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DIALYSIS – TRANSPLANTATION

Estimation of body fluid changes during peritoneal dialysis by segmental bioimpedance analysis

FANSAN ZHU, DANIEL SCHNEDITZ, ALLEN M. KAUFMAN, and NATHAN W. LEVIN

Renal Research Institute, and Division of Nephrology and Hypertension, Beth Israel Medical Center, New York, New York, USA; and Department of Physiology, Karl-Franzens University, Graz, Austria

Estimation of body fluid changes during peritoneal dialysis by segmental bioimpedance analysis.

Background. Commonly used bioimpedance analysis (BIA) is insensitive to changes in peritoneal fluid volume. The purpose of this study was to show, to our knowledge for the first time, that a new segmental approach accurately measures extracellular fluid changes during peritoneal dialysis (PD).

Methods. Fourteen stable PD patients were studied during a standard exchange with fluids of known conductivity. Bioimpedance was continuously measured in the arm, trunk, and leg and from wrist to ankle. Volume changes were calculated using both a newly developed sum of segmental BIA (SBIA) and current wrist-to-ankle BIA (WBIA) and were compared with actual volume changes measured gravimetrically.

Results. When 2.19 ± 0.48 L were removed from the peritoneal cavity during draining, 95.2 ± 13.8% of this volume was detected by SBIA compared with only 12.5 ± 24.3% detected by WBIA. When 2.11 ± 0.20 L of fresh dialysate was infused into the peritoneal cavity during filling, 91.1 ± 19.6% of this volume was detected by SBIA compared with only 8.8 ± 21.1% detected by WBIA.

Conclusion. The good agreement between measured and calculated data using SBIA was due to: (*a*) improved placement of electrodes, (*b*) estimation of trunk extracellular volume based on a new algorithm, and (*c*) consideration of changes in dialysate conductivity. Correct estimation of fluid volume in the trunk is a prerequisite for applications in which direct analysis of fluid changes cannot be performed such as with peritoneal equilibration tests and continuous flow PD.

Accurate estimation of body composition and hydration plays an important role in the care of the end-stage renal disease patient for a correct prescription of dialysis including ultrafiltration volume [1–3]. There is interest in noninvasive, simple, and inexpensive techniques capable of estimating fluid content in different body compartments in order to determine optimum hydration. Bioimpedance analysis (BIA), which is used in nutritional analysis and intervention, is considered such a technique [4–6]. However, the value of BIA for hemodialysis and peritoneal dialysis (PD) has been questioned in several studies. Continuous monitoring of fluid changes during dialysis with large changes in fluid volume within short periods of time is difficult to follow using current bioimpedance techniques [7, 8]. In particular, BIA fails to detect fluid changes during peritoneal fluid exchanges [9–11]. In this mode of dialysis, dialysate introduced into the peritoneal cavity is confined largely to one body segment, the trunk. However, the current wrist-to-ankle technique (so-called whole-body technique) is insensitive to changes of fluid content in the trunk [12, 13]. Therefore, BIA has been dismissed as a rather unreliable tool in the field of dialysis [14, 15].

An alternative to the wrist-to-ankle technique is the measurement using body segments [16, 17]. Recently, we have introduced a technique measuring bioimpedance in three body segments, that is, the arm, the leg, and the trunk, with an overall sampling period of one minute. This technique and a new theoretical approach for the calculation of fluid volume in the trunk can be used for continuous measurements so that dynamic processes such as changes in regional fluid distribution can be analyzed. We call this technique the sum of segmental BIA (SBIA) [18, 19]. This technique has been successfully applied to analyze the changes in regional fluid distribution in hemodialysis patients [20].

The PD patient represents an ideal model for studying isolated, localized changes in body fluid. The aim of our study was to investigate whether SBIA would be successful in detecting changes in trunk volume caused by draining dialysate from and infusing dialysate into the peritoneal cavity during a standard dialysate exchange in a group of PD patients. It was found that calculated volume changes corresponded to actual volume changes. This can be considered a prerequisite to use this technique for future evaluation of peritoneal fluid volume and ultrafiltration in PD.

Key words: dialysis adequacy, conductivity, extracellular volume, regional fluid distribution, peritoneal equilibrium.

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METHODS

Fourteen stable PD patients (9 males and 5 females, mean ages 44.8 ± 13 years, body mass 83.8 ± 15 kg) were studied during 22 treatments. All patients gave informed consent for this study, which was approved by the Committee on Scientific Activities of Beth Israel Medical Center. All patients were free of peripheral edema and had no elevation of jugular venous pressure. Before treatment, the lengths and circumferences of body segments were measured (right arm, trunk, and leg) in all subjects. Draining and filling volumes were measured using a scale and assuming an approximate fluid density of 1 g/cm^3.

Bioimpedance

Segmental BIA was performed to measure segmental body resistance continuously. Current (0.8 mA) was injected into the body using two electrodes placed on the dorsal surfaces of the hand and the foot on the same side of the body. For each measurement, current was injected at 10 frequencies covering a range from 5 to 500 kHz. Sensing electrodes were placed on the same side of the body as the injecting electrodes, which were placed on the wrist (S1), the shoulder (acromion; S2), the buttock (S3), and the ankle (S4; Fig. 1). The patients were in a sitting body position during the fluid exchange. Bioimpedance was continuously recorded in the arm, trunk, and leg segment, as well as between the wrist and the ankle using a bioimpedance analyzer (Xitron 4000B; Xitron Technologies, Inc., San Diego, CA, USA) and a technique described previously [21]. The duration of a cycle of arm, trunk, leg, and wrist-to-ankle measurements was 1 minute. Extracellular resistance (R) was calculated using the bioimpedance modeling technique supplied by the manufacturer of the bioimpedance device.

Segmental extracellular volumes (ECVs) were calculated according to

$$ECV_S = k_S \frac{1}{\sigma_{ECV}} \cdot \frac{L_S^2}{R_S} \qquad \text{(Eq. 1)}$$

where σ_{ECV} is the conductivity of the extracellular fluid; L_S is the length; R_S is the resistance of the segment; and $k_S = 1$ for the arm and the leg, and $k_S = 4$ for the trunk, depending on the dimensions of the segment, as discussed elsewhere [21]. Conductivity is used in equation 1 instead of resistivity ($\rho = 1/\sigma$) because of the common use of conductivity in clinical practice and because of the implications of variable dialysate conductivity with PD.

The sum of segmental extracellular volume is calculated as

$$ECV_{SBIA} = 2(ECV_{arm} + ECV_{leg}) + ECV_{trunk} \qquad \text{(Eq. 2)}$$

Extracellular volume by wrist-to-ankle measurements (ECV_{WBIA}) was calculated as

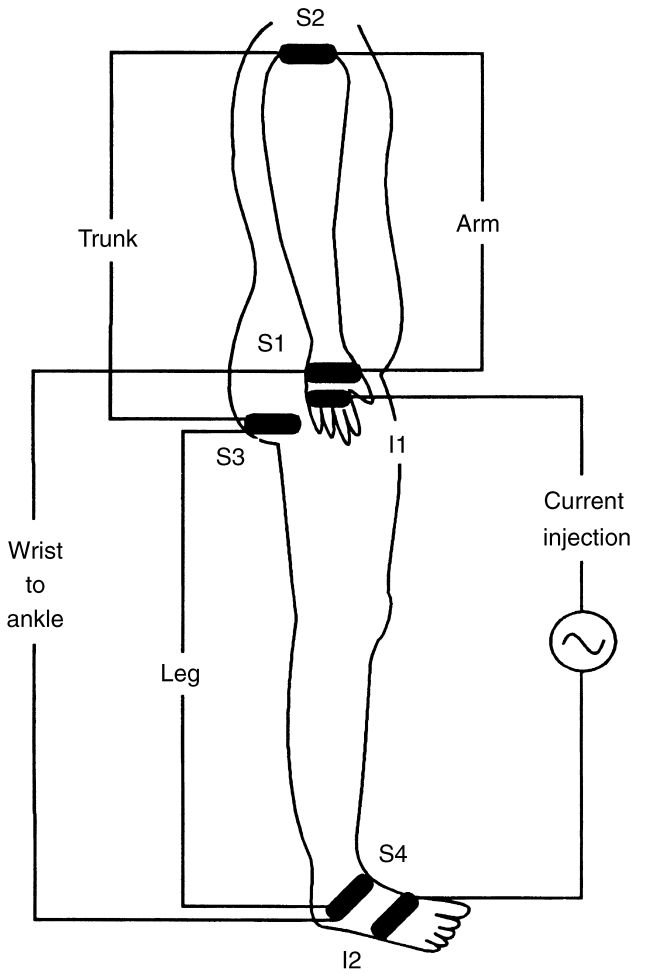

Fig. 1. Electrode placement and bioimpedance measurement in peritoneal dialysis (PD) patients.

$$ECV_{WBIA} = k_{ECV}\left(\frac{H^2\sqrt{M}}{R}\right)^{2/3} \qquad \text{(Eq. 3)}$$

where H is body height (cm); M is body mass (kg); R is resistance measured between the wrist and ankle; and k_{ECV} is a factor related to segmental body size and conductivity [22].

Conductivity

Conductivity of fresh and equilibrated dialysate was measured at ambient temperature and corrected for a standard temperature of 20°C (Ionometer HFK; Fresenius Medical Care, Bad Homburg, Germany).

The conductivity of extracellular fluid volume at body temperature was assumed to be 21.3 ms/cm, corresponding to a resistivity of 47 Ωcm [22]. This is different from the conductivity of isotonic saline (14.4 ms/cm) [23] or dialysate at 20°C because of temperature effects. To correct for temperature effects, conductivity of filling volume at body temperature (σ_2) was calculated from con-

ductivity of extracellular fluid at body temperature (σ_1) and a scaling factor derived from the ratio of conductivities measured in filling (σ_f) and draining volumes (σ_d) at 20°C according to

$$\sigma_2 = \sigma_1 \cdot \frac{\sigma_f}{\sigma_d} \qquad \text{(Eq. 4)}$$

Isoelectric conditions can be assumed for the case of constant dialysate conductivity during PD when $\sigma_f = \sigma_d$. With constant conductivity, extracellular fluid and volume infused into or drained from the peritoneal cavity can be modeled as a homogeneous compartment. However, if dialysate conductivity changes during equilibration and $\sigma_f \neq \sigma_d$, conductivity of dialysate at body temperature will differ from the tabulated value. In this case, extracellular fluid volume in the trunk must be treated as a mixture of volumes with different conductivities.

The conductivity of electrolyte solutions is a nonlinear function of electrolyte concentration [24]. However, within a narrow range of concentrations, the conductivity (σ_m) of a mixture of solutions with identical ionic species (σ_1, σ_2) can be approximated by the sum of conductivities of each component weighted by their volume fraction (fV) according to

$$\sigma_m = \sigma_1 \cdot fV_1 + \sigma_2 \cdot (1 - fV_1) \qquad \text{(Eq. 5)}$$

where fV_1 is the volume fraction of solution 1 given as $V_1/(V_1 + V_2)$.

With PD, σ_1 and V_1 refer to tabulated extracellular conductivity and extracellular volume at the end of the draining phase. σ_2 and V_2 refer to dialysate conductivity as defined by equation 4 and volume infused into the peritoneal cavity during the filling phase.

Changes in extracellular volume (ΔECV) caused by the fluid exchange with PD were calculated both by wrist-to-ankle (ΔECV_{WBIA}) and by sum of segments techniques (ΔECV_{SBIA}).

Study protocol

The study consisted of three phases, each lasting approximately 10 to 15 minutes during which the peritoneal cavity was drained and filled by gravity in the usual fashion, and where bioimpedance was measured by both approaches without interruption.

Measurements of wrist-to-ankle and segmental bioimpedance were taken with electrodes placed on one side of the body. Measurements were started after an initial dwell time of three to four hours. Patients were sitting during the whole study. The initial phase referred to the final stage of the preceding dwell time. Then the peritoneal cavity was manually emptied by gravity, and measurements were continued for five minutes after the cessation of fluid flow. The whole draining volume (V_D) was measured. The last phase started with the infusion of a 2 or 2.5 L bag of warmed 2.5% dextrose dialysate solution into the peritoneal cavity and ended five minutes after having returned all of the filling volume (V_F).

Bioimpedance was continuously measured throughout the study phase with a sampling period of one minute in each segment and for the wrist-to-ankle configuration. The noise of raw data was reduced taking the moving average with a frame width of five minutes. The calculation of volumes before draining and filling was based on mean values obtained during these phases. Volumes at the end of draining and filling were automatically detected from minimum and maximum values measured after completion of draining and filling flows, respectively.

Table 1. Patient characteristics

Patients	Male	Female	Male & female	Unit
Number	9	5	14	
Age	45.4 ± 14	42.8 ± 10	44.8 ± 13	year
Height H	177 ± 7	164 ± 11	174 ± 9.4	cm
Body mass M	86.8 ± 13	73.9 ± 17.9	83.9 ± 14.7	kg
BMI	27.7 ± 3.7	27.4 ± 4.8	27.6 ± 3.9	kg^{-2}
Arm				
L	57.8 ± 3.5	52.8 ± 3.6	56 ± 4.2	cm
C	25.9 ± 1.9	23.4 ± 2.5	25 ± 2.4	cm
Trunk				
L	72.6 ± 3.3	63.3 ± 7.8	69 ± 6.8	cm
C	104.1 ± 10	100.3 ± 15	103 ± 12	cm
Leg				
L	72.3 ± 7.2	68.8 ± 6.8	71 ± 7	cm
C	39.3 ± 2.8	37.3 ± 2.7	38.6 ± 2.8	cm

Abbreviations are: BMI, body mass index; L, length of segment; C, circumference of segment.

Statistical analysis

Results are reported as mean values ± SD. The difference between calculated and actual volume changes was tested using the nonparametric one-sample sign test. A $P < 0.05$ was considered significant to reject the null hypothesis (H_0).

The relationship between actual volumes determined gravimetrically and extracellular volumes estimated by segmental analysis (ΔECV_{SBIA}) was analyzed by linear regressions and by Bland-Altman analysis.

RESULTS

Fourteen patients were studied in 22 treatments. Patient and treatment characteristics are summarized in Tables 1 and 2. In the mean, arm, trunk, and leg segments were longer and had a larger circumference in males than in females. However, body mass indices were comparable in male and female patients.

The average volume of equilibrated dialysate drained from the peritoneal cavity was 2.2 ± 0.5 L. Subsequent infusion volume varied from 2 to 2.5 L, with a mean value of 2.1 ± 0.2 L. Thus, a mean negative volume

Table 2. Treatment characteristics ($N = 22$)

Variable	Gender	Draining		Filling		Unit
		Start	End	Start	End	
σ	m	13.17 ± 0.37		12.15 ± 0.24		ms/cm
	f	12.90 ± 0.29		12.20 ± 0.24		ms/cm
	m and f	13.11 ± 0.37		12.16 ± 0.24		ms/cm
V_D, V_F	m		2.14 ± 0.51		2.09 ± 0.19	L
	f		2.35 ± 0.37		2.21 ± 0.22	L
	m and f		2.19 ± 0.48		2.11 ± 0.20	L
R, arm	m	247.5 ± 41.6	251.3 ± 40.3	255.4 ± 41.4	258.0 ± 44.2	Ω
	f	264.7 ± 43.2	256.1 ± 50.1	264.28 ± 51.2	268.4 ± 58.1	Ω
	m and f	250.2 ± 39.5	251.7 ± 40.1	256.4 ± 40.7	259.0 ± 43.3	Ω
R, trunk	m	56.9 ± 8.5	62.6 ± 9.1	62.5 ± 9.2	56.6 ± 8.2	Ω
	f	56.5 ± 14.4	64.1 ± 14.4	63.5 ± 14.5	56.44 ± 11.5	Ω
	m and f	55.7 ± 8.7	61.9 ± 8.9	61.7 ± 8.9	56.0 ± 8.3	Ω
R, leg	m	183.5 ± 37.3	186.4 ± 37.2	186.9 ± 39.4	185.7 ± 42.2	Ω
	f	196.1 ± 18.7	190.6 ± 26.9	197.3 ± 28.9	200.8 ± 25.5	Ω
	m and f	187.5 ± 34.1	188.0 ± 34.6	190.3 ± 36.8	189.7 ± 39	Ω
R, wrist-to-ankle	m	487.2 ± 67.8	499.9 ± 67.2	519.2 ± 54	496.9 ± 76.2	Ω
	f	513.2 ± 44.7	510.2 ± 58	503.1 ± 74.1	531.1 ± 54	Ω
	m and f	491.2 ± 61.3	500.8 ± 62.2	505 ± 67.8	502.4 ± 69.5	Ω
ECV_{SBIA}	m	25.18 ± 2	23.12 ± 1.9	23.19 ± 1.76	24.91 ± 1.93	L
	f	22.37 ± 4.9	20.26 ± 4.9	20.14 ± 3.64	21.85 ± 3.61	L
	m and f	24.54 ± 3	22.47 ± 2.98	22.5 ± 2.57	24.21 ± 2.65	L
ECV_{WBIA}	m	23.7 ± 1.7	23.41 ± 1.4	23.32 ± 1.45	23.5 ± 1.61	L
	f	19.24 ± 2.9	18.92 ± 3.07	18.76 ± 2.72	18.78 ± 2.6	L
	m and f	22.69 ± 2.7	22.39 ± 2.64	22.29 ± 2.62	22.43 ± 2.71	L

Abbreviations are: N, number of studies; σ, dialysate conductivity; f, female; m, male; V_D; draining volume; V_F, filling volume; R, resistance; ECV_{SBIA}, extracellular volume measured by sum of segments bioimpedance analysis; ECV_{WBIA}, extracellular volume measured by wrist-to-ankle bioimpedance analysis.

balance of approximately 100 mL was achieved during 22 treatments. The conductivity of equilibrated dialysate drained from the peritoneal cavity was higher (13.1 ± 0.4 ms/cm) than the conductivity of fresh dialysate (12.2 ± 0.2 ms/cm) infused into patients (Table 2).

Extracellular volume calculated from SBIA and WBIA was calculated assuming a constant conductivity (21.3 ms/cm) for the draining phase and a variable conductivity according to equation 5 for the filling phase, respectively.

An example of measured and calculated volume changes during the three phases of the study is shown in Figure 2. The ΔECV calculated from segmental measurements followed the actual changes caused by draining and filling the peritoneal cavity. However, extracellular volume calculated from wrist-to-ankle measurements showed only minimal changes during the fluid exchange.

The same pattern was seen in all studies (Table 3). Extracellular volume determined from segmental measurements decreased from 24.5 ± 3.0 to 22.5 ± 3.0 L during draining and increased from 22.5 ± 2.6 to 24.2 ± 2.7 L during filling. However, when wrist-to-ankle data were analyzed by conventional means (equation 3), extracellular volume fell from only 22.7 ± 2.7 to 22.4 ± 2.6 L during draining and increased from 22.3 ± 2.6 to 22.4 ± 2.7 L during filling. A detailed summary of extracellular resistance measured in different segments and in the wrist-to-ankle configuration is given in Table 2.

A summary of volume changes measured in all studies is given in Table 3. The change in ECV calculated from SBIA during the draining and filling phases (–2.0 ± 0.5 and 1.70 ± 0.45 L) was close to the measured volume changes (–2.15 ± 0.48 and 2.1 ± 0.2 L). In contrast to

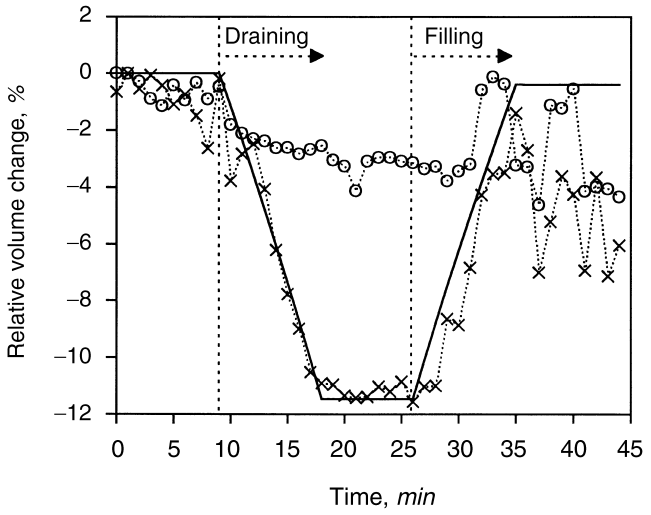

Fig. 2. Relative volume changes with peritoneal dialysis. Relative volume changes calculated from segmental analysis (×), wrist-to-ankle analysis (○), and exchanged fluid (——) in study #GJ80903a (male, 23 years, 77.1 kg body weight, 170 cm height, 2.6 L draining volume, 2.5 L filling volume). Extracellular volume changes (ΔECV) calculated from segmental (SBIA) and wrist-to-ankle (WBIA) bioimpedance analysis were 2.43 L (SBIA) and 0.84 L (WBIA) during draining compared with 2.24 L (SBIA) and 0.18 L (WBIA) during filling phases, respectively.

Table 3. Extracellular volume changes by WBIA and SBIA ($N = 22$)

Variable	Gender	WBIA	SBIA	Unit
ΔECV_D	m	0.29 ± 0.55	2.06 ± 0.51	L
	f	0.32 ± 0.36	2.11 ± 0.56	L
	m and f	0.30 ± 0.5	2.07 ± 0.51	L
$\Delta ECV_D/V_D$	m	12.7 ± 27.1	97 ± 12.9	%
	f	12 ± 13.5	89.2 ± 16.5	%
	m and f	12.5 ± 24.3	95.2 ± 13.8[a]	%
ΔECV_F	m	0.21 ± 0.48	1.94 ± 0.49	L
	f	0.03 ± 0.28	1.87 ± 0.27	L
	m and f	0.17 ± 0.45	1.93 ± 0.44	L
$\Delta ECV_F/V_F$	m	10.9 ± 22.6	91.5 ± 21.2	%
	f	1.8 ± 14.2	89.8 ± 14.8	%
	m and f	8.8 ± 21.1	91.1 ± 19.6[a]	%

Abbreviations are: WBIA, wrist-to-ankle analysis; SBIA, sum of segments analysis; *N*, number of studies; ΔECV, changes in ECV during filling; ΔECV/V, percentage of volume recovered by bioimpedence analysis (BIA); index F, related to filling; index D, related to draining.

[a] P = NS, one-sample sign test, $H_0 = 100$

that measurement, the ECV calculated from wrist-to-ankle measurements during the draining and filling phases was much smaller (–0.27 ± 0.51 and 0.14 ± 0.46 L) than the measured volume changes.

A comparison of estimated to expected volume changes showed that segmental analysis detected 95 ± 14 to 91 ± 20% of the changes during draining and filling. This was not different from expected values measured by gravimetry ($H_0 = 100$, one-sample sign test). The wrist-to-ankle technique only detected 13 ± 24 to 9 ± 13% of the actual volume changes and therefore significantly underestimated the actual volume changes (Table 3).

A comparison of volume changes estimated by segmental analysis and actual volumes drained from or infused into the peritoneal cavity showed that data were close to the line of identity (Figs. 3 and 4A). The mean relative difference between techniques was 0.13 ± 0.3 and 0.19 ± 0.40 L during draining and filling, respectively. The difference was not significantly different from zero ($H_0 = 0$, one-sample sign test) and independent of the actual volume exchange during draining (Fig. 3B). The linear pattern in Figure 4 is caused by uniform infusion volumes with 2 L of infusate in 17 studies and 2.5 L in 5 studies, respectively.

Analysis of extracellular volumes in different segments shows that the main volume change during peritoneal fluid exchange occurred in the trunk (Fig. 5). However, small volume changes were also observed in the arms and in the legs.

Eight patients were studied twice using alternate body sides for impedance analysis. The results demonstrate that changes in extracellular volumes were insensitive to body side (Table 4).

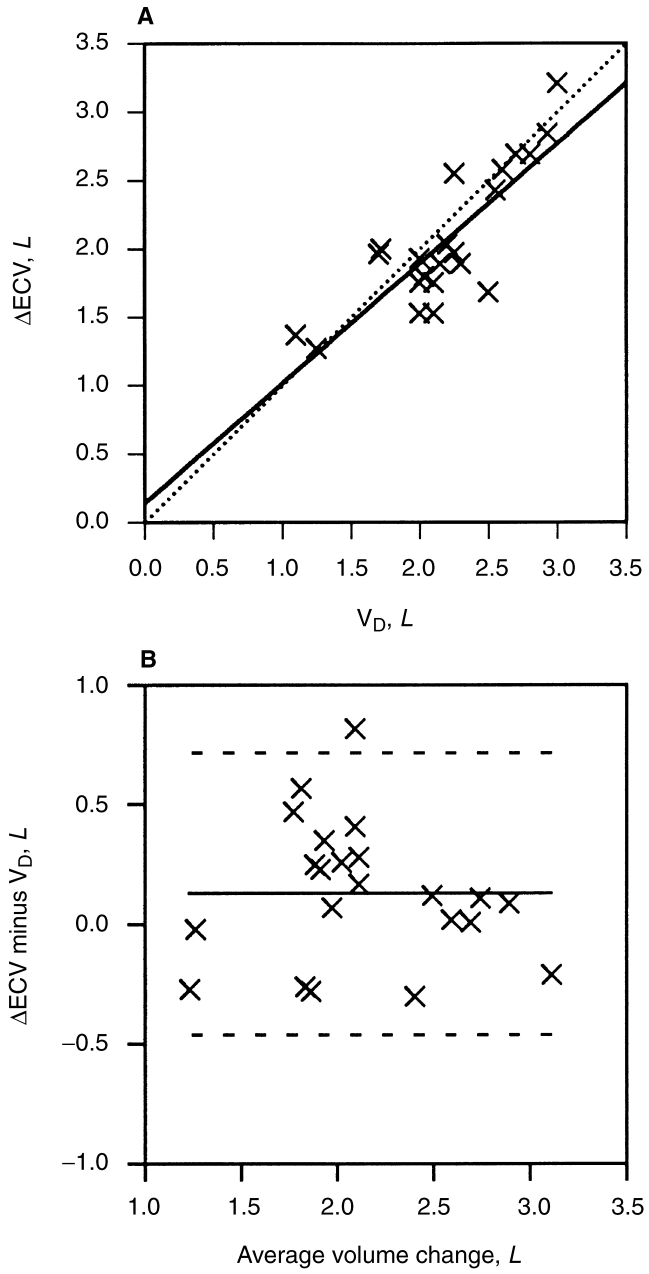

Fig. 3. Calculated and actual volume changes with peritoneal dialysis. (*A*) Identity plot of volume changes measured by segmental bioimpedance analysis (SBIA) compared with actual volume changes during draining (×) compared with line of identity (- - -). Linear regression between calculated (ΔECV_{SBIA}) and actual (V_D) volume changes (——; $\Delta ECV_{SBIA} = 0.877 * V_D + 0.137$; $r^2 = 0.68$). (*B*) Bland–Altman analysis of volume changes measured by SBIA compared with actual volume changes during draining (×). Average difference between measured and estimated volume changes (——) and upper and lower 95% confidence intervals (- - -).

DISCUSSION

This article reports the results of a new bioimpedance technique that provides continuous information on changes in extracellular volume in three body segments, the trunk, the leg, and the arm, applied to the measurement of changes in regional fluid distribution during PD. In contrast to previous approaches (wrist-to-ankle), the new technique is capable of accurately measuring fluid

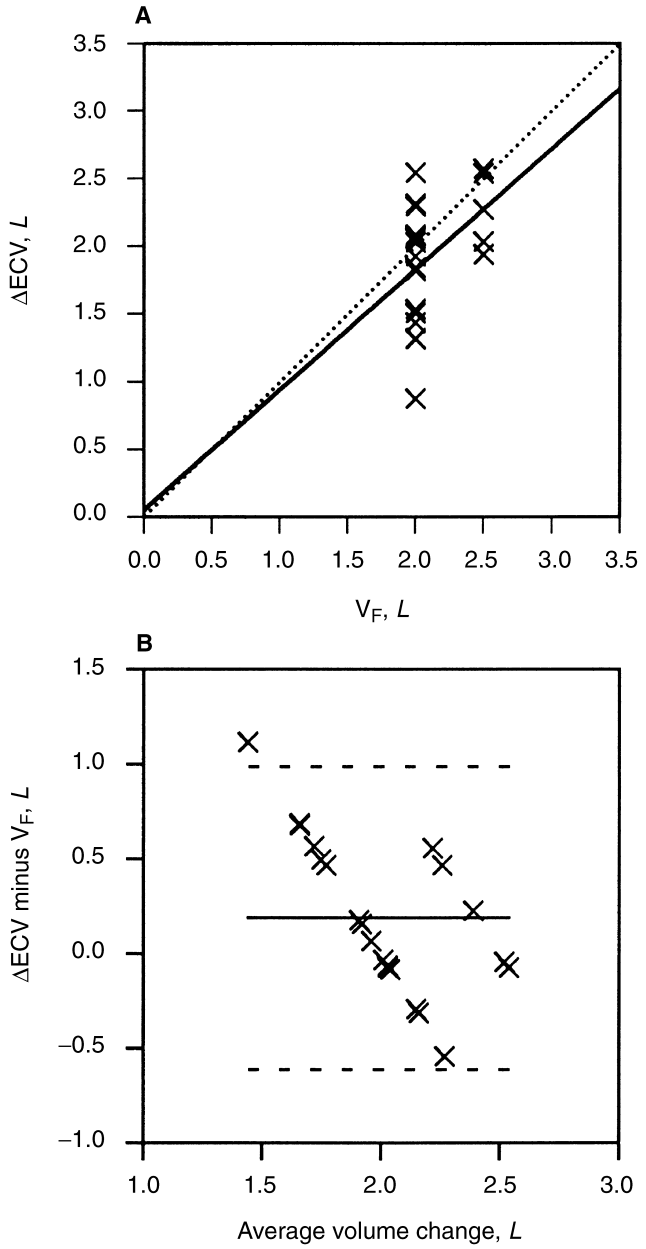

Fig. 4. Calculated and actual volume changes with peritoneal dialysis. (*A*) Identity plot of volume changes measured by segmental bioimpedance analysis (SBIA) compared with actual volume changes during filling (×) compared with line of identity (- - -). Linear regression between calculated (ΔECV_{SBIA}) and actual (V_F) volume changes (——, $\Delta ECV_{SBIA} = 0.889 * V_F + 0.047$, $r^2 = 0.19$). (*B*) Bland-Altman analysis of volume changes measured by SBIA compared with actual volume changes during draining (×). Average difference between measured and estimated volume changes (——) and upper and lower 95% confidence intervals (- - -).

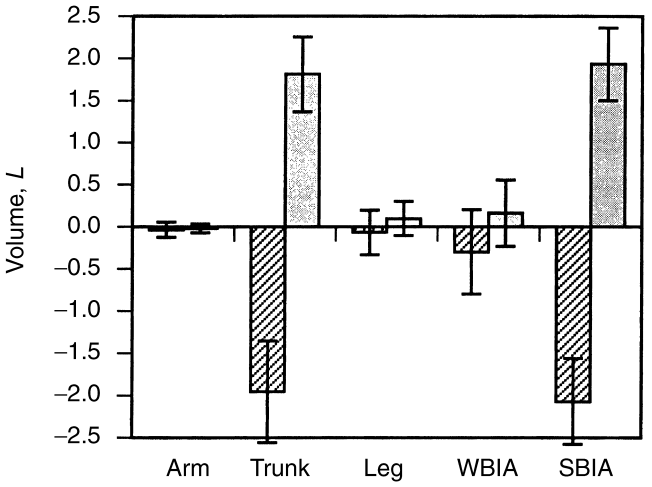

Fig. 5. Changes in extracellular volume with peritoneal dialysis. Changes in extracellular volume in arm, trunk, and leg compared with changes determined from wrist-to-ankle (WBIA) and sum of segments bioimpedance analysis (SBIA) during peritoneal dialysis. Volume removal measured during draining is indicated by a negative value (▨). Volume increase measured during filling is indicated by a positive value (■).

Table 4. Comparison of body sides ($N = 8$)

Body side	V_D (L)	ΔECV_D (L)	V_F (L)	ΔECV_F (L)
Right	2.14 ± 0.53	1.95 ± 0.46	2.14 ± 0.23	1.73 ± 0.53
Left	2.23 ± 0.55	2.12 ± 0.62	2.13 ± 0.23	1.71 ± 0.59
ΔRL	0.09 ± 0.31	0.17 ± 0.49[a]	0.01 ± 0.2	0.02 ± 0.3[a]

Abbreviations are: *N*, number of studies; V, volume of exchanged fluid; ΔECV, change in ECV measured by sum of segments bioimpedance analysis (SBIA); index F, related to filling; index D, related to draining; ΔRL, absolute difference between left and right measurements.

[a] P = NS, one-sample sign test, $H_0 = 0$

changes in the trunk caused by the exchange of dialysate during PD.

Previous studies have shown that wrist-to-ankle as well as other approaches to segmental bioimpedance methods are insensitive in detecting fluid changes caused by PD [9]. The failure to detect changes in fluid volume was attributed to geometrical relations and/or to local changes in conductivity [13]. Several authors have reported that bioimpedance and resistance measured in the trunk were unexpectedly low with fluid changes during PD. Consequently, BIA was dismissed as an unreliable technique in the measurement of regional body fluid [25, 26]. In our study, the erroneous underestimation of volume changes during PD using wrist-to-ankle measurements was confirmed. However, when trunk data were analyzed according to the new approach as described previously, the volume change calculated from SBIA data was not different from the actual volume exchanged during PD.

Trunk volume and bioimpedance

The trunk contains approximately 60% of the extracellular fluid volume (approximately 10 L) but accounts for only 10% of wrist-to-ankle resistance. Increasing the extracellular volume in the trunk by 20% (approximately

2 L) changes the whole-body extracellular volume by 12% [13]. However, wrist-to-ankle resistance changes only by 2% if trunk resistance changes by 20%. Therefore, removing or infusing 2 L of dialysate from or into the peritoneal cavity will cause only a small change in wrist-to-ankle resistance. In this study, almost 100% of the change in extracellular volume was caused by changes in the trunk (Fig. 5). Changes in the legs and arms were not significant. In 8 out of 14 patients, segmental bioimpedance measurements were repeated in a subsequent treatment using the other side of the body. There was no difference in calculated volume changes using alternate body sides, which indicates that the trunk can be considered symmetric for the purpose of measuring fluid changes during PD (Table 4).

Since most of the volume changes occurred in the trunk, the difficulties of previous bioimpedance studies to accurately detect the fluid changes must reside in the measurement and in the calculation of trunk volume.

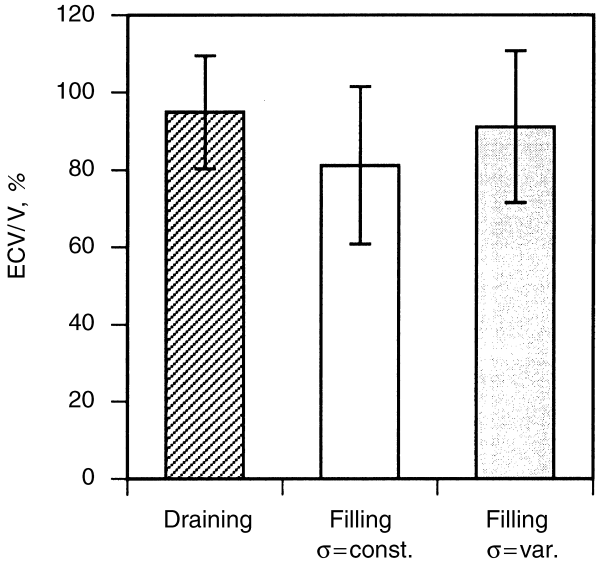

Fig. 6. Relative changes in extracellular volume (ECV). Changes in extracellular volume measured by segmental bioimpedance analysis (SBIA) relative to actual volume (ΔECV/V) for the draining phase (▨) and the filling phase, assuming a constant (σ = constant, □) or variable extracellular conductivity (σ = variable, ■) of the trunk according to equation 5.

Measurement

In this study, the trunk electrodes were not placed on their usual position as in our previous study [20]. If sensing electrodes for the trunk were placed on the shoulder and on the iliac crest, a considerable part of the peritoneal cavity would be located below the cylinder edged by the pair of sensing electrodes. Thus, a large fraction of peritoneal fluid volume would be excluded from the trunk measurement. Therefore, if patients assume a sitting position during their fluid exchange, the pair of electrodes sensing the trunk must be placed on the top and on the bottom of the cylinder to be measured, that is, on the shoulder and on the buttocks (Fig. 1).

Calculation

Even if bioimpedance is measured in individual segments using the correct position of sensing electrodes, the extracellular volume of the trunk is underestimated from the measurement of trunk length, trunk cross-sectional area, and trunk resistance (Eq. 1). The reason for this discrepancy can be related to the nonuniform distribution of electrical current in the trunk. The shortness of the trunk compared with its large cross-sectional area leads to an inhomogeneous current density in the plane of the cross-sectional area across the trunk when current is injected into the trunk through the arm and through the leg on one side of the body [27]. It can be shown that such inhomogeneity causes a spuriously high resistance measured between electrodes placed on one side of the trunk. Consequently, a spuriously low trunk volume is calculated from this resistance. In this configuration, only one fourth of the trunk extracellular volume is measured, and a factor $k_S = 4$ is used for the calculation of trunk volume in order to account for the inhomogeneity of the current in the trunk. The theoretic explanation for this has been previously developed [21].

Conductivity

The calculation of extracellular volume depends on extracellular conductivity as described in equation 1. If a constant conductivity of 21.3 ms/cm (which refers to a tabulated resistivity of 47 Ωcm, both measured at 37°C [22]) is assumed during peritoneal fluid exchanges, the filling volume was considerably underestimated by SBIA (Fig. 6). The volume change measured by SBIA using a constant conductivity would be only 80% of dialysate volume infused.

Solutions used in PD contain significant amounts of nonelectrolytes such as glucose to increase osmotic pressure. The fresh dialysate containing 2.5% glucose had a mean conductivity of 12.2 ms/cm, whereas equilibrated dialysate had a conductivity of 13.1 ms/cm (both measured at 20°C). Therefore, infusion of fresh dialysate with reduced conductivity into the peritoneal cavity was likely to affect the mean conductivity of extracellular fluid volume. The effect of a decrease in mean extracellular conductivity as a function of infusion volume according to equation 4 led to improved estimates for filling volumes determined by SBIA (Table 3 and Fig. 6). The volume change measured by SBIA using a decreasing conductivity detected 91% of dialysate volume infused. Dialysate conductivity increased during equilibration, which can be explained by the decrease in glucose concentration both because of glucose clearance and be-

cause of osmotic absorption of extracellular fluid into the peritoneal cavity.

If the draining volume is equilibrated and conductivities of intraperitoneal and extracellular volumes are equal, the removal of draining volume will not affect the mean conductivity of extracellular fluid volume in the trunk. Therefore, a constant conductivity was assumed for calculation of extracellular volume changes during the draining phase. The volume change measured by SBIA using a constant conductivity detected 95% of volume drained from the patient.

The results presented in this communication show that changes in extracellular volume in the trunk are correctly estimated by SBIA. Correct estimation is based on: (*a*) sensing electrodes placed in correct positions, (*b*) consideration of inhomogeneous distribution of electrical current in the trunk in the calculation of volume, and (*c*) correction for changes in dialysate conductivity caused by changes in the concentration of nonelectrolytes such as glucose.

The value of correct volume estimation appears trivial in settings where filling and draining volumes can be measured by a scale with much higher fidelity. However, the information gathered by segmental bioimpedance measurements is of potential interest in applications in which gravimetric analysis cannot be performed, such as with continuous flow PD or peritoneal equilibration tests. Studies dealing with these clinical aspects remain to be performed in future.

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Reprint requests to Daniel Schneditz, Ph.D., Department of Physiology, Graz University, Harrachgasse 21/5, 8010 Graz, Austria.

REFERENCES

1. Arkouche W, Fouque D, Pachiaudi C, Normand S, Laville M, Delawari E, Riou JP, Traeger J, Laville M: Total body water and body composition in chronic peritoneal dialysis patients. *J Am Soc Nephrol* 8:1906–1914, 1997
2. Lindholm B, Werynski A, Bergström J: Fluid transport in peritoneal dialysis. *Int J Artif Organs* 13:352–358, 1990
3. Korbet MS: Evaluation of ultrafiltration failure. *Adv Ren Replace Ther* 5:194–204, 1998
4. Dumler F: Use of bioelectric impedance analysis and dual-energy X-ray absorptiometry for monitoring the nutritional status of dialysis patients. *ASAIO J* 43:256–260, 1997
5. Armstrong LA, Kenefick RW, Castellani JW, Riebe D, Kavouras SA, Kuznicki JT, Maresh CM: Bioimpedance spectroscopy technique: Intra-, extracellular, and total body water. *Med Sci Sports Exerc* 29:1657–1663, 1997
6. Fisch BJ, Spiegel DM: Assessment of excess fluid distribution in chronic hemodialysis patients using bioimpedance spectroscopy. *Kidney Int* 49:1105–1109, 1996
7. Zaluska WT, Schneditz D, Kaufman AM, Morris AT, Levin NW: Relative underestimation of fluid removal during hemodialysis hypotension measured by wrist to ankle bioimpedance. *ASAIO J* 44:823–827, 1998
8. Jaffrin MY, Maasrani M, Boudailliez B, Gourrier AL: Extracellular and intracellular fluid volume monitoring during dialysis by multifrequency impedancemetry. *ASAIO J* 42:M533–M538, 1996
9. Rallison LR, Kushner RF, Penn D, Schoeller DA: Errors in estimating peritoneal fluid by bioelectrical impedance analysis and total body electrical conductivity. *J Am Coll Nutr* 12:66–72, 1993
10. Kurtin PS, Shapiro AC, Tomita H, Raizman D: Status and body composition of chronic dialysis patients: Utility of bioelectric impedance plethysmography. *Am J Nephrol* 10:363–367, 1990
11. Jones CH, Smye SW, Newstead CG, Will EJ, Davison AM: Extracellular fluid, determined by bioelectric impedance and serum albumin in CAPD patients. *Nephrol Dial Transplant* 13:393–397, 1998
12. Johnson DW, Thomas BJ, Fleming SJ, Moran D, Ward LC: Monitoring of extracellular and total body water during hemodialysis using multifrequency bioelectrical impedance analysis. *Kidney Blood Press Res* 19:94–99, 1996
13. Thomas BJ, Ward LC, Cornish BH: Bioimpedance spectrometry in the determination of body water compartments: Accuracy and clinical significance. *Appl Radiat Isot* 49:447–455, 1998
14. De Lorenzo A, Deurenberg P, Andreoli A, Sasso GF, Palestini M, Docimo R: Multifrequency impedance in the assessment of body water loss during dialysis. *Ren Physiol* 17:326–332, 1994
15. Mandolfo S, Farina M, Imbasciati E: Bioelectrical impedance and hemodialysis. *Int J Artif Organs* 18:700–704, 1995
16. Organ LW, Bradham GB, Gore DT, Lozier SL: Segmental bioelectrical impedance analysis: Theory and application of a new technique. *J Appl Physiol* 77:98–112, 1994
17. Bracco D, Thiebaud D, Chiolero RL, Landry M, Burckhardt P, Schutz Y: Segmental body composition assessed by bioelectrical impedance analysis and DEXA in humans. *J Appl Physiol* 8:2580–2587, 1996
18. Zhu F, Schneditz D, Wang E, Levin NW: Continuous measurement of segmental and whole body bioimpedance. *Proc IEEE EMBS* 19:2086–2088, 1997
19. Zhu F, Schneditz D, Wang E, Levin NW: Dynamics of segmental extracellular volumes during changes in body position by bioimpedance analysis. *J Appl Physiol* 85:497–504, 1998
20. Zhu F, Schneditz D, Wang E, Martin K, Morris AT, Levin NW: Validation of changes in extracellular volume measured during hemodialysis using a segmental bioimpedance technique. *ASAIO J* 44:M541–M545, 1998
21. De Lorenzo A, Andreoli A, Matthie JR, Withers PO: Predicting body cell mass with bioimpedance by using theoretical methods: A technological review. *J Appl Physiol* 82:1542–1558, 1997
22. Zhu F, Schneditz D, Levin NW: Estimation of trunk extracellular volume by bioimpedance. *Proc IEEE EMBS* 20:3104–3107, 1998
23. Weast RC: *CRC Handbook of Chemistry and Physics* (sec D, 55th ed). Cleveland, CRC-Press, 1974, p D224
24. Kohlrausch F: Über die Ionenbeweglichkeiten im Wasser. *Z Elektrochemie Angewandte Physikalische Chemie* 13:333–352, 1907
25. Woodrow G, Oldroyd MB, Smith A, Turney JH: The effect of arteriovenous fistulae in hemodialysis patients on whole body and segmental bioelectrical impedance. *Nephrol Dial Transplant* 12:524–527, 1997
26. Zillikens MC, van den Berg JWO, Wilson JHP, Swart GR: Whole-body and segmental bioelectrical-impedance analysis in patients with cirrhosis of the liver: Changes after treatment of ascites. *Am J Clin Nutr* 55:621–625, 1992
27. Kushner RF: Bioelectrical impedance analysis: A review of principles and applications. *J Am College Nutr* 11:199–209, 1992