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Correlation of whole-body impedance with total body water volume

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HOFFER, EARL C., CLIFTON K. MEADOR, AND DAVID C. SIMPSON. *Correlation of whole-body impedance with total body water volume.* J. Appl. Physiol. 27(4): 531–534. 1969.—A relationship between whole-body electrical impedance and total body water content is presented. Twenty normal volunteers were studied for total body water by a tritium-dilution technique, total body impedance using a 100-kc, 100-μa signal, and various anthropometric data. These data were then compared with similar data on 34 patients in various degrees of hydration on whom tritium space was also known. Analysis of these data suggests that a definable relationship does exist between impedance and total body water which shows promise for development into a simple, inexpensive, bedside method for estimating total body water content.

electrical impedance; conductivity; impedance plethysmography; body composition; tritiated water; body measurement, electrical; edema

THE ELECTRICAL CHARACTERISTICS of biological systems have intrigued scientific investigators for many years. This investigation is concerned with the determination of total body electrical impedance as a biological measurement that could be used with other data to predict total body water. The original studies using whole-body impedance as a measure of total body water were done by Thomasset (6). Other investigators have used electrical impedance measurements in the study of arterial pulse waveforms and pulsatile flow in various organs. The monograph by Nyboer (4) contains extensive references to these investigations, but does not mention the application of body impedance as described in this study. A simple bedside method for determining body compartment fluid volumes would be a valuable clinical tool for fluid and electrolyte management problems and in body composition studies. Our studies indicate that a good correlation does exist between body impedance and body water volume.

MATERIALS AND METHODS

The hypothesis that body impedance can be used to measure total body water is based on the following principle: impedance of simple geometric systems is a function of conductor length and configuration, conductor cross-sectional area, and signal frequency. Using a fixed signal frequency and a relatively constant conductor configuration, the impedance becomes a function of conductor length and cross section or conductor volume.

In this study, we measured body height, weight, and wrist circumference as a measure of body size. These data were analyzed together with impedance for possible correlations with total body water volume. Actual or true total body water volume was determined by radioisotope-dilution measurements.

Electrical conduction in biological substances is ionic in type and is related to the free ion content of the various contained salts, bases, and acids, their concentration, mobilities, and conducting medium temperature. Assuming the signal frequency and conductor configuration to be constant, the impedance (Z) to the flow of current can be related to the size or volume of the conductor as follows:

$$Z = \rho L/A \qquad (1)$$

where Z = impedance in ohms, ρ = specific resistivity in ohm-centimeters, L = conductor length in centimeters, and A = conductor cross-sectional area in square centimeters. Multiplying *equation 1* by L/L gives

$$Z = \rho L^2/AL \qquad (2)$$

in which AL is equal to volume (V). Rearranging gives

$$V = \rho L^2/Z \qquad (3)$$

While there are many difficulties in applying this principle in a system with complex geometry such as the human body, this relation (*eq 3*) is presented as a background for the empirical relationship to be presented subsequently.

Twenty normal male medical students in good health were studied for: *a*) electrical impedance (Z), *b*) total body water volume (TBW), and *c*) anthropometric data as follows.

A) Impedance was measured as a steady-state phenomenon with a four-surface electrode technique between the right hand and left foot with the subject supine (i.e., the greatest length of the conductor) (see Fig. 1). The tetrapolar electrode technique was utilized because it minimizes the contact resistance, or electrode-skin interaction, at the signal or current inducing probe electrode site. Standard ECG salt-bridge surface electrodes, (part no. 0853-0005, Hewlett-Packard, Inc., Palo Alto, Calif.) with electrode paste (Beckman electrode paste, Beckman Instrument, Inc., Offner Division, Schiller Park, Ill.) were applied after cleansing the skin contact area with acetone. Electrode locations were as follows: the voltage sensing electrodes (connected to voltmeter V_1 of Fig. 1) were applied on the mid-dorsum of the wrist with the distal bony prominence of the radius and ulna as landmarks, and on the mid-anterior aspect of the ankle with the medial and lateral malleoli as location landmarks. The current or signal inducing electrodes (connected to voltmeter V_2 and the signal generator, Fig. 1) were placed on the middorsum of the hand midway between voltage electrodes and the proximal metacarpal-phalangeal joint line, and similarly on the appropriate foot. The electrodes were held in place by "Velket" type stretch bonds (adult-size Velcro tourniquet, Propper Manufacturing Co., Inc., Long Island City, N.Y.). Thomasset (6) utilized a two-electrode system with 0.4 x 20 mm stainless steel needles inserted subcutaneously on the dorsum of the hand and foot; however, our initial studies using needles showed some problems in reproducibility due to small variations in insertion depth, possible tissue trauma, and patient acceptance. Other impedance studies such as those of Nyboer (4), Kubicek et al. (2), and Rehm (5) also utilized the tetrapolar electrode method. Figure 2 shows the general relation between signal frequency and impedance for both the bipolar needle and tetrapolar surface electrode methods. The higher impedance values for the needles are due to the electrode to tissue voltage drop which is minimized by the four-electrode method.

The excitation current for the impedance measurement was supplied by an alternating current sine-wave signal generator (model 200 CD wide-range oscillator, Hewlett-Packard). A current (I) of 100 μa rms (root-mean-square) was used. The current was adjusted to 100 μa for each determination by measuring with a vacuum tube voltmeter the potential difference across a 10,000 ohms ± 1% precision resistor in series with the subject (model 400 D vacuum tube voltmeter, Hewlett-Packard). The potential difference (E) rms across the subject was also measured with another vacuum tube-type voltmeter (model 427 A vacuum tube voltmeter, Hewlett-Packard). Measurements were made at 100, 1000, 10,000 and 100,000 cycles/sec signal frequency, and the absolute value of the impedance (Z) was calculated according to the relation $Z = E/I$. The accuracy and stability of the measuring equipment was verified for each set of data by replacing the patient with a standard test load (a 1,000 ohm ± 1% precision resistor). On several occasions, the reproducibility of electrode connection to the patient was tested by serially removing and replacing the electrodes and repeating the impedance measurement. Variations of ± 2% were not uncommon, and occasional differences of 5% were noted on consecutive measurements taken 10–15 min apart.

An isolation transformer was used between the building power source and the measuring equipment to assure patient safety.

B) Total body water (TBW) was determined by the tritiated water method of Moore and associates (3) using 500 μc, with blood samples drawn after 5- and 6-hr equilibration periods with correction for urine losses of the isotope.

C) Anthropometric data were obtained for each subject. These included weight, height, and wrist circumference. The wrist circumference was measured with a flexible steel tape pulled snugly over bony prominences of the distal radius and ulna. The wrist measurement and height are among the more constant anatomical measurements (1), and are less affected, in the adult, by changes in body composition than are many other measurements, such as weight.

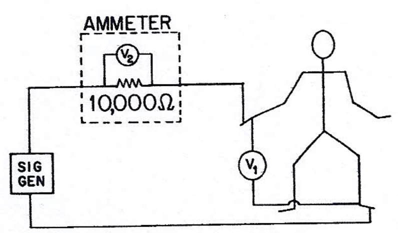

FIG. 1. Experimental arrangement showing patient test setup in schematic form. V_1 = vacuum tube voltmeter, Hewlett-Packard model 427A. V_2 = vacuum tube voltmeter, Hewlett-Packard model 400D. Sig Gen = wide-range oscillator, Hewlett-Packard model 200CD.

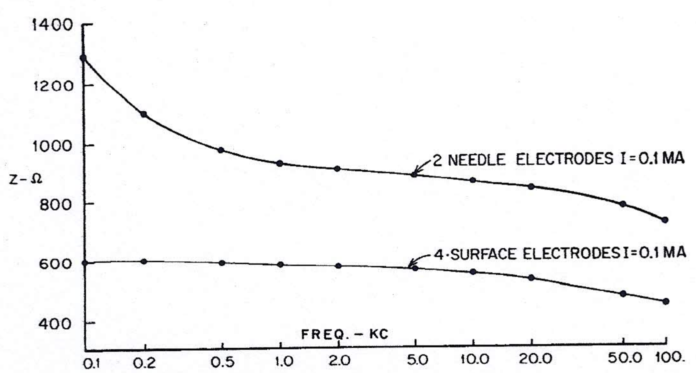

FIG. 2. Typical curves of whole-body impedance (Z) vs. excitation signal frequency for two-needle and four-surface electrode techniques. Current (I) = 100 μa (rms) in both methods.

TABLE 1. *Composite data 20 normal volunteers*

Subj	Age, yr	Weight, kg	Height, cm	TBW, liters	Z-100 kc, ohms
1	23	79.82	181.6	49.24	427
2	23	73.98	177.8	40.09	505
3	23	87.03	176.5	46.05	384
4	24	115.19	184.2	56.63	359
5	28	89.00	186.1	50.73	409
6	29	75.74	177.2	42.65	467
7	24	91.72	181.0	55.94	376
8	23	86.45	185.4	55.12	391
9	22	68.59	182.9	40.71	491
10	25	89.80	194.3	48.94	468
11	23	84.81	177.8	42.94	475
12	21	72.34	180.9	45.94	476
13	23	61.34	182.3	38.19	488
14	24	73.58	177.2	44.80	447
15	24	96.60	193.0	53.89	448
16	21	58.62	176.2	37.09	501
17	26	88.89	173.4	43.04	388
18	38	75.96	182.9	46.23	431
19	30	66.89	171.5	40.05	441
20	28	76.45	174.0	46.58	379

TBW = total body water in liters measured by tritium dilution. Z = impedance in ohms measured at 100 kc and 100 μa (rms).

TABLE 2. *Composite data from 34 patients*

Subj	Age, Sex	Weight, kg	Height, cm	TBW, liters	Z-100 kc, ohms	Clinical Diagnosis	Subj	Age, Sex	Weight, kg	Height, cm	TBW, liters	Z-100 kc, ohms	Clinical Diagnosis
21	77-F	65.80	162.6	40.82	411	CHF	38	68-F	50.0	166.4	29.24	622	CHF
22	29-F	53.29	171.8	31.70	683	RF	39	27-M	55.44	166.4	38.36	467	RF
23	55-F	58.80	158.8	29.05	598	CHF	40	36-M	69.93	172.7	34.18	585	RF
24	39-F	50.43	167.0	32.39	500	RF	41	29-F	56.24	171.8	35.45	595	RF
25	41-M	52.70	172.1	36.49	532	RF	42	48-M	77.80	178.4	48.40	327	CHF
26	55-F	58.30	158.8	28.35	601	CHF	43	55-F	61.10	158.8	32.32	592	CHF
27	48-M	66.21	178.4	39.98	471	RF	44	66-F	61.50	154.9	25.06	702	CHF
28	55-M	89.12	179.7	69.56	209	RF	45	24-F	53.42	150.5	33.93	457	RF
29	63-F	69.84	164.5	38.74	463	OB	46	36-M	74.10	172.7	37.97	532	RF
30	18-M	77.90	160.0	31.40	619	CS	47	48-M	65.76	178.4	44.73	507	RF
31	48-F	60.77	163.2	31.98	491	CHF	48	63-F	73.24	164.5	39.99	426	CHF
32	69-M	65.71	166.2	42.83	428	CHF	49	48-M	117.69	177.8	59.71	363	RF
33	41-M	52.29	167.0	41.73	507	RF	50	48-F	57.65	163.2	28.79	532	CHF
34	48-F	57.65	163.2	28.79	532	CHF	51	46-M	94.83	177.2	49.88	400	CHF
35	68-F	51.20	166.4	30.03	590	CHF	52	68-F	52.50	166.4	30.65	552	CHF
36	22-F	53.06	167.0	29.15	665	RF	53	72-M	70.63	175.3	51.18	350	CHF
37	56-M	70.29	175.9	41.21	502	CHF	54	48-F	52.15	153.7	39.09	396	RF

TBW = total body water in liters measured by tritium dilution. Z = impedance in ohms measured at 100 kc and 100 μa (rms). CHF = congestive heart failure; RF = renal failure; CS = Cushing's syndrome; OB = obesity; M = male; F = female.

TABLE 3. *Summary of regression relationships*

	20 Normals, r	34 Patients, r
TBW vs. wt	0.83	0.74
TBW vs. Z	0.70	0.86
TBW vs. T/Z	0.84	0.91
TBW vs. T^2/Z	0.92	0.93
Ionic mass vs. T^2/Z	0.92	0.93

TBW = total body water. T = patient height. Z = impedance in ohms measured at 100 kc and 100 μa (rms). Ionic mass = (see text). r = correlation coefficient.

Using the above studies on 20 normal volunteer subjects as a base line, we measured the same parameters in 34 patients, with various diseases and degrees of hydration. These patients included individuals with acute and chronic renal failure, Cushing's syndrome, obesity, and congestive heart failure.

RESULTS

A representative plot of the relationship between excitation signal frequency and impedance using the tetrapolar electrode system is shown as the lower curve of Fig. 2. The flat portion of the curve between 100 cycles/sec and 1.0 kc (1.0 kilocycle = 1,000 cycles/sec) is assumed to represent conduction via the extracellular fluids. The decrease in impedance at frequencies above 1.0 kc is thought to be due to increasing conduction via the intracellular fluids by capacitive coupling across the cell membranes and is most notable at 100 kc. This effect was demonstrated in in vitro experiments by Thomasset (7) using plasma, whole blood, and packed cells. Other investigators (2, 4) have utilized a 100-kc frequency signal in studies of cardiac output, arterial pulses, and pulsatile flow. With these data in mind, all of our measurements were performed using a 100-kc excitation current.

The composite data for the 20 normal subjects are presented in Table 1. From these data, regression analyses were conducted to determine the correlations between TBW, impedance, and the anthropometric parameters noted previously. The relationship of TBW vs. body weight, which gave a correlation of $r = 0.83$ for the normal subjects, was chosen as a basic value to be improved upon by the impedance technique. Using Thomasset's approach (8), the theoretical normal volume (Vt) and normal impedance Zt for each subject was determined using the height (T) in meters and wrist circumference (C) in decimeters. These relationships, TBW (or Vt) vs. C^2T and Zt vs. T/C^2 gave correlations of $r = 0.86$ and $r = 0.87$, respectively. Many other relationships were evaluated for correlation with TBW. The best relationship found was that of TBW vs. T^2/Z for which the correlation coefficient, r, was 0.92.

The possibility of achieving better correlations by including body electrolyte concentration data was considered. Thus, a measure of total body electrolyte content, identified as ionic mass, can be determined according to the relationship ionic mass = TBW $(Na_s + K_s)/\%\ H_2O$; where Na_s and K_s are serum sodium and potassium concentrations, respectively, and $\%\ H_2O$ = percent serum water, as determined by optical refraction (TA meter, catalogue no. 10402, A.O. Inst. Co., Buffalo, N.Y. 14215). The correlation of the relationship ionic mass vs. T^2/Z was $r = 0.92$. Since this constituted no evident improvement over previous relationships, further efforts along this line were discontinued for the purposes of this initial study.

The composite data for 34 patients are presented as Table 2. Regression analyses were conducted with these data for comparison with those obtained on the normal subjects. Pertinent results are summarized as Table 3. Examination of Table 3 suggests that the use of (Z) as an indicator of TBW is significantly better than weight alone in abnormal hydration states. Furthermore, incorporation of anthropometric data improves the correlation relationship even more. The reason for failure to improve the above relation by incorporation of electrolyte concentration is not immediately apparent. It may mean that the range of sodium and potassium concentrations in these patients was so narrow that the effect of changes in serum electrolytes on impedance were not adequately tested in this series of normal subjects and patients. In patients with extreme variations of serum electrolyte concentrations, incorporation of ionic mass in TBW predictions might lead to significant improvement in the correlations.

A regression equation taking the form TBW $= AT^2/Z+B$ was derived from the 20 normal volunteers and used to predict TBW for the 34 patients. This prediction formula had an r of 0.92 and predicted the TBW of the 34 patients with a standard deviation of 3.89 liters. In each case, the tritium determined TBW was used as the standard of comparison.

DISCUSSION

The results of these studies using whole-body impedance, measured at 100 kc, indicate that a measurable relationship between conductor volume and impedance can be defined. This relationship and the resulting regression equation, TBW $= AT^2/Z+B$, are empirically derived. However, a comparison of this equation with *equation 3*, from the materials and methods section, indicates a similarity in that ρ is included in the A term, and T^2 is analogous to L^2. As previously noted, the human body is not a simple geometrical conductor and therefore application of such a relationship for estimation of TBW volume raises several questions. For instance, these studies have assumed a uniform and symmetrical distribution of body fluids, and thus the effects of unequal fluid localization, such as ascites or hydrothorax, need to be studied. Furthermore, the use of patient height as a measure of conductor length instead of the actual pathway length might be questioned; however, this dimension was used because it represents a standard easily obtainable, constant anatomical parameter. The prediction of TBW, in this series of 34 patients, for which tritium volume was also known, was moderately successful. Since the standard deviation of the prediction was relatively large, further development and refinement will be necessary before this method can be a useful clinical tool. A more detailed consideration of body geometry may be necessary to achieve accurate predications from impedance measurements.

Conclusion. A relationship has been demonstrated between in vivo electrical impedance at 100 kc and total body water volume. A high level of correlation between TBW and body impedance was demonstrated in both normal subjects and in patients with overhydration. The good correlation indicates that the impedance method has promise for prediction of total body water volume easily and quickly at the bedside.

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