Simulating Non-Specific Influences of Body Posture and Temperature on Thigh-Bioimpedance Spectroscopy during Continuous Monitoring Applications

A H Ismail and S Leonhardt
Philips Chair of Medical Information Technology, RWTH Aachen University,
Pauwelsstrasse 20, 52074 Aachen, Germany
E-mail: ismail@hia.rwth-aachen.de

Abstract. Application of bioimpedance spectroscopy (BIS) for continuous monitoring of body fluid volumes is gaining considerable importance in personal health care. Unless laboratory conditions are applied, both whole-body or segmental BIS configurations are subject to non-specific influences (e.g. temperature and change in body position) reducing the method’s accuracy and reproducibility. In this work, a two-compartment mathematical model, which describes the thigh segment, has been adapted to simulate fluid and solute kinetics during change in body position or variation in skin temperature. The model is an improved version of our previous one offering a good tradeoff between accuracy and simplicity. It represents the kinetics of fluid redistribution, sodium-, potassium-, and protein-concentrations based on simple equations to predict the time course of BIS variations. Validity of the model was verified in five subjects (following a sequence of 7 min supine, 20 min standing, and 40 min supine). The output of the model may reduce possible influences on BIS by up to 80 %.

1. Introduction
Recent advances in personal health care demonstrated the feasibility of applying bioimpedance spectroscopy (BIS), as an alternative for gold standard methods, to determine human body composition (e.g. fat / fluid content). Beyond non-invasivity and simplicity of the method, our obvious advantage would be the option for real-time continuous monitoring if integrated into daily clothes via textile electrodes. Such a scenario would be highly favourable from a dialysis patient point-of-care, as it would offer a bridge between inter- and intra-dialectic health monitoring.

Despite aforementioned advantages, non-specific factors (as changes in skin temperature, body posture, and / or consumption of food and beverage) can limit the method’s accuracy and reproducibility. Accordingly, several authors have suggested application of standardize “laboratory” conditions (include performing the measurements in supine position after a period of recumbence up to 10 min and, when possible, always at the same time of the day [1]) and appropriate physiological models [2, 3] to achieve adequate detection limit for clinical measurement of hydration status.

Unfortunately, these conditions cannot always be fulfilled, and alternative tools are required to maintain the reliability of the BIS method.

In this sense, this article presents a two-pool physiological model, representing the thigh segment, to simulate potential changes in BIS-measured data associated with changes in body posture and / or skin temperature. The model is an improved version of our previous one [4] offering a good compromise between accuracy and simplicity. It includes additional solutes (Na⁺, K⁺, Cl⁻) with their excreted...
osmotic pressure, enhanced description of lymphatic system, modelling of protein transport across capillary membrane, and influence of variations in skin temperature on physiological parameters

2. Material and methods

Influence of body posture on body fluids: Changing body’s orientation in space leads to different hydrostatic blood pressures due to gravity altering the hydrostatic and osmotic pressures balance between body compartments. As a result, fluid redistribution takes place. Maw et al. [5] have showed that this fluid redistribution is limited to extracellular space and no significant change in intracellular fluid is expected. Based on all aforementioned factors, in this work the influence of body posture on BIS was simulated only extracellular (between plasma and interstitial spaces) using a two-pool model as described below.

Two-pool model: Fluid redistribution between interstitial (IntF) and plasma (Pl) compartments under the influence of changes in body posture are described considering the fluid’s filtration through capillaries ($Q_{cap}$) and the action of lymphatic pump ($Q_{lym}$), as following

$$\frac{dV_{IntF}(t)}{dt} = -\frac{dV_{oIntF}(t)}{dt} = -Q_{cap}(t) + Q_{lym}(t)$$  \tag{1}

Following the Starling equations [6, 7], filtration rate across capillaries is calculated based on hydrostatic and osmotic pressure gradients in both compartments [8], given

$$Q_{cap}(t) = K_f \left[ (P_{cap}(t) - P_{oIntF}(t) - \Pi_{t.(n,PL)}(t) - \Pi_{t.(o,IntF)}(t)) - \sum_s (\Pi_{s,PL}(t) - \Pi_{s,IntF}(t)) \right]$$  \tag{2}

where $P$ represents the hydrostatic pressure in the capillaries ($P_{cap}$) and in the interstitial compartment ($P_{IntF}$), and $K_f$ is the fluid filtration coefficient. The osmotic pressure in each compartment includes that excreted by protein ($\Pi_{o,PL}$) and by small ions ($\Pi_t$) respectively, where the subscript $s$ accounts for the ions of sodium ($Na^+$), potassium ($K^+$), and chloride ($Cl^-$). Protein osmotic pressure was determined as a function of protein concentration ($C_{Pro}$) as follows [9];

$$\Pi = 2.1 \cdot C_{Pro} + 0.16 \cdot C_{Pro}^2 + 0.009 \cdot C_{Pro}^3$$  \tag{3}

The hydrostatic pressure in IntF is determined by the actual interstitial fluid volume ($V_{IntF}$) and the tissue’s compliance. In order to calculate the change in ($P_{IntF}$), the curve presented in [10] was expressed in terms of relative amount of IntF’s volume to pressure, and a mathematical approximation for $P_{IntF}$ were obtained using fitting curve algorithm

$$P_{IntF}(t) = \frac{-1}{0.3 \cdot \left[ V_{IntF,end}(t) - 0.61 \right] + 5.17}$$

$$V_{IntF,end}(t) = \frac{V_{IntF}(t)}{V_{IntF}(0)}$$  \tag{4}

Protein transport rate across the capillary membrane was modelled according to [8, 11] considering protein reflection coefficient ($\eta$) and protein permeability-surface area product (PS)

$$Q_{n,o} = Q_{lym}(1 - \eta) \left[ \frac{C_{Pro,o,PL} - C_{Pro,o,IntF}}{e^{\frac{\eta}{PS}}} \right] \left[ e^{\frac{\eta}{PS}} - 1 \right]$$  \tag{5}

The lymphatic system was described as a nonlinear relationship between lymphatic flow rate ($Q_{lym}$) and the interstitial pressure ($P_{IntF}$) considering lymphatic flow sensitivity (LS), according to [8, 12]
where $P_{\text{IntF,ex}}$ is the interstitial pressure corresponding to the excluded interstitial volume, and $Q_{\text{Lym,norm}}$ and $P_{\text{IntF,norm}}$ are the normal steady state value of $Q_{\text{Lym}}$ and $P_{\text{IntF}}$, respectively.

**Influence of temperature on BIS:** Body response to change in skin temperature involves different mechanisms as vasodilatation and changes in cardiac output. Levick and Michel [13] reported different capillary pressures ($P_{\text{Cap}}$) in relation to change in skin temperature ($T_s$). Based on their values, a mathematical approximation linking both parameters was drawn in this work as follows

$$P_{\text{Cap}} = 2.4 \cdot K_T \cdot T_s - 47.1 \quad \forall \quad 20 \leq K_T \cdot T_s \leq 40 \quad (7)$$

where $K_T$ is a temperature coefficient defined as the ratio between interstitial ($T_{\text{IntF}}$) and skin ($T_s$) temperatures. $K_T$ is applied for the thigh segment at which thickness of fat layer cannot be ignored and may cause that $T_{\text{IntF}}$ and $T_s$ is not equal. Additionally, conductivity of electrolytes depend on temperature as shown by [14], which can be expressed in case of IntF using reference conductivity ($\sigma_{\text{IntF,0}}$) and temperature ($T_{s,0}$) values, respectively.

$$\sigma_{\text{IntF}} = \sigma_{\text{IntF,0}} \cdot [1 + 0.02\% \cdot K_T \cdot (T_s - T_{s,0})] \quad (8)$$

**Study design:** Thigh segmental BIS was performed on 5 healthy male test subjects (2 for control) aged between 22 and 26, using a commercial bioimpedance device (Xitron Hydra 4200, Xitron Technologies Inc., San Diego, CA, USA) and tetra-polar standard hydrogel-aluminum BIS electrodes (Fresenius Medical Care, Bad Homburg, Germany). A sequence of 7 min supine, followed by 20 min standing, and then 40 min supine position (scenario 1) was applied to simulate influence of body posture on BIS. To study effect of temperature on BIS, ambient temperature was heated-up starting from 25 ± 1°C to 40 ± 1°C and then cooled down to 10 ± 1°C, each within 50 min phase (scenario 2), and variations in skin temperature were detected using an infrared camera (Vario CAM hr head, Infratec, Dresden, Germany). Measurements were done every 5 min (scenario 1) or 17 min (scenario 2), and each one was an average of five runs made every 3 sec. Cole-Cole model [15] was fitted to the measured data to extract extracellular resistance (Re) values. A period of at least 4 hours without eating or drinking and 48 hours without heavy physical exercises were prerequisites for the tests.

3. Results and discussion

The thigh segment’s extracellular resistance (Re) increases during the supine position and very quickly decreases during the vertical position with measured $\Delta$Re (% Re) of -4.55 ± 0.31 (standing 20 min) and 5.12 ± 0.22 (supine 40 min) for all subjects. The simulations are in agreement with the measured data. The mean values of difference between measured and simulated data, in % of initial measured Re, for all subjects are 0.67 ± 0.21 % (standing 20 min) and 0.89 ± 0.16 % (supine 40 min), respectively. During ambient temperature’s change, measured $\Delta$Re (% Re) was -5.71 ± 2.81 (heat-up) and 12.92 ± 5.39 (cool-down), while simulated values were relatively higher with -8.74 ± 5.78 (heat-up) and 15.47 ± 8.14 (cool-down). An example from two selected test subjects is given in figure 1. The presented results suggested the capability of the model to reproduce influences of selected external factor on thigh-BIS data. Nevertheless, the applicability of the model could be extended to other body segments if appropriate adaptation was applied. Sensitivity analysis (data not shown) suggested that slope of the mathematical approximation (equation 7) is the most important element affecting the accuracy of the temperature model. As this approximation is based on published results of only two subjects (the authors themselves [13]), this could explain the relatively higher obtained simulation error. Finally, if the presented model were to be applied for determining effective changes...
in thigh’s fluid during specific amount of time, while removing non-specific influences and given actual body posture profile, error in BIS could be reduced by up to 79.45 %.

![Figure 1](image-url)

**Figure 1.** Measured and simulated thigh-Re values under the influence of changes in body posture (a) and ambient temperature (b).

4. Conclusion

The application of a physiological model for reducing artefact in BIS data is highly attractive, as it may enable measuring scenarios where BIS accuracy is questionable. Based on our results, the model reduces the influences of changes in body posture and temperature on BIS by up to 80 %. Despite that, further improvements to the presented method are still necessary, especially if the human thermoregulatory response (passive and active system), validity of the model for all body segments, and the individual difference in body composition are considered.

References

[1] Fresenius Medical Care 2006 Body composition monitor (BCM) operating instructions.
[2] Krämer M, Rode C, and Wizemann V 2006 *Kidney Int.* **69** 1609.
[3] Chamney P W, Krämer M, Rode C, and Wizemann V 2002 *Kidney Int.* **61** 2250.
[4] Medrano G, Eitner F, Walter M, and Leonhardt S 2010 *Med. Biol. Eng. Comput.* **48** 531.
[5] Maw G, Mackenzie I, and Taylor N 1995 *Acta Physiol Scand* **155** 157.
[6] Guyton A C 1986 *Textbook of Medical Physiology 7th ed.* (Philadelphia: W. B. Saunders Co.) pp 382 – 392.
[7] Levick J R 1995 Changing perspectives on microvascular fluid exchange. In: Cardiovascular Regulation ed D Jordan, and J Marshall. (London: the Physiological Society, Portland Press) pp 127–132.
[8] Fernandez Canete J and Del Saz Huang P 2010 *Comput. Biol. Med.* **40** 740.
[9] Hamilton W 1965 *Handbook of physiology* ed P Dow (Washington DC: Waverly Press) pp 961–1034.
[10] Guyton A, Granger H, and Taylor A 1971 *Physiol. Rev.* **51** 527.
[11] Bresler E H and Groome L J 1981 *Am. J. Physiol.* **241** 468
[12] Chapple C, Bowen B D, Reed R K, Xie S L, and Bert J L 1993 *Comput. Methods Programs Biomed.* **41** 33.
[13] Levick J R and Michel C C 1978 *J. Appl. Physiol.* **274** 97.
[14] Grimnes S and Martinsen O 2008 *Bioimpedance and bioelectricity basics.* (New York: Academic Press).
[15] Cole K and Cole R 1941 *J. Chem. Phys.* **9** 341.