Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Continuous Measurement of Calf Resistivity in Hemodialysis Patients using Bioimpedance Analysis

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Abstract-This study demonstrates a technique to measure electrical resistivity of the calf in hemodialysis (HD) patients during HD treatment. To continuously monitor and calculate resistivity, a model of calf volume based on its geometrical size and measurement of its electrical resistance has been developed. The model makes it possible to continuously estimate reduction of the calf circumference during HD. Seventeen HD patients were studied during HD using a multi-frequency bioimpedance device (Xitron 4200). Circumference of the calf was measured by a measuring tape pre- and post- HD for each treatment. Results showed a high correlation between measurement and calculation circumference in post HD (r^2=0.985). Further, the value of resistivity normalized by body mass index (BMI) provides information about patients' hydration state in comparison to those in healthy subjects. This technique is useful for identifying the range of optimal hydration states for HD patients.

Index Terms–Bioimpedance, circumference, resistivity, body fluid, dry weight.

I. INTRODUCTION

Estimation of the state of hydration in dialysis patients is an important and difficult task. Since there is no commercial device for hydration measurement, the target for the removal of excess body fluid volume in HD patients is largely dependent on clinical assessment. Bioimpedance analysis has been suggested to measure body fluid volumes [1]. Calf electrical resistivity provides information about a subject's hydration state which is particularly helpful for estimation of the optimal post-dialysis weight hemodialysis ("dry weight"). Resistivity can be calculated as:

$$\rho = \frac{RA}{L} \qquad \text{Eq.1}$$

with resistance (R) measured by a bioimpedance device; cross sectional area (A) as $A = \frac{C^2}{4\pi}$, where C is the circumference and L the length of segment measured. To monitor a patient's hydration state during HD, R and C must be known; however, there is a practical problem in measuring C because the diameter of the calf is continuously decreasing. This study presents a method for continuously estimating values of circumference of the calf during HD, based on the relationship between calf resistance and its geometrical volume.

II. METHODS

A. Principle of volume model

As shown in Fig.1, the calf is represented as cylinder the resistance whose volume is measured suing the bioimpedance technique. We assure that reduction of calf circumference during HD is due to the decrease of its fluid volume.

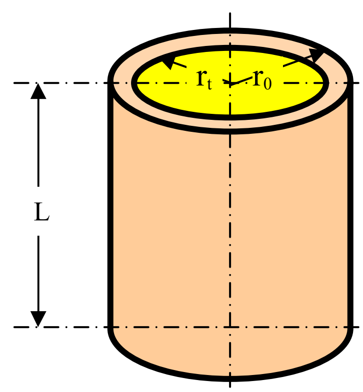

Fig. 1 Geometrical volume model, where r_0, r_t are radii of the pre and post HD volumes respectively. L is the length of the calf segment measured.

The change in fluid volume, ΔV, in the calf can be calculated as follows.

$$\Delta V = (\pi r_0^2 - \pi r_t^2)L = \pi L(r_0^2 - r_t^2) \qquad \text{Eq.2}$$

Substituting $\Delta r = r_0 - r_t$

$$\Delta V = \pi L(2r_0\Delta r - \Delta r^2) \qquad \text{Eq.3}$$

Since circumference $C_0 = 2\pi r_0$ and $C_t = 2\pi r_t$, the change in C can be calculated as:

$$\Delta C = C_0 - C_t = 2\pi(r_0 - r_t) = 2\pi\Delta r \qquad \text{Eq.4}$$

Thus, $\Delta r = \frac{\Delta C}{2\pi}$ and the change in volume can be calculated as

$$\Delta V = \frac{2C_0\Delta C - \Delta C^2}{4\pi}L \qquad \text{Eq.5}$$

Eq.5 can be simplified to give:

$$C_0 - \Delta C = \sqrt{C_0^2 - \frac{4\pi}{L}\Delta V} \qquad \text{Eq.6}$$

The change in fluid volume can also be calculated using the value of change in resistance as follows:

$$\Delta V = \rho L^2 \left(\frac{1}{R_0} - \frac{1}{R_t}\right) = \rho L^2 \left(\frac{R_t - R_0}{R_0 R_t}\right) = \frac{\rho L^2}{R_0}\left(1 - \frac{R_0}{R_t}\right) \qquad \text{Eq.7}$$

where ρ is resistivity, L is the length of the calf, R_0 and R_t are resistances measured by bioimpedance at the initial time and at time t, respectively. According to Eq.5 and Eq.7, the change in circumference (C_t) can be finally calculated from R_0/R_t and the initial circumference (C_0) as shown in Eq.8.

$$C_t = C_0 - \Delta C = \sqrt{C_0^2 - \frac{4\pi\rho_0 L}{R_0}\left(1 - \frac{R_0}{R_t}\right)} \qquad \text{Eq.8}$$

where C_0 and R_0 are measured at the start of dialysis ρ_0 is a constant value which is known from previous study, L is set as a constant (typically 10 cm) and R_t is measured using a bioimpedance device. Eq.8 allows calculation of the circumference using only one variable R_t. Other variables, such as R_0, C_0 and L are all known in each study. Thus, once the initial circumference is known, the resistivity of the calf can be calculated by combining Eq.1 and Eq.8, as follows.

$$\rho_t = \frac{\lambda[R_0 C_0^2 - 4\pi\rho_0(1-\lambda)]}{4\pi L} \qquad \text{Eq.9}$$

where ρ_t is the continuous measured resistivity and λ is the ratio R_0/R_t. To reduce the effect of body composition differences among subjects, the resistivity was normalized by BMI, (body weight/height) as follows.

$$\rho_N = \frac{\rho_t}{BMI} \qquad \text{Eq.10}$$

B. Experiments methods

Fig.2 shows a device of multi-frequency bioimpedance measurement device (Xitron 4200, Xitron Technologies, San Diego CA) and the placement of its electrodes on the calf.

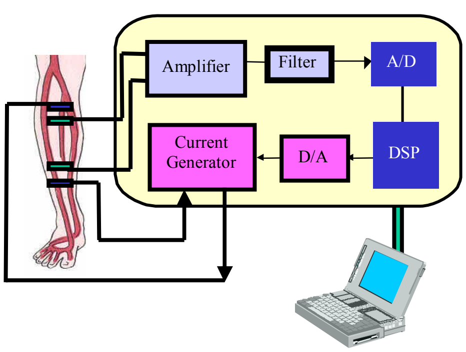

Fig.2 Principle of measurement of calf bioimpedance

The minimal (C_{min}) and maximal (C_{max}) values of circumference in the calf were measured pre- and post- HD using a soft tape with 0.1 cm accuracy. Four electrodes were placed on one calf of each HD patient, two of which were used to measure the voltage over a distance of 10 cm and the other two to inject current, one placed 5cm higher than the upper measuring electrode and the other 5 cm lower than the lower measuring electrode [2]. Bioimpedance was continuously measured and calculated to provide raw data for calculating resistance, reactance, impedance and phase angle in the frequency range 5 kHz to 1000 kHz. A program based on the Cole-Cole model was used to estimate extracellular and intracellular resistance [3]. The change in calf resistivity (ρ_t) was calculated by Eq.9 using the values of extracellular resistance (R_E), circumference (C_t) and resistivity (ρ_0). Seventeen patients (10m/7f) were studied in 90 HD treatments. After three initial base line (BL) measurements, clinical staff estimated a target body weight at the end of dialysis. Studies were then performed by decreasing body weight in steps (<0.5 kg), observing changes in resistance, normalized resistivity and clinical symptoms, such as hypotension, until the estimated dry weight was reached [4]. According to the hypothesis, if the patient had reached the true dry weight (DW), the curve of resistance change with time should have zero slopes and the normalized resistivity should be in the range of healthy subjects estimated in a previous study.

III. RESULTS

Fig.3 shows the correlation between calculated (Eq.8) and manually measured calf circumference post HD. There were highly corrected (r^2=0.985) and showed small differences of their means and standard deviation (0.07±0.56 cm).

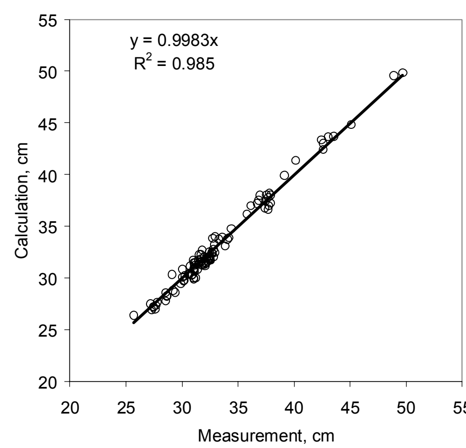

Fig.3 shows correlation between measured and calculated calf circumference in patients post HD. the calculation used Eq.8, (n=90)

Fig.4 shows changes in normalized resistivity (ρ_N) measured in a patient with two different hydration states: base line (BL) and normal hydration (DW). In this case, the increase ρ_N in each treatment was more than 35%. In addition, ρ_N increased most when the patient's body weight decreased and, eventually, reached the normal minimal hydration range. Table 1 summarizes the results of change in body weight and calf normalized resistivity in the different hydration states: BL and DW. Significant differences in body weight (Wt), pre ($p<0.004$) and post-HD ($p<0.07$) as well as ρ_N pre ($p<0.001$) and post-HD (p<0.0001) between BL and DW, respectively, were observed.

Table 1

	pre-Wt [kg]	post-Wt [kg]	Pre-ρ_N [$\Omega m^3/kg$]	Post-ρ_N [$\Omega m^3/kg$]
BL	84.6±29	81.5±29	0.0136±0.001	0.0171±0.002
DW	83.2±28	80.2±28	0.0149±0.002	0.018±00.002
p	0.004	0.007	0.001	0.0001

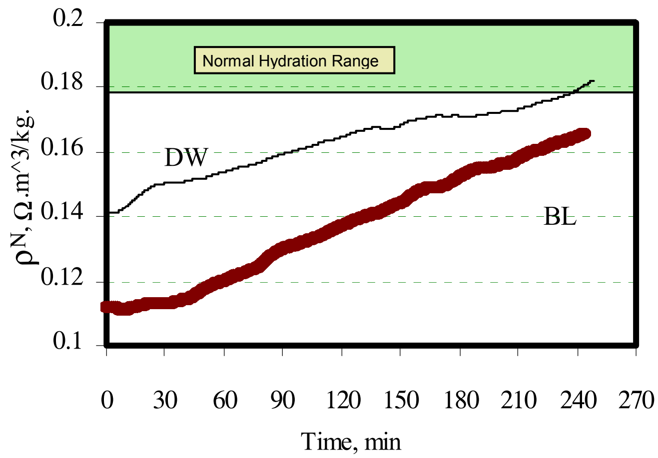

Fig.4 Continuous measurement of resistivity in different hydration states for one patient during HD

IV. DISCUSSION

This study described a technique to continuously measure resistivity of the calf in HD patients during HD. This technique is useful in monitoring the patients' hydration state. Results show that the value of normalized resistivity by BMI can be used to identify the hydration state of patient in comparison to healthy subjects.

Accurate estimation of HD patients' dry weight is one of the most important issues in dialysis practice. without a reliable technique which can be used to provide information about patient's hydration state, many patients were suffer from overload of body fluid after dialysis because of underestimation of their excess body fluid volume. On the other hand, if excess fluid is overestimated, the patient could develop serious hypotensive symptoms during treatment due to over removal of body fluid. Many studies have attempted to overcome the problem using different techniques without success.

Bioimpedance techniques are attractive because their measurement are no invasive, simple and inexpensive. However, the current standard bioimpedance method using wrist to ankle measurement, (the so-called whole body bioimpedance analysis, WBIA), is unable to provide enough accuracy for clinical practice. With the WBIA method, the errors come from different distribution of body fluid volume and/or body composition. Many authors have pointed out that 90 % of the resistance that WBIA produces comes from the arm and leg, due to the difference of cross-sectional area between trunk and limbs. In addition, excess fluid distribution tends to shift more fluid to the legs because of the effect of gravity. Therefore, to understand a dialysis patient hydration state, the lower leg (calf) may be the best place to make measurement. Recently, we have developed a calf bioimpedance method to continuously monitor the change in resistance of the calf during HD, associating hydration state with the slope of the resistance curve. Moreover, degree of hydration was indicated by resistivity. Since the resistance was measured from the skin, this value represents contributions from three major components: fat mass, muscle mass and extracellular fluid volume. To measure extracellular volume only, extracellular resistance or lower frequency resistance was used to calculate resistivity and then the resistivity was normalized by BMI to reduce the effect of body composition.

To continuously calculate resistivity, a model based on a cylindrical volume and its electrical resistance was successfully created to make it possible to infer the circumference during continuous reduction of its diameter. It should be noticed that with direct measurement of circumference using a tape, errors could arise from many sources, such as differences in the locations of electrodes and the tape measure, varying tension of the tape by different operators and changes in leg position. In addition, it is impossible to continuously measure circumference manually during HD.

Resistivity alone only provides information concerning hydration as related to a normal population in which there is at any particular time a range of degrees of hydration state. The continuous measurement indicates when the extracellular fluid volume cannot decrease further and therefore this approach is in principle more accurate. Furthermore, clinical assessment of blood pressure is unreliable in detecting degree of body hydration since plasma refilling may be impaired even in overhydration.

The method shown in this study could be applied in other research areas where geometrical measurement of the size of a cylinder is required

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