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Bioimpedance Spectroscopy as a Non-invasive Method of Determination of the Hydration Status in Hemodialysis Patients

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KEY WORDS

Body composition monitor, body composition model, bioimpedance spectroscopy, dielectric dispersion, collapsibility index, inferior vena cava, hemodialysis, hydration status, optimal dry weight

ABSTRACT

In this article we introduced a new diagnostic device Body Composition Monitor (BCM) by Fresenius, which use for the determination of hydration status in hemodialysis patients the bioimpedance spectroscopy technique (measurements at 50 frequencies, from 5 to 1 000 kHz) and a unique three-compartment body composition model. Brief description of the physical principle of bioimpedance spectroscopy measurements is

followed. In final section, we compared the results of measurements using BCM with traditional ultrasound method (collapsibility index of inferior vena cava CI–IVC – measurement of diameter and the collapse of IVC) by correlation analysis. We confirmed a statistically significant correlation between both methods.

INTRODUCTION

Achievement of a normal hydration status of patients with chronic renal disease and assessment of optimal dry body weight in hemodialysis patients is one of the most important goals for nephrologists. Increased hydration may cause in these patients various cardiovascular complications, e.g. cardiac decompensation and circulatory collapse associated with pulmonary and peripheral edema, volume dependent hypertension, and left ventricular hypertrophy; prolonged overhydration may cause cardiac failure and sudden death. On the other hand reduced hydration may cause intra or post dialysis arterial hypotension associated with untimely demise of residual renal function.

In this article we will introduce a new diagnostic device called BCM (Body Composition Monitor) developed by Fresenius that provides quantitative information on the amount of water in the human body using bioimpedance spectroscopy and unique three compartment body composition model [1]. BCM non-invasively measures whole body bioimpedance at 50 specific frequencies in the range from 5 to 1000 kHz in the area of dielectric β-dispersion. For a precise assessment of hydration status, i.e. for a precise measurement of body fluid volumes, including extracellular water (ECW), intracellular water (ICW) and total body water (TBW), BCM uses the Maxwell - Weber - Hanai mixture theory [2] together with the Cole - Cole theory [3]. By analysis of the impedance and shift at different frequencies, the resistance of extracellular water (RE) and intracellular water (RI) of the tissue body may be derived [4]. The values of both RE and RI depend on the volume of fluid in the respective tissue compartments.

THEORY

Body Composition Model

Devices based on conventional two-component models assume that the human body is composed of fat (FAT MASS) and non-fat tissue (FAT FREE MASS). BCM is the first device that uses a three-compartment body composition model (see Fig. 1) [1]. According to this model, whole body weight equals a sum of Lean Tissue Mass (LTM), Adipose Tissue Mass (ATM) and pathologic Overhydration (OH), i.e.

$$body\ weight = LTM + ATM + OH \qquad (1)$$

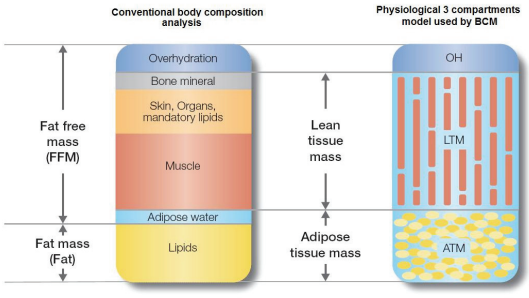


Fig. 1 *Body Composition model conventional model (left) versus three compartments model of BCM monitor (right)*

In a state of normal hydration with no excess fluid **lean tissue** (mainly muscle) consists of **70% water** whilst the remaining mass is protein and mineral. **Adipose tissue** (the majority of which is lipid) consists of **20% water** and **excess fluid** (overhydration) is almost 100% extracellular water.

The two compartments ATM and LTM bind a completely different ratio of intracellular and extracellular water (Wang & Pierson 1976, Morse & Soeldner 1963). In lean tissue **intracellular** water is predominant whilst in adipose tissue **extracellular** water is predominant.

Even in healthy subjects the distribution of lean and adipose tissue mass will lead to significant differences in the ratio of extracellular to intracellular water (E/I). Therefore E/I alone does not provide sufficient information about the hydration status.

Employing the latest **bioimpedance spectroscopy (BIS) technique** the BCM - Body Composition Monitor assess the precise hydration status [1].

Bioimpedance Spectroscopy

Bioimpedance in harmonic sinusoidal circuits is a complex number which denotes the relation between the input voltage and the input current for a given frequency. It contains information about magnitude equal to the relation of magnitudes and phase equal to the difference of phases and can be expressed as follows:

$$Z = \frac{U}{I} = R + jX = |Z|.\cos\varphi + j.|Z|.\sin\varphi[\Omega] \qquad (2)$$

The real part of impedance (R) causes the power loss, and it is called the resistance of the material. The imaginary part (X) causes only a delay between the voltage and the current and it is called the reactive part of impedance or reactance [5].
The impedance of the capacitor is calculated as:

$$Z = \frac{-j}{2\pi fC} \qquad (3)$$

In capacitance low frequencies currents are almost blocked, whilst at high frequencies, when impedance approximates zero, electric current is free to flow through the biological material (this precondition is fulfilled by human cells).
Cell membranes have the same properties at low and high frequencies as a capacitance. A simple electrical model for the cell can be induced. The current injected into the extracellular medium can flow trough the cell across the bilayer lipid membrane (Cm) or across the ionic channels (Rm) or can circulate around the cell (Re). Once the current is into the cell it 'travels' trough the intracellular medium (Ri) and leaves the cell across the membrane (Rm || Cm). Therefore, the equivalent cell circuit can be modeled by a combination of resistances associated with the extracellular and intracellular environments and the capacitance of the cell membrane (see the fig. 2).

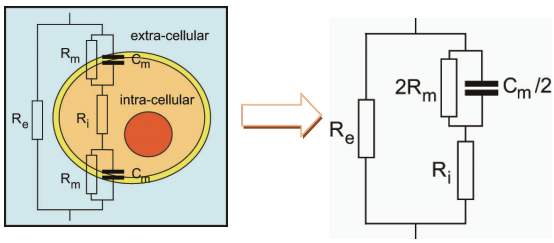


Fig. 2 *Equivalent cell model*

This property represents the basic principle of bioimpedance measurements. While high frequency current passes through the total body water (the whole body bioimpedance is proportional to the volume of TBW), at low frequencies the current cannot penetrate cell membranes and thus flows exclusively through extracellular water – the whole body bioimpedance is thus proportional to the extracellular fluid volume (ECW). The intracellular fluid volume can be easily calculated using the formula:

$$ICW = TBW - ECW \qquad (4)$$

Bioimpedance spectroscopy is closely related to dielectric dispersion, which is defined as the dependence of permittivity of the dielectric at the frequency of the alternating current. Conductivity of material changes as a consequence of changes in permittivity.
Schawn [5] defined three frequency regions for the dielectric properties of biological materials from the observed main dispersions of the conductivity and the permittivity (see the Fig. 3).
The large dielectric dispersions appearing between 10 Hz and tens of MHz (α and β dispersion regions) are generally considered to be associated with the diffusion processes of the ionic species (α dispersion) and the dielectric properties of the cell membranes and their interactions with the extra and intra-cellular electrolytes (β dispersion). The dielectric properties at the γ region are mostly attributed by the aqueous content of the biological species and the presence of small molecules [6].

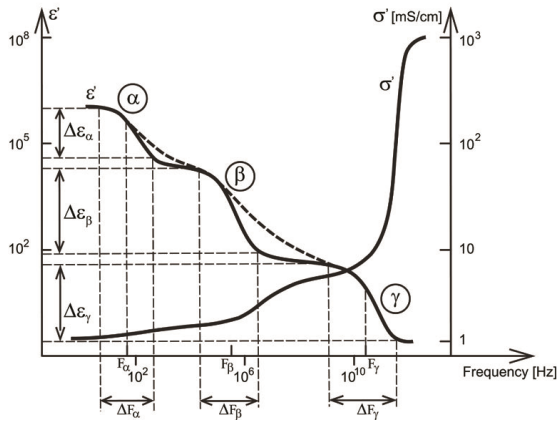


Fig. 3 *Dependence of permittivity of dielectric and material conductivity on the frequency of the electric field*

It is usually suitable to introduce a complex permittivity in cases involving a harmonic alternating current flowing through a dielectric. This value is used to derive the relationships for calculation of the volume of extracellular and intracellular fluids (Hanai mixture formula) [7].
Derivation of these expressions exceeds the scope

of this article.

Calculation of Overhydration

We measured the LTM, ATM and OH values using the BCM.

We did not assume overhydration in healthy individuals and their body was considered to be composed of only LTM and ATM.

For pathological overhydration states, we assumed that there was only an increase in the ECW, while the ICW remained unchanged. When there is excessive extracellular fluid (ECW) it can either accumulate in muscle or fat tissue which causes edema or it can remain as a separate entity, which does not change the hydration status of basic tissues. In this latter case, the fluid presents as ascites or pulmonary exudates in patients.

BCM **enables clear separation** between extracellular and intracellular water by the extremely wide range of measurement frequencies.

From the measured values of ATM and LTM the value of ECW can be calculated. Then the difference between our measured value and expected "normal" reference value of ECW defines the pathologic overhydration or hypohydration.

The BCM model has been validated in multicentre studies against the respective gold standards in healthy subjects and in hemodialysis patients. Dilution methods are considered as gold standard for measuring extracellular (sodium bromide) and total body (deuterium, tritium) volumes (total body water), whereas the total body potassium method is used to determine intracellular volume. The calculated body composition has been validated in more than 500 healthy subjects and patients against the reference methods dual energy X-ray absorptiometry, air displacement plethysmography and 4-compartment modelling. The validity of the calculated fluid overload has been demonstrated via clinical assessment in several hundred hemodialysis patients and additionally via the withdrawn ultrafiltration volume. A very good agreement in all gold standard comparisons was achieved [8] [9].

SUBJECTS AND METHODS

In our pilot study [10] we tried to verify the diagnostic sensitivity of BCM and compare this method with traditionally used ultrasound methods of determining hydration status, i.e. measurement of diameter and collapse of IVC (inferior vena cava) using the collapsibility index, which was defined by Cheriex and Leunissen, in 1989 [11], as follows:

$$CI[\%] = \frac{IVC_{exp} - IVP_{insp}}{IVC_{exp}}.100 \qquad (5)$$

where IVCexp is the diameter of the inferior vena cava in deep expiration and IVCinsp is the diameter of the inferior vena cava in deep inspiration.

The criteria for determination of hydration status according to Cheriex and Leunissen:

Intravascular normal hydration CI:40% – 75%, including borderline values

Intravascular hypohydration CI > 75%

Intravascular overhydration CI < 40%

RESULTS

We performed both examinations on 25 hemodialysis patients: male/female ratio was 72% / 28%, mean age of patients was 68 years, mean HDF (haemodiafiltration) treatment time was 29 months, average interdialytic weight gain (due to retention of fluids) was 2,15 kg, 35% of patients were diabetics, and arterial hypertension was diagnosed in 32% of patients.

Mean values together with median, variability and the standard deviation for both measured values are listed in Tab. 1.

	N	Mean	Median	Variability	Standard deviation
CI-IVC	25	67.73	71.40	203.61	14.27
BCM	25	0.24	0.00	4.42	2.10

Tab. 1 *Mean value, median, variability, standard deviation CI-IVC and BCM*

In our analysis we tried to demonstrate a correlation between the measured values of hydration status using BCM and the collapsibility index. Because both values meet the conditions for normal distribution, we were able to use the Pearson's correlation coefficient for determination of the correlation. STATISTICA software, version 9 (StatSoft Inc.) was used for the statistical analysis. MedCalc software was used to calculate the needed sample size for our calculated correlation coefficient.

The correlation between CI-IVC and BCM equaled -0,11, p = 0,000, the needed sample size for the calculated correlation coefficient, for the level of significance α=0,05and for the power of the test β=0,10

was N = 16. Calculated sample size is lower then our number of patients, so correlation between both measurements is really statistically significant. The graph of correlation of both quantities is shown in Fig. 4.

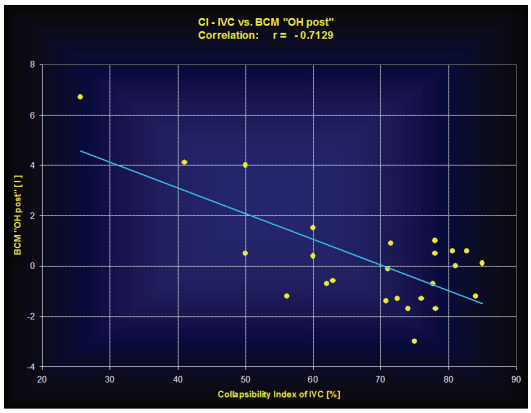


Fig. 3 *Correlation between the collapsibility index CI-IVC and BCM corrected for body mass index BMI*

CONCLUSIONS

In our study we found a highly significant level of correlation between standard method for determination of hydration status in hemodialysis patients (ultrasound method – measurement of the diameter and collapse of IVC) and a new method – Body Composition Monitor of Fresenius.

Both methods are clinically very useful and extend the spectrum of examination methods. Both are non-invasive, simple and results are available instantly. Only one limitation exists, i.e. the necessity of high experienced ultrasound operator, which is in a controversy with the simple performance of BCM measurements.

REFERENCES

[1] BCM – Body Composition Monitor [online] [cit 2010-07-02], http://bcm-fresenius.com/

[2] Cole K. S., Cole R. H.: Dispersion and absorption in dielectrics: 1. Alternating current characteristics. J. Chem Phys. 9 341–51, 1941

[3] Hanai T.: Theory of dielectric dispersion due to the interfacial polarization and its application to emulsions. Kolloid Z. 171 23–31, 1960

[4] Cornish B. H., Thomas B. J., Ward L. C.: Improved prediction of extracellular and total body water using impedance loci generated by multiple frequency bioelectric impedance analysis. Phys Med Biol 38:337–346, 1993

[5] Foster K. R., Schawn H. P., ' Dielectric properties of tissues and biological materials: a critical review', CRC Critical Reviews in Biomedical Engineering, vol. 17, no. 1, 25-104, 1989

[6] Ivorra A.: Bioimpedance monitoring for physicians: an overview. Hospital Clinic de Barcelona, July 2003

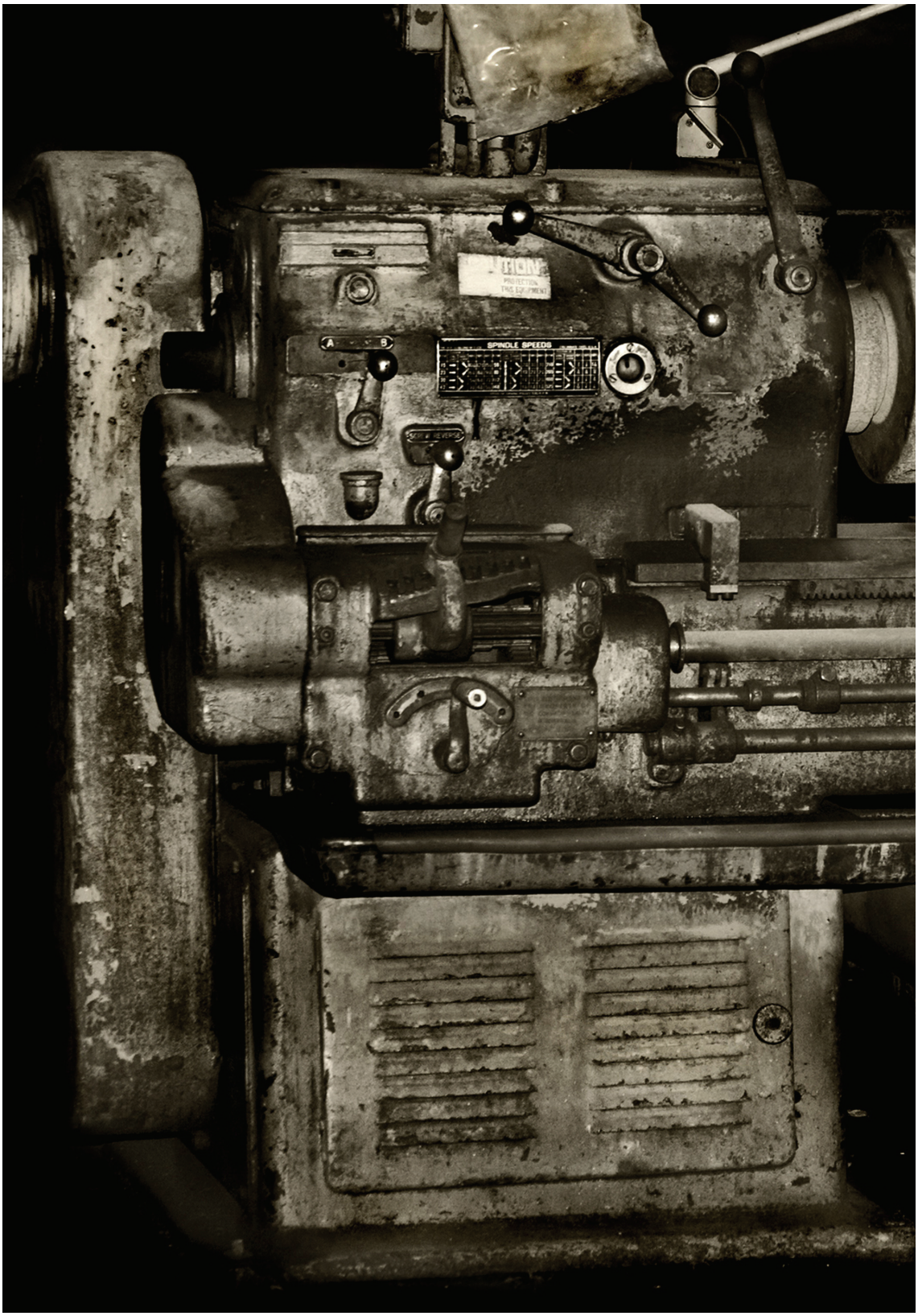
[7] Adohi B. J.-P., Vanga Bouanga C., Fatyeyeva K., Tabellout M.: Application of the Maxwell–Wagner–Hanai effective medium theory to the analysis of the interfacial polarization relaxations in conducting composite films. J. Phys. D: Appl. Phys. 42 (2009) 015302 (10pp)

[8] Wabel, P. et al., Accuracy of bioimpedance spectroscopy (BIS) to detect fluid status changes is hemodialysis patients. Poster presentation ERAEDTA 2007

[9] Moissl U. M., Wabel P., Chamney P. W., Bosaeus I., Levin N. W., Bosy-Westphal A., Korth O., Muller M. J., Ellegård L., Malmros V., Kaitwatcharachai C., Kuhlmann M. K., Zhu F., Fuller N. J.: Body fluid volume determination via body composition spectroscopy in health and disease. Physiol. Meas. 27 (2006) 921–933

[10] Nehezova K., Remes O., Vranova J., Veresova J., Rychlik I.: Estimation of hydration status in patients on haemodiafiltration - comparison of different methods (Body Composition Monitor, collapsibility index and flat ratio of vena cava inferior, diameter of v. hepatica dx.): Poster presentation, World Congress of Nephrology, May 22-26, Milan, Italy

[11] Cheriex E, Leunissen K, Janssen J, Mooy J, Van Hoof J: Echography of the inferior vena cava is a simple and reliable tool for estimation of "dry weight" in hemodialysis patients. Nephrol Dial Transplant 4:563–568, 1989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