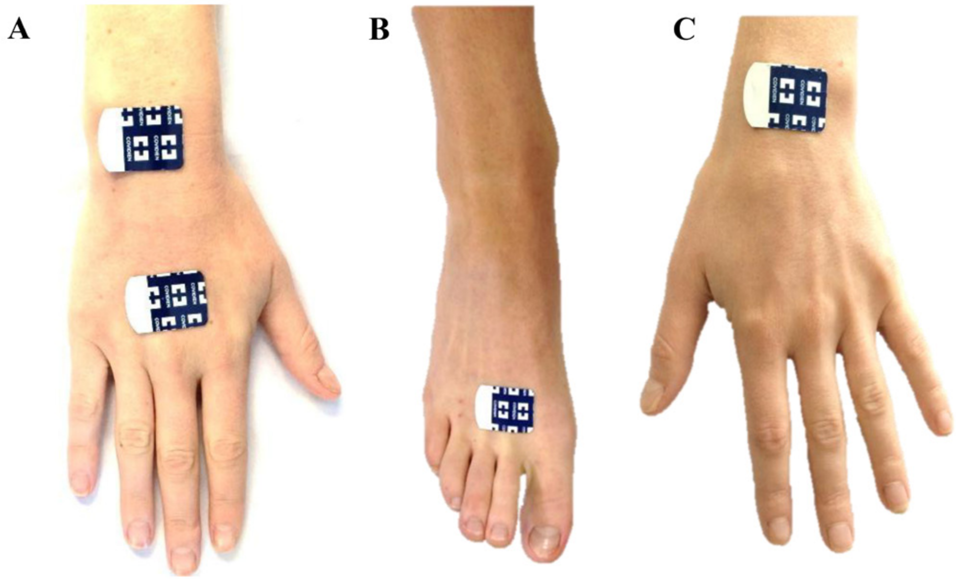

Figure 2. Standard electrode position for right upper limb segmental BIS (A–C). For the alternate position, electrode positions A and B were moved to the ventral surface and electrode position C remained on the dorsal surface.

were included in the analysis, therefore multilevel mixed-effects linear regression analyses were used to assess associations with differences in BIS variables between the different electrode positions. The multilevel mixed-effects model was chosen as it allows for a hierarchical analysis with multiple levels of nesting of the observations and provides the greatest statistical power. Prior to interpreting the results of the models, several assumptions were evaluated, confirming that each variable in the regression was approximately normally distributed. A separate model was fitted for each of the raw (resistance at zero frequency (R_0), resistance at infinite frequency (R_∞) and resistance of the intracellular compartment (R_i) and predicted (TBW

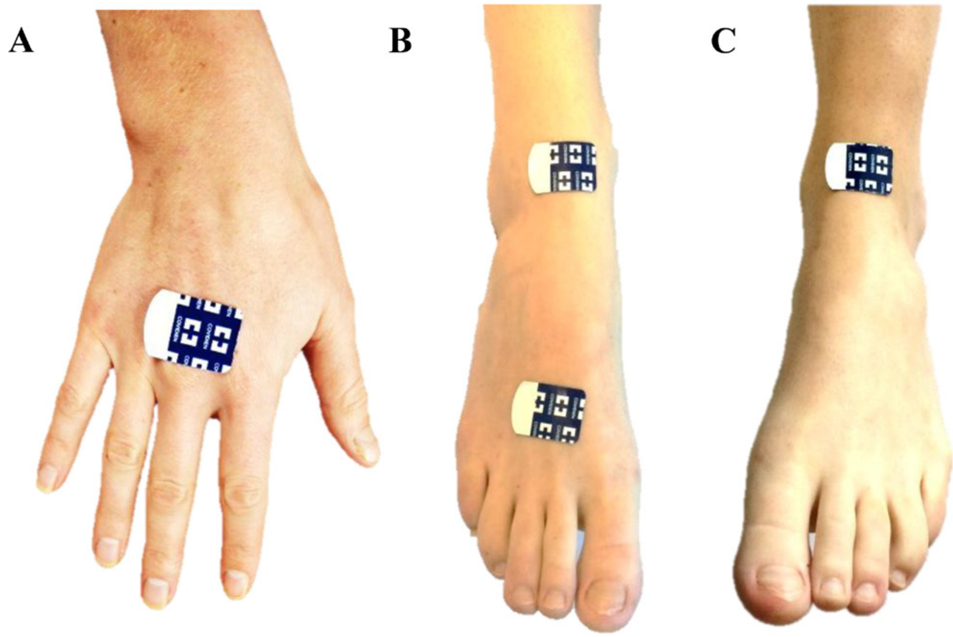

Figure 3. Standard electrode position for right lower limb segmental BIS (A–C). For the alternate position, electrode positions A and B were moved to the ventral surface and electrode position C remained on the dorsal surface.

extracellular fluid (ECF), intracellular fluid (ICF) and fat mass), BIS variables for whole body measurements. Only the raw BIS variables (R_0, R_i and R_∞) were analysed for upper limb and lower limb segmental measurements. The results from the regression analyses were reported as regression coefficients, with 95% confidence intervals. For all analyses a p value of less than 0.05 was considered statistically significant.

Additionally, as body mass index (BMI), age and gender are known to influence BIS variables, we wanted to ascertain if these factors had the potential to influence or confound electrode position results. Therefore a series of mixed model regressions were conducted to assess if there was any interactions between electrode position and; age, gender or BMI for any of the BIS variables. Examination of the p values and regression coefficients demonstrated that many of the BIS variables were independently influenced by age, gender and/or BMI. Therefore these factors were included as covariates in the regression models when examining the associations with changes in BIS variables between the different electrode positions. Interactions between age, BMI, gender and electrode placement were examined, where only statistically significant interactions were included in the final models.

3. Results

3.1. Subjects

Thirty-two healthy adults (17 females and 15 males) were recruited for this study. The mean age of the participants was 38.00 (SD = 13.43) years; with a mean BMI of 24.03 (SD = 2.98) kg m^{-2}.

3.2. Whole body BIS alternate electrode positions

Means and standard deviations for whole body BIS variables for each electrode position are presented in table 1. The regression analysis demonstrated that in comparison to the standard electrode position (WB1), alternate electrode position WB3 did not significantly influence any of the BIS variables ($p = 0.211$–0.973) (table 2). However, significant differences in all of BIS variables assessed were present when electrode positions WB2 and WB4 were utilised. In comparison to the standard electrode position (WB1), the alternate electrode position WB2 significantly reduced R_0, R_i and R_∞ values by −11.9 ohms ($p < 0.001$),−112.0 ohms ($p < 0.001$) and −15.7 ohms ($p < 0.001$) respectively. This resulted in significantly increased ECF, ICF and TBW values by 0.2 L ($p < 0.001$), 0.6 L ($p = 0.002$) and 0.8 L ($p < 0.001$) respectively and significant decrease in fat mass of 1.1 kg ($p < 0.001$) (table 2), in comparison to the standard electrode position. The alternate electrode position WB4 also resulted in significantly reduced R_0 (−9.5 ohms, $p < 0.001$), R_i (−131 ohms, $p < 0.001$) and R_∞ values (−16.7 ohms, $p < 0.001$) in comparison to WB1. Consequently, ECF, ICF and TBW were all significantly increased by 0.2 L ($p < 0.001$), 0.7 L ($p < 0.001$) and 0.9 L ($p < 0.001$) respectively (table 2), when electrode position WB4 was utilised. Fat mass was significantly reduced by 1.2 kg ($p < 0.001$), when electrode position WB4 was compared to the standard electrode placement for whole body BIS.

Examination of the regression coefficients demonstrated that age, gender and BMI were significantly associated with most of the whole body BIS variables measured in this study. Being of the male gender resulted in significantly decreased R_0, R_i, R_∞ and fat mass (table 2). Male gender also resulted in significantly increased ECF, ICF and TBW by 7.3 L, 8.1 L and 14.6 L respectively. The interaction between gender and electrode placement significantly influenced R_i and R_∞. Where the differences in R_i and R_∞ between WB1 and WB2, and WB1 and WB4 were significantly less in males as compared to females (table 2). There was no interaction between gender and electrode placement for R_i and R_∞ for the electrode position WB3. Additionally, there were no interaction effects between electrode placement gender for the remainder of the whole body BIS variables.

Age was also significantly associated with all of the whole body BIS variables, whereby a one year increase in age resulted in significant increases in R_0, R_i, R_∞ and fat mass by 1.7 ohms, 23.2 ohms, 2.6 ohms and 0.2 kg respectively. A year increase in age also resulted in a significant reduction of 0.2 L in both ICF and TBW. Age did not influence ECF. There were no interactions between electrode placement and age for any of the whole body BIS variables assessed.

BMI was also significantly associated with BIS variables, whereby a one unit increase in BMI resulted in significant decreases in R_0, R_i, R_∞ (table 2). A unit increase in BMI also resulted in a significant increase in ICF by 0.5 L, TBW by 0.7 L and fat mass by 1.4 kg. ECF was not influenced by BMI. There were no interactions between electrode placement and BMI for any of the BIS variables assessed.

3.3. Segmental BIS alternate electrode positions

Means and standard deviations for upper and lower limb segmental BIS variables for each electrode position are presented in table 3. For upper limb segmental BIS, there was no significant difference between the standard (UL1) and alternate (UL2) electrode positions for any of the BIS variables measured ($p = 0.393$–0.604) (table 4).

Age, gender and BMI were significantly associated with all of the upper limb BIS variables. Being of male gender resulted in significantly decreased R_0, R_i, R_∞ (table 4). A one

Table 1. Whole body BIS values obtained from the standard (WB1) and alternate electrode positions (WB2, WB3, WB4). Data presented as means (standard deviations) and difference (%) (of the value obtained from the standard position WB1).

BIS variable	WB1	WB2	WB3	WB4
R_0 (ohms)	619.32 (84.25)	607.33 (83.99)	619.62 (84.83)	609.82 (84.05)
R_0 (%)	—	−1.95 (2.02)	0.05 (1.65)	−1.54 (1.92)
R_i (ohms)	1458.41 (581.82)	1388.82 (540.40)	1470.61 (572.05)	1375.59 (544.99)
R_i (%)	—	−4.01 (−9.04)	1.65 (9.47)	−5.17 (8.37)
R_∞ (ohms)	428.19 (84.05)	416.61 (81.64)	429.77 (82.89)	416.13 (81.96)
R_∞ (%)	—	−2.63 (3.58)	0.49 (3.09)	−2.78 (3.08)
ECF (L)	17.45 (4.19)	17.69 (4.27)	17.45 (4.22)	17.64 (4.25)
ECF(%)	—	1.34 (1.38)	−0.02 (1.10)	1.06 (1.33)
ICF (L)	24.27 (6.63)	24.84 (6.59)	24.04 (6.31)	24.64 (6.67)
ICF (%)	—	2.68 (5.13)	−0.57 (4.83)	3.24 (4.68)
TBW (L)	41.72 (10.69)	42.53 (10.71)	41.49 (10.38)	42.63 (10.74)
TBW (%)	—	2.09 (3.19)	−0.36 (2.82)	2.32 (2.82)
FM (kg)	15.26 (6.94)	14.17 (7.31)	15.58 (7.08)	14.03 (7.50)
FM (%)	—	−10.42 (22.90)	2.49 (16.38)	−12.09 (22.90)

R_0 = resistance at zero frequency, R_i = intracellular resistance, R_∞ = resistance at infinite frequency, ECF = extracellular fluid, ICF = intracellular fluid, TBW = total body water, FM = fat mass.

unit increase in age significantly increased R_0, R_i, R_∞, and all upper limb BIS variables were significantly decreased with increasing BMI (table 4). There were no interactions between electrode placement and age, gender or BMI for any of the upper limb BIS variables assessed.

For lower limb segmental BIS, the results of the regression analysis demonstrated that in comparison to the standard electrode position LL1, the alternate electrode position LL2 significantly reduced R_0 and R_∞ values by −9.52 ohms ($p < 0.001$), and −11.06 ohms ($p < 0.001$) respectively (table 5).

Age, gender and BMI were significantly associated with some of the lower limb BIS variables. Being of male gender resulted in significantly decreased R_0, R_i, R_∞ (table 5). Increasing age resulted in significantly increased R_0, R_i, R_∞. There was a significant interaction between age and electrode placement for R_i, whereby the difference between LL1 and LL2 was decreased with increasing age (table 5). An increase in BMI resulted in significantly decreased R_i, however BMI did not significantly influence R_0 and R_{inf} (table 5). There were no interactions between electrode placement and gender or BMI.

4. Discussion

The results of this study demonstrated that for whole body BIS, if the drive and sense electrodes on the hand and wrist are moved to ventral positions, but the foot and ankle electrodes remained in the standard position (as in position WB3), then all whole body BIS variables were comparable to that of the standard electrode positioning (WB1). When electrode position WB3 was compared with the standard electrode position (WB1), with the exception of fat mass, the percentage differences in the values of the measured BIS variables were all less than 2% (range = 0.01 to 1.65%). These differences are within the typical variation for within day intra-individual total body resistance, which has been reported to range from 0.3 to 1.9% (Kushner and Schoeller 1986). Additionally, it has recently been reported that variations

Table 2. Changes in whole body BIS variables when alternate electrode positions (WB2, WB3 and WB4) are compared to the standard electrode position (WB1).

BIS variable	Covariate	Coefficient	*p*-value	95% confidence intervals	
				Lower	Upper
R_0 (ohms)	WB2	−11.9	<0.001[a]	−16.1	−7.9
	WB3	0.3	0.887	−3.8	4.4
	WB4	−9.5	<0.001[a]	−13.6	−5.4
	Male gender	−83.2	<0.001[a]	−125.3	−41.1
	Age	1.7	0.027[a]	0.2	3.3
	BMI	−8.1	0.018[a]	−14.8	−1.4
R_i (ohms)	WB2	−112.0	<0.001[a]	−157.7	−66.3
	WB3	−4.9	0.831	−50.7	40.7
	WB4	−131.0	<0.001[a]	−176.7	−85.3
	Male gender	−467.3	<0.001[a]	−689.1	−245.5
	Age	23.2	<0.001[a]	15.2	31.1
	BMI	−56.9	0.001[a]	−91.7	−22.3
	WB2#Male gender	90.5	0.008[a]	23.7	157.3
	WB3#Male gender	36.6	0.282	−30.1	103.4
	WB4#Male gender	102.8	0.003[a]	36.0	169.6
R_∞ (ohms)	WB2	−15.7	<0.001[a]	−21.3	−10.1
	WB3	0.5	0.866	−5.1	6.1
	WB4	−16.7	<0.001[a]	−22.2	−11.1
	Male gender	−85.5	<0.001[a]	−119.5	−51.5
	Age	2.6	<0.001[a]	1.3	3.8
	BMI	−8.2	0.003[a]	−13.6	−2.9
	WB2#Male gender	8.8	0.033[a]	0.7	16.9
	WB3#Male gender	2.4	0.571	−5.8	10.5
	WB4#Male gender	9.8	0.018[a]	1.7	17.9
ECF (L)	WB2	0.2	<0.001[a]	0.2	0.3
	WB3	0.1	0.973	−0.1	0.1
	WB4	0.2	<0.001[a]	0.1	0.3
	Male gender	7.3	<0.001[a]	5.9	8.8
ICF (L)	WB2	0.6	0.002[a]	0.2	0.9
	WB3	−0.2	0.211	−0.6	0.1
	WB4	0.7	<0.001[a]	0.4	1.1
	Male gender	8.1	<0.001[a]	5.7	10.5
	Age	−0.2	<0.001[a]	−0.3	−0.1
	BMI	0.5	0.020[a]	0.1	0.8
TBW (L)	WB2	0.8	<0.001[a]	0.4	1.2
	WB3	−0.2	0.258	−0.6	0.2
	WB4	0.9	<0.001[a]	0.5	1.3
	Male gender	14.6	<0.001[a]	10.9	18.4
	Age	−0.2	0.002[a]	−0.4	−0.1
	BMI	0.7	0.025[a]	0.1	1.3

(*Continued*)

Table 2. (*Continued*)

BIS variable	Covariate	Coefficient	*p*-value	95% confidence intervals	
				Lower	Upper
FM (kg)	WB2	−1.1	<0.001[a]	−1.6	−0.6
	WB3	0.3	0.258	−0.2	0.9
	WB4	−1.2	< 0.001[a]	−1.8	−0.7
	Male gender	−4.4	0.016[a]	−7.9	−0.8
	Age	0.2	0.001[a]	0.1	0.4
	BMI	1.4	<0.001[a]	0.8	1.9

R_0 = resistance at zero frequency, R_i = intracellular resistance, R_∞ = resistance at infinite frequency, ECF = extracellular fluid, ICF = intracellular fluid, TBW = total body water, FM = fat mass. $p < 0.05$

Table 3. Upper and lower limb segmental BIS values obtained from the standard (UL1 and LL1) and alternate electrode positions (UL2 and LL2). Data presented as means (standard deviations) and difference (%) (of the value obtained from the standard position UL1 and LL1).

	Upper limb		Lower limb	
	UL1	UL2	LL1	LL2
R_0 (ohms)	314.20 (54.74)	313.14 (53.83)	275.05 (32.37)	265.53 (32.58)
R_0 (%)	—	−0.24 (3.76)	—	−3.47 (3.50)
R_i (ohms)	797.35 (403.06)	816.89 (429.62)	656.60 (218.24)	587.72 (199.85)
R_i (%)	—	3.51 (15.42)	—	−10.35 (8.67)
R_∞ (ohms)	220.68 (52.70)	221.43 (51.76)	191.62 (31.92)	180.55 (31.26)
R_∞ (%)	—	0.61 (4.59)	—	−5.79 (4.82)

R_0 = resistance at zero frequency, R_i = intracellular resistance, R_∞ = resistance at infinite frequency.

Table 4. Changes in upper limb segmental BIS variables when the alternate electrode position (UL2) was compared to the standard electrode position (UL1).

BIS variable	Covariate	Coefficient	*p*-value	95% confidence intervals	
				Lower	Upper
R_0 (ohms)	UL2	−1.06	0.604	−5.05	2.94
	Male gender	−63.38	<0.001[a]	−86.56	−40.20
	Age	0.85	0.047[a]	0.01	1.70
	BMI	−5.99	0.001[a]	−9.68	−2.30
R_i (ohms)	UL2	19.54	0.393	−25.31	64.39
	Male gender	−289.20	0.003[a]	−481.16	−97.25
	Age	14.33	<0.001[a]	7.33	21.32
	BMI	−47.10	0.003[a]	−77.65	−16.52
R_∞ (ohms)	UL2	0.75	0.672	−2.76	4.25
	Male gender	−58.20	<0.001[a]	−78.76	−37.85
	Age	1.21	0.001[a]	0.46	1.95
	BMI	−5.83	<0.001[a]	−9.07	−2.59

R_0 = resistance at zero frequency, R_i = intracellular resistance, R_∞ = resistance at infinite frequency. $p < 0.05$

Table 5. Changes in lower limb segmental BIS variables when the alternate electrode position (LL2) was compared to the standard electrode position (LL1).

				95% confidence intervals	
BIS variable	Covariate	Coefficient	*p*-value	Lower	Upper
R_0 (ohms)	LL2	−9.52	<0.001[a]	−12.86	−6.17
	Male gender	−21.99	0.027[a]	−41.54	−2.45
	Age	0.83	0.027[a]	0.10	1.60
R_i (ohms)	LL2	−5.20	0.854	−60.62	50.23
	Male gender	−116.88	0.005[a]	−198.22	−35.55
	Age	11.38	<0.001[a]	8.34	14.42
	BMI	−12.13	0.066	−25.08	0.82
	LL2#Age	−1.68	0.017[a]	−3.05	−0.30
R_∞ (ohms)	LL2	−11.06	<0.001[a]	−14.13	−8.01
	Male gender	−23.71	0.002[a]	−38.98	−8.44
	Age	1.24	<0.001[a]	0.66	1.81

[a] $p < 0.05$, R_0 = resistance at zero frequency, R_i = intracellular resistance, R_∞ = resistance at infinite frequency.

in some BIS variables below 5.6%, may be considered measurement error (Pichonnaz *et al* 2015). Although the percentage difference in fat mass between WB1 and WB3 was 2.49%, the absolute difference in fat mass was only 0.32 kg which was not statistically significant. Therefore the alternate electrode position WB3, where ventral hand and wrist electrode placements are utilised, is a suitable alternative for measuring whole body impedance when wounds are present on the dorsal surface of hands and/or wrists.

In contrast, when the drive and sense electrodes on the foot and ankle were moved ventrally (WB2 and WB4), whole body BIS variables were generally not within the range of the typical variations expected, when compared with the standard electrode position (WB1). This was regardless of whether the wrist and hand electrodes were placed in the standard (WB4) or alternate (WB2) position. There were statistically significant differences in all raw and predicted BIS values when electrode positions WB2 and WB4 were utilised. This was also reflected in the percentage change scores. When electrode position WB2 was compared with the standard electrode position, the mean percentage differences in the raw and predicted values of the measured BIS variables ranged from 1.345–10.42%. Likewise, when electrode position WB4 was compared to WB1, the percentage differences in measured BIS variables ranged from 1.06–12.09%. Using the alternate electrode positions WB2 and WB4, TBW, ECF and ICF were all significantly overestimated, when compared with the standard electrode position. Changes in ECF were the smallest (~0.24 L), with the changes in FM resulting in the largest discrepancies (~1.2 kg). The statistically significant differences in BIS values would not support the clinical use of the alternate positions WB2 and WB4.

The results of the upper limb segmental BIS analysis were in line with the results obtained for the whole body analysis. For upper limb segmental BIS, when the drive electrodes on the hand and foot are moved to ventral positions, and both wrist sense electrodes are positioned on the ventral surface of the right and left wrists (as in position UL2), then all upper limb segmental BIS variables were comparable to that of the standard electrode positioning (UL1). The differences in upper limb resistance values ranged from 0.24–3.51%. While the difference in upper limb R_i of 3.51% is greater than the typical variation for within day intra-individual total body resistance reported by Kushner and Schoeller (1986), this change was not statistically significant and we feel this change is not clinically significant. However, for lower limb segmental BIS, in comparison to the standard electrode position (LL1), the alternate electrode position (LL2) significantly reduced all measured BIS variables. The differences in lower limb resistance values ranged from 3.47–10.35%. Therefore it appears that only the alternate upper limb position is able to be utilised clinically.

In the standard electrode position, all electrodes were placed over hairy skin, whereas the ventral foot positioning required that the drive electrode be positioned on glabrous skin, on the sole of the foot. Given anatomical differences exist between the glabrous and hairy skin types, this may be responsible for the differences in BIS variables when alternate positions WB2 and WB4 were utilised. Impedance of skin is affected by the thickness of the stratum corneum (Birgersson *et al* 2011). Stratum conreum is much thicker in glabrous skin (on the sole of the foot and palm of the hand), which therefore has the potential to affect BIS results. It has been demonstrated that the skin receptors in the glabrous skin of the foot have elevated activation thresholds in comparison with the glabrous skin of the hand, which is likely to have resulted from an increased skin thickness in the foot in comparison with the hand (Kennedy and Inglis 2002). This may explain why ventral positioning of hand electrode did not affect whole body BIS measures, but ventral foot placement of electrodes did.

A second explanation for the differences in BIS variables when ventral foot and ankle electrode positions were utilised is that the distance between the drive and sense electrodes on the foot and ankle may not have been at equivalent distances from one another when standard and alternate positions were utilised. It has been demonstrated that reducing the distance between the drive and sense electrodes results in increased impedance (Shiffman 2013) and that fixed distance electrodes reduce the reproducibility errors associated with BIS (Moon *et al* 2010). While we ensured that the drive and sense electrodes were positioned at least 5 cm apart, the actual distance between the two electrodes was not recorded. This is a limitation of this study, as the possibility of variable differences between drive and sense electrodes in the different electrode configurations may further confound the impedance results as demonstrated by Shiffman (2013). Nevertheless, further research is required to determine an improved alternative position for foot and ankle electrodes if standard positioning is inhibited by wounds. Going forward, alternative positions should control the distance between drive and sense electrodes in standard and alternate electrode positions.

The majority of the BIS variables for the whole body and segmental analysis were influenced by age, gender and BMI. This is to be expected given that it is well accepted that age, gender and BMI influence body tissue resistance (R_i, R_0 and R_∞) and fluid distribution parameters (ECF, ICF, TBW). The fluid distribution parameters are calculated by the SF-B7 software, using regression equations available in the literature, which utilise the raw resistance BIS variables as well as age, gender and BMI. The interaction between electrode placement and gender seen in the raw BIS variables R_i and R, was not evident in the calculated fluid distribution parameters once gender had been accounted for in the regression equations. Interestingly ECF was not influenced by age and BMI, so appears to be the measure that is least effected by participant variables. Additionally ECF demonstrated the smallest percentage change in response to changing electrode positions, out of all of the BIS variables measured (table 1). The percentage change values in ECF ranged from 0.01–1.35% regardless of whether position WB2, WB3 or WB4 was used. These differences are within the typical variation for within day intra-individual variation (0.3–1.9%), reported by Kushner and Schoeller (1986). This may be of particular importance given that ECF is the variable of interest when measuring fluid parameters in a patient population. If we can demonstrate that ECF is sensitive to known fluid changes over time, but is not influenced by age, BMI and electrode placement, then the use of BIS to measure ECF may become a useful clinical tool in the assessment and management of oedema and fluid resuscitation, even if wounds are present over the standard electrode placements.

In conclusion, if wounds or dressings are present on the hands and/or wrist, then the results of this study provides alternate electrode positioning, whereby electrodes can be placed on the ventral surface of the hand and wrist for whole body and upper limb segmental BIS. Further research is required to determine an optimal alternate positioning of ankle and foot electrodes. Additionally ECF may be a variable that can be validly measured, regardless of electrode placement.

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