

Invited Review

Bioelectrical Impedance: From Theories to Applications

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ABSTRACT

Total body bioelectrical impedance is a measure for total body water. From total body water the fat free mass and, by difference with body weight, the fat mass (body fat percent) can be calculated. Prediction formulas for body fat percent based on impedance assume a constant hydration of the fat free mass, an assumption that might be violated in individuals, thus resulting in biased individual predictions. The electrical properties of the human body depend on water distribution between extra- and intra-cellular space and also on geometrical water distribution. In addition, body build factors also influence total or segmental impedance values. As body build and water distribution can differ between populations, impedance formulas aiming to quantify water compartments or body fat percent should also be population specific. In addition other factors like body position, skin and/or body temperature and osmotic values of the body fluids have an impact on the measured impedance values. This, together with likely disturbances in body water distribution in patients, makes the quantitative use of impedance in clinical practice difficult and prone to misinterpretations.

For the prediction of body fat percent in populations, the method can be suitable. But, as there are differences in body build between (ethnic) population groups, for example in relative leg length and in slenderness, it is likely that that prediction formulas have different bias across ethnic groups. This means that for meaningful comparisons between population groups, formulas have to be validated in these groups.

INTRODUCTION

The organisation of body composition into five distinct levels by Wang *et al.* (1992) is generally accepted now as a easy and helpful tool in the understanding of body composition and body composition changes. According to Wang *et al.* (1992) all body composition methods can be categorised in one of these five levels: atomic (I), molecular (II), cellular (III), tissue (IV) or whole body (V).

Bio-electrical impedance is a method that can be classified under different levels of body composition research (Heymsfield & Wang, 1994). In the impedance method, the resistance or impedance of the body towards an electrical current is measured. As the conductivity of the

current is determined mainly by the amount of water (and its dissolved electrolytes), the impedance method measures body water on a molecular level. The physical properties of the cell membranes cause a reactance to the applied current which is related to the amount of body cell mass. Thus impedance is also linked to body composition on the cellular level. Finally, the geometry of the body and of body segments influence the measured impedance and/or reactance values and hence impedance is also a body composition technique that measures at level V, the whole body level.

These considerations are not only of theoretical importance. In this short paper, the practical importance of this will be indicated. In addition, other information that is important for the interpretation of body impedance values is discussed.

The molecular level and bioelectrical impedance

In bioelectrical impedance, a small alternating current is applied to the body. The body is able to conduct the current due to the presence of electrical conductive materials, which are all in the fat free mass of the body. The main conductor is water, which is, however, only able to conduct the current due to the dissolved electrolytes (extra cellular: sodium; intra cellular: potassium). Provided that the applied current is able to penetrate the cell membranes, the measured resistance or impedance is theoretically inversely proportional with the amount of total body water (Lukaski *et al.*, 1985):

$$R = \rho \times \frac{L}{A} \text{ (Ohm)} \quad \text{(I)}$$

$$R = \rho \times \frac{L \times L}{A \times L} \text{ (Ohm)} \quad \text{(II)}$$

$$A \times L = V = \rho \times \frac{L^2}{R} \text{ (kg)} \quad \text{(III)}$$

R = resistance (Ohm) is proportional with length of conductor (L e.g. body height) and specific resistivity (ρ) and inversely proportional with cross-sectional area (A) of the conductor. The specific resistivity depends on kind and amount of electrolytes and temperature. Multiplying the right side of equation (I) with L/L and re-arranging the equation II results in equation III, which is the basis for quantitative assessments of the volume (V) of total body water.

It is known that not all electrical current passes the cell membrane and that at very lower frequencies the current only passes the extra cellular fluids, due to the high reactance of the cell membrane. At higher frequencies the reactance of the cell membranes decreases and consequently with increasing frequency not only extra cellular water is measured but also an increasing part of intra cellular water.

The multi-frequency impedance technique can be used to assess body water compartments (NIH, 1994). Prediction equations using body impedance at low frequencies (1-5 kHz) provide estimates of extra cellular water (ECW) and at higher frequencies (> 50 kHz) total body water

(TBW) can be predicted. From TBW, the fat free mass can be calculated, assuming that 73% of the fat free mass consists of water. This opens the possibility to use bioelectrical impedance to assess body fat percent. As body impedance is not only determined by the amount of body water but also by other factors like body water distribution, body build, body temperature and osmolarity, prediction formulas developed in healthy populations may not be valid under clinical conditions when usual used assumptions are violated (NIH, 1994). This explains the often-reported observation that, despite a used prediction formula showing a significant bias, the relationship between measured body water compartments and impedance is high, also in groups of patients. Many authors conclude from this that ‘population specific’ prediction formulas should be used. This, however, can be questioned, as it would in fact require ‘a priori’ information on the subject’s body composition.

The cellular level and bioelectrical impedance

The cell membrane behaves as an electrical capacitor and as such causes a reactance when current is applied to the body. The reactance value is theoretically related to the amount of cells, thus giving information on body composition at the cellular level. Reactance is not the only indicator that gives body composition information on the cellular level. Impedance measurements at low and high frequencies also provide information on the amount of extra cellular water and total water respectively, and by difference the amount of intra-cellular water can be calculated.

Several studies on multi-frequency impedance, also those using Cole-Cole modelling of impedance data, show that the resistivity of the intra-cellular water component is higher compared to the extra cellular water component (Marken Lichtenbelt van *et al.*, 1994; Deurenberg *et al.*, 1995). The consequence is that differences in water distribution between- and within-subjects are responsible for relatively large variations and fluctuations in body impedance values, both at low as well as at high frequency. At high levels of extra cellular water compared to total body water (as in oedema) the amount of extra cellular water at low frequency is under predicted and the amount of total body water is over predicted (Deurenberg *et al.*, 1995). This is a serious drawback of the impedance methodology as it limits the validity of predicted values of body water compartments in subjects with disturbances in water homeostasis (NIH, 1994).

The whole body level and bioelectrical impedance

The geometry of the body is important in impedance measurements. Total resistance depends on the lengths of the conductor as well as the cross-sectional area (Lukaski *et al.*, 1985). Baumgartner *et al.* (1989) reported disproportionate impedance values of extremities and trunk in comparisons with their water content. Figure 1 shows in a calculation example what the consequences are for the validity of the prediction of TBW when water changes are predominantly in the trunk. In the subject, (Figure 1), there is an increase in water in the trunk e.g. due to ascites. That will lower impedance values of the trunk but impedance of arm and leg will not be affected. As the trunk impedance is low (due to relative short length and large cross-sectional area) the change in trunk impedance will be relatively small and consequently the change in total body water is underestimated. Thus, although the actual change in total body water in the example is more than 7 kg, the corresponding change in total body impedance is not

more than 12 Ohm from which a change in body water of only 1.3 kg can be calculated. This theoretical calculation example is in accordance with findings in the literature on intra-peritoneal fluid loss (Guglielmi *et al.*, 1991).

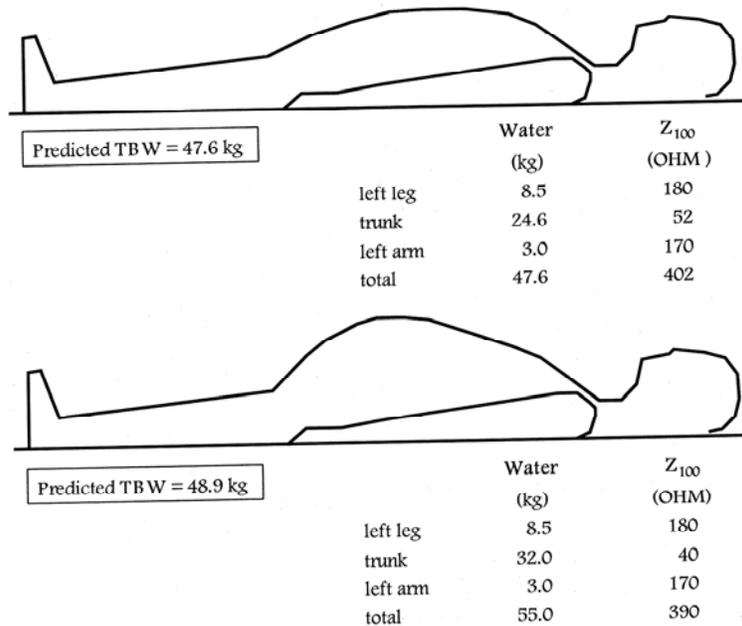


Figure 1. Calculation example of disproportionate changes in impedance and body segments in relation to body water.

Legend:

Upper subject: normal values, water amounts calculated from DXA measurements assuming water to be 73% of lean mass;

Lower subject: assumed (30%) increased trunk volume only, resulting in a 30% decrease in trunk impedance (impedance and volume are inversely related); used prediction formula:

$$TBW = 0.513 * Height^2 / Z_{100} + 6.3 \quad (6)$$

Table 1. Changes in body water compartments and their impact on impedance at low and high frequency and on the impedance ratio

Changes in:	TBW	ECW	ICW	ECW/TBW	Z _{low}	Z _{high}	Z _{low} /Z _{high}
	↓↓	↓	↓↓	==	↑↑	↑↑	==
	↓↓	==	↓↓	↑↑	==	↑*	↓*
	↓↓	↓	==	↓	↑↑	↑↑↑*	↑↑↑*
	↑↑	↑↑	↑↑	==	↓	↓	==
	↑↑	==	↑↑	↓	==	↓*	↑*
	↑↑	↑↑	==	↑↑	↓	↓↓↓*	↓↓↓*
	==	↑↑	↓	↑↑	↓	↓*	↓*
	==	↓	↑↑	↓	↑↑	↑↑↑*	↑↑↑*
	==	==	==	==	==	==	=

TBW: total body water; ECW: extra cellular water; ICW: intra cellular water, Z_{low} : impedance at low frequency; Z_{high} : impedance at high frequency qq: increase in the parameter; QQ: decrease in the parameter; == : no change in the parameter; * relative high or low change due to changes in specific resistivity of total body fluid.

Other factors influencing body impedance measurements

The effect of skin temperature on impedance has been reported many years ago (Caton *et al.*, 1988), but until now no paper on the effect of body temperature has been published. In theory impedance values are lower when body temperature is higher. This has to be borne in mind when patients with fever are measured, but it could also influence impedance measurements in the tropics. Measurements made under laboratory conditions (air-conditioned room) could be higher than measurements made under field conditions in the open air.

Several authors reported the impact of different plasma osmolarity on impedance values. Roos *et al.* (1989) demonstrated, using infusions of either mannitol or saline, that impedance changes are related to sodium concentration in plasma. This is predictable, as the electrolytes in the body fluid are responsible for the conductivity of the water compartment. We observed in a study in elderly subjects with disturbed water homeostasis that very low plasma sodium values coincided with higher impedance values (unpublished results).

Several studies show the impact of body position and the time being supine before the actual impedance measurements are performed (Gudivaka *et al.*, 1994). Differences up to 30–50 Ohms can be the result of not standardising the time being supine before the measurements. The effect is explained by differences in water distribution over the trunk and the extremities, due to gravity. In practice, it means that patients must always be measured in the morning, before getting up to avoid ‘changes’ in impedance over time not due to treatment or diseased state.

Apart from the mentioned factors impedance in clinical practice may be characterised by difficulties in the standardisation of the measurements. It will not always be possible to have the measurements done by the same observer and differences in electrode placement, for example, can cause a remarkable error (NIH, 1994; Deurenberg, 1994).

All these factors indicate the difficulty in using prediction formulas based on impedance for body water (compartments) in clinical practice. It can be concluded from this that in clinical practice it may only be useful to use absolute changes in impedance and perhaps changes in impedance ratios as measures of body water changes/shifts. As body water shifts may be different in extremities compared to the trunk, impedance measurements of body segments may provide additional information, or even better information on water shifts. Table 1 (Deurenberg & Schutz, 1995) indicates how impedance changes at low and at high frequency, as well as changes in the impedance ratio Z_1/Z_{100} are indicative of changes in water compartments. It has to be realized that small changes in body water compartments will only result in such small changes in impedance that the normal variability level is not exceeded.

Up to now, only a limited number of studies has been published in which the impedance methodology was used in clinical practice for monitoring patients. A good example of such a

study is the follow up of patients after cardio-pulmonary bypass surgery (Korsten *et al.*, 1989) where impedance changes over the chest were used as a measure of fluid imbalance. The use of impedance after dialysis (De vries, 1989), although rather promising, is not yet widely used for monitoring the dialysis process.

It can be concluded that, due to different error sources, a *quantitative* interpretation of impedance is difficult and is, especially in an individual, unreliable. Changes in impedance and in impedance ratios may be more useful as *qualitative* indicators for changes in body water compartments. Measurements of body segments may provide additional information, but again standardisation of the electrode placement is absolutely necessary.

Segmental impedance measurements

In recent years there has been new developments in impedance methodology. For monitoring body fat percent for the 'general public', impedance analysers incorporated in weighing scales have been developed (TANITA® and TEFAL® body fat monitors), and other instruments (OMRON®, YAMATO®) measure impedance from hand-to-hand and use this value, together with pre-entered personal data to calculate body fat percent. Although these instruments have the advantages of ease of use and affordability (because of mass production), the obtained values of body fat percent remain estimates and are theoretically slightly less accurate compared to the 'classical' tetra polar instruments (Deurenberg *et al.*, in press). As impedance is related to the length of the conductor and inversely related to its cross-sectional area, it can be argued that instruments measuring segmental impedance give relatively high impedance values in subjects with long (and thin) extremities and consequently body fat percent is likely to be overestimated. As there are marked differences between ethnic groups in body build, for example Chinese and Malays having relatively shorter legs and arms than Indians, the use of those instruments in comparing body composition between ethnic groups may lead to systematic biases. In a recent paper this issue was addressed for Chinese, Malays and Indians in Singapore (Deurenberg & Deurenberg, 2001). As the incorporated formulas in those instruments may have been developed in populations with different body composition and body build, systematic biases in applying it to local populations may occur.

CONCLUSIONS

Bioelectrical impedance provides a measure of water and dissolved electrolytes and can be used to predict total body water. From total body water, body-fat percent can be calculated, assuming a constant hydration of the fat free mass. The obtained value is dependent on many factors that have to be borne in mind in interpreting the values. Impedance can provide information on body fat percent at a population level as long as used prediction formulas are validated in the population under study. For use in individual patients, be it for the estimation of water compartments, or for the estimation of body fat percent, the error in calculated quantitative figures could be too high to be the measurement of practical value. In such a situation, a qualitative judgement of a change in impedance may be more appropriate.

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