Overview of bioelectrical impedance analyzers[1-3]

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ABSTRACT Six commercial bioelectrical impedance analyzers were evaluated to determine their accuracy as impedance meters, their sensitivity to contact impedance, and other operating parameters such as maximum current amplitude and test waveform. Over a range of impedances that simulate human body impedance, analyzer errors varied from $< 1\%$ to nearly 20%. Larger errors were observed when the contact impedance was at the limits of the operating range of the analyzer. Body models, sources of error, and several simple tests that the user can perform are also discussed. *Am J Clin Nutr* 1996;64(suppl):405S–12S.

KEY WORDS Bioelectrical impedance analysis, BIA, body composition, bioelectrical impedance analyzer, impedance

INTRODUCTION

The class of instruments referred to as bioelectrical impedance analyzers is designed to measure human body impedance—an index that has been used to estimate body composition based on algorithms that also include height, weight, sex, age, and physical activity level. The algorithms have been described in the literature (1–4), as have evaluations of commercial bioelectrical impedance analyzers in human subjects (5). I describe an investigation, funded by the National Institutes of Health and conducted at the National Institute of Standards and Technology (NIST), of the electrical properties of these instruments, specifically their accuracy as electrical impedance meters.

Six manufacturers submitted instruments for this study. Four of the instruments measure impedance at a single frequency (nominally 50 kHz) and two measure impedance at multiple frequencies between 300 Hz and 1 MHz. All the instruments use a four-terminal (tetrapolar) rather than a two-terminal measurement method.

In the simple two-terminal method shown in **Figure 1**, a current source supplies a constant known current through the test subject and a voltmeter, Vm, measures the associated voltage across the subject. The total body impedance is given by the following equation:

$$Z = V/I = R + jX \qquad (1)$$

where Z is the complex impedance, I is the complex current, V is the complex voltage, R is the resistive component of Z, X is the reactive component of Z, and j is $\sqrt{-1}$, which indicates that X is orthogonal to R.

Some bioelectrical impedance analyzers display R and X whereas others display the magnitude of the impedance $|Z|$ and the phase angle ϕ between the voltage and the current, which are defined by the following equations, respectively:

$$|Z| = (R^2 + X^2)^{1/2} \qquad (2)$$

$$\phi = tan^{-1}(X/R) \qquad (3)$$

A significant part of Z is the contact impedance, which depends on terminal (electrode) area, surface moisture and hair, impedance of the surface tissue (skin and subcutaneous fat), and other variables. The remainder of Z is the impedance of the deep body tissue Z_B, which is mainly a function of the amount of water and electrolytes contained in skeletal muscle and organs (1–4).

In the four-terminal method (shown in **Figure 2**), the objective is to measure Z_B independently of the surface impedance. The test current is introduced through one set of terminals and the voltage is measured at a second set, placed within a few centimeters of the corresponding current terminals. Five of the bioelectrical impedance analyzers tested used clip leads that attached to adhesive electrodes placed on the skin surface. Measurements are typically made between the wrist and ankle on one side of the body. However, by changing the electrode placement, impedance measurements can be made between any two points. The sixth analyzer tested was designed specifically to measure leg impedance; for this analysis, the subject stands on a scale that has current electrodes under the front of each foot and voltage electrodes under the heels.

The conductivity of surface tissue is much lower than that of deep tissue, so once the current penetrates the surface, most of it is conducted through the deep tissue. To penetrate the surface (represented by an impedance Z_S), a voltage is developed between the current electrode and the deep tissue. Thus, the magnitude of the voltage V_B at the deep tissue, directly below the electrode, is smaller than the magnitude of the surface voltage V_S. To measure V_B, a voltage electrode is placed on the surface near the current electrode. The voltage that appears at this electrode will be approximately V_B if a negligible current

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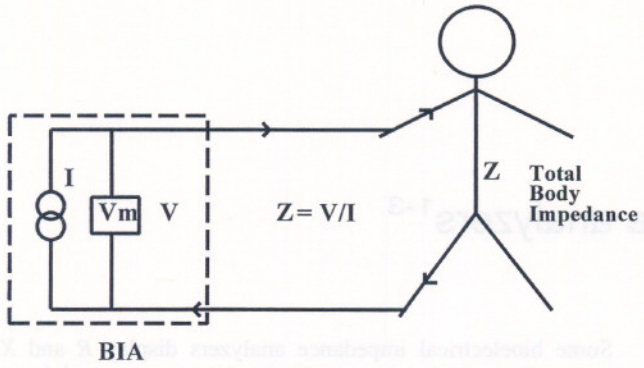

FIGURE 1. Two-terminal body impedance measurement method. *I*, current; Vm, voltmeter; *V*, voltage; BIA, bioelectrical impedance analyzer; *Z*, impedance.

is drawn through the electrode and if the surface impedance between electrodes Z_L is much higher than the deep tissue impedance between electrodes. The deep-body impedance is then

$$Z_B = V_B I \qquad (4)$$

BODY IMPEDANCE MODELS

The sources of error associated with a measurement of deep-body impedance can be analyzed by using the simple model shown in **Figure 3**. The bioelectrical impedance analyzer consists of a constant current source and a voltmeter. Ideally, these elements have infinite source and input impedances, respectively; however, in practice they have some finite impedance. They can be modeled as an ideal current source shunted by Z_I and an ideal voltmeter shunted by Z_V. The body is modeled as a homogeneous area of deep tissue with total impedance between the voltage electrodes of Z_B and variable surface layers with impedances Z_1, Z_2, . . . Z_7. To ensure that the current source causes less than an m% error in the measurement, $|Z_I|$ should be $> 100(|Z_1| + |Z_B| + |Z_2|)/m$. Similarly, to ensure that the voltmeter causes less than an m% error, $|Z_V|$ should be $> 100(|Z_4| + |Z_B| + |Z_5|)/m$.

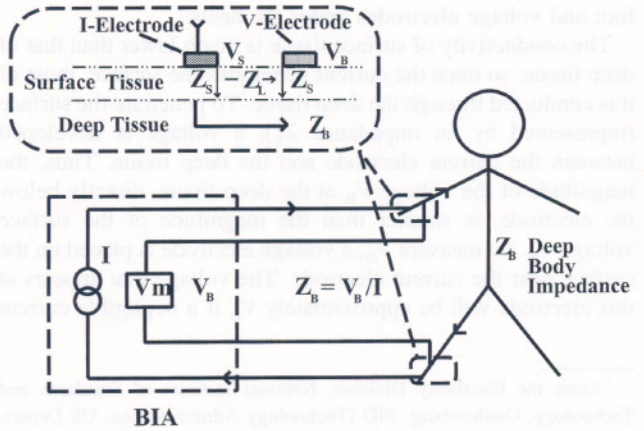

FIGURE 2. Four-terminal body impedance measurement method. The test current is injected through one set of electrodes and the voltage developed across the deep body tissue is measured at another set of electrodes placed at the points of interest. *I*, current; *V*, voltage; V_S, surface voltage; V_B, deep-tissue voltage; Z_L and Z_S, surface impedances; Z_B, deep-tissue impedance; Vm, voltmeter; BIA, bioelectrical impedance analyzer.

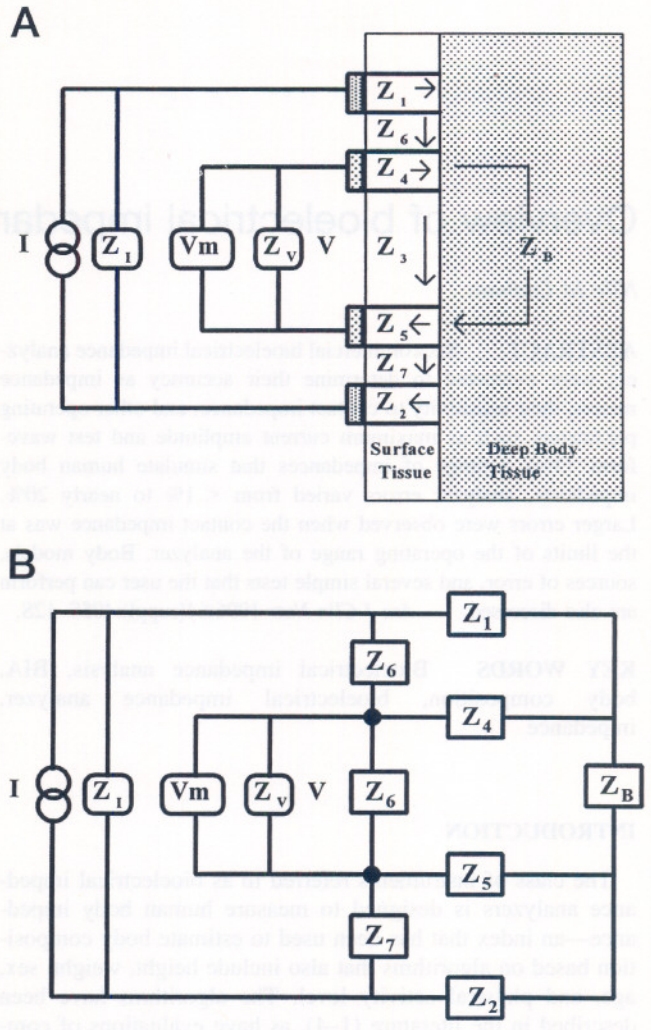

FIGURE 3. A) Block diagram model of the impedances encountered in a measurement of deep-body impedance. *I*, current; *Z*, impedance; Z_I, current impedance; Vm, voltmeter; Z_S, voltmeter impedance; *V*, voltage; Z_B, deep-body impedance. B) The circuit diagram used to simulate the interaction of various impedance components.

Leakage along the surface between terminals is another source of error requiring that the lateral surface impedances between electrodes be high compared with the transverse surface impedances, eg, $|Z_6| > 100|Z_1|/m$ and $> 100|Z_4|/m$. This model was implemented in a software circuit simulator to help analyze the interaction of highly reactive surface impedances on the mostly resistive deep-body impedance. Results of these simulations are described below. Each element (shown in the circuit model in Figure 3B) can be adjusted in resistance and reactance.

A commonly used model for deep-body impedance is shown in **Figure 4**A. The rationale for this model is that skeletal muscle and organs consist of extracellular water (ECW) that flows between the cells and intracellular water (ICW). At low frequencies, the impedance of the cell walls is high relative to both internal and external fluids, so current is conducted

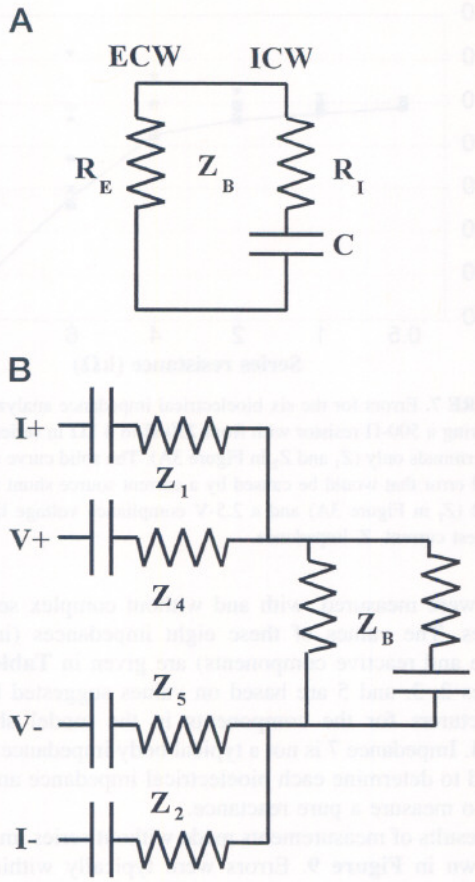

FIGURE 4. A) The commonly used extracellular water (ECW)–intracellular water (ICW) model of the deep body tissue. R_E, extracellular resistance; Z_B, deep-tissue impedance; R_I, intracellular resistance; C, cell membranes. B) The whole-body model, including the ECW-ICW model with simulated surface impedances added (plus and minus signs are used only to identify the two different sets of leads, not to indicate polarity). I, current; V, voltage.

mainly in the ECW path. As the frequency increases, the impedance of the cell walls decreases, allowing a larger portion of the current to be conducted in the ICW path. At 50 kHz, at which ECW provides the main current path, the deep-body impedance is primarily resistive, R_E. Cells that make up the deep tissue are modeled as a series resistive-capacitive network consisting of ICW, R_I, and cell membranes. Surface impedances are modeled as complex impedances in series with the current and voltage terminals as shown in Figure 4B.

TESTS

To determine the appropriate impedance range to test the bioelectrical impedance analyzers, complex impedance measurements were performed on > 15 subjects with various analyzers. For all the subjects, the impedance $|Z_B|$ (measured from wrist to ankle or from one foot to the other) fell within the range of from 300 to 700 Ω. These values are consistent with measurements on human subjects described in the literature (1–5). The range of surface impedance was also estimated by measuring different body segments of the test subjects through use of both two- and four-terminal methods. The two-terminal measurement gives the total body impedance (surface and deep tissue) and the four-terminal measurement gives the deep tissue impedance only. Thus, the surface impedance Z_S can be estimated by the following:

$$2Z_S \approx (Z_{2T} - Z_{4T}) \quad (5)$$

where Z_{2T} is the two-terminal body impedance and Z_{4T} is the four-terminal body impedance. The surface impedance Z_S varies from 50 to 300 Ω (resistive) and from 100 to 300 Ω (reactive) and the deep-body impedance Z_B varies from 300 to 700 Ω (resistive) and from 40 to 100 Ω (reactive).

To test the bioelectrical impedance analyzers, a four-terminal impedance synthesizer was constructed that can be programmed to simulate any complex impedance between 100 and 1000 Ω at 50 kHz. A block diagram of this synthesizer is shown in **Figure 5**. The synthesizer consists of relay-switched complex impedances based on the model shown in Figure 4A. To simulate any complex impedance, the synthesizer uses an electronic circuit that converts the bioelectrical impedance analyzer test current to a voltage, which can be amplified or attenuated and phase shifted before it is applied to the analyzer voltage terminals (6). It is also possible to insert complex impedances in series with all four terminals to simulate the surface impedance as in Figure 4B. All impedance values used to test the bioelectrical impedance analyzers were measured with a commercial four-terminal impedance meter that was calibrated by using impedance standards maintained at NIST and found to have 1 SD uncertainties < 0.2% at 50 kHz (7, 8).

Connections were made to the impedance synthesizer terminals by using the four clip leads provided with each bioelectrical impedance analyzer. A special clip-lead adaptor was constructed for the analyzer that required the subject to stand on the four electrodes. The position of the test analyzer and its leads relative to the impedance synthesizer was varied to ensure that there was no significant interference or crosstalk. The impedance reading Z_T of each analyzer was compared with the impedance reading of the reference impedance meter Z_R to

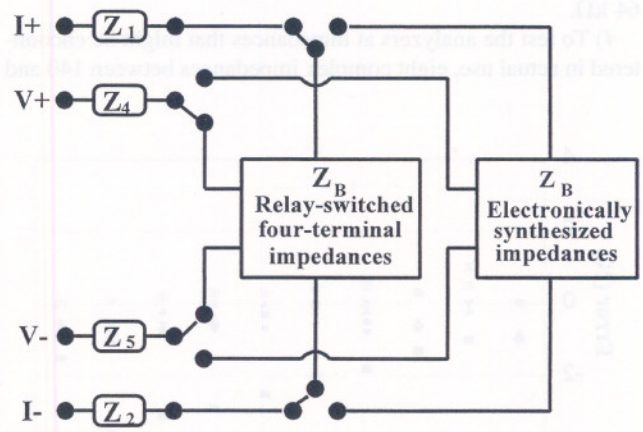

FIGURE 5. Block diagram of the impedance generator used in the bioelectrical impedance analyzer evaluation. Z_B (deep-tissue impedance) is simulated by relay-switched components (resistors and capacitors) or by electronically synthesized signals applied to the analyzer's voltage terminals. Simulated surface impedances can be placed in series with any of the terminals. I, current; Z, impedance; V, voltage.

determine the percentage error E of the analyzer under test. This error is given by the following equation:

$$E = 100(Z_T - Z_R)/Z_R \quad (6)$$

The following tests were performed with each of the six analyzers:

1) To test the analyzers as basic alternating-current ohmmeters, 10 calibrated resistors between 100 and 1000 Ω with uncertainties $< 0.1\%$ were measured with the bioelectrical impedance analyzer current and voltage terminals tied together at the resistor terminals. This is the most basic measurement, a two-terminal resistance. Results of this test are shown in **Figure 6**; most of the data points fell within ± 1% error. Only one analyzer had errors exceeding 2%.

2) To measure the influence of source resistance and compliance voltage of the bioelectrical impedance analyzer current source, a 500-Ω resistor was measured, with 0–4 kΩ (resistive) in series with each current terminal (Z_1 and Z_2 in Figure 5). The voltage terminals were connected directly to the 500-Ω resistor. Results of this test are shown in **Figure 7**. Errors were typically within a few percent up to a total series resistance of 1 kΩ (500 Ω in series with each current lead). One of the analyzers was insensitive to series resistance, remaining within ± 1% over the entire range. However, with 8-kΩ series resistance, the other analyzers were in error from 20% to −40%, indicating that high surface resistance can be a serious source of error. The solid curve in Figure 7 is a simulation of the error caused by a current source shunt impedance Z_I of 64 kΩ and a compliance voltage limit of 2.5 V (for a 0.5-mA test current).

3) To measure the influence of input resistance of the bioelectrical impedance analyzer voltmeter, a 500-Ω resistor was measured with 0–4 kΩ in series with each voltage terminal. The current terminals were connected directly to the 500-Ω resistor. Results of these measurements are shown in **Figure 8**. Two of the analyzers were relatively insensitive to series resistance. At 8 kΩ, the other analyzers were in error from 6% to 50%, again indicating that it is important to keep surface impedance < 500 Ω. The solid curve in Figure 8 is a simulation of the error caused by a voltmeter shunt impedance Z_V of 64 kΩ.

4) To test the analyzers at impedances that might be encountered in actual use, eight complex impedances between 140 and 700 Ω were measured, with and without complex series impedances. The values of these eight impedances (including resistive and reactive components) are given in **Table 1**. Impedances 2, 3, and 5 are based on values suggested by three manufacturers for the components in the model shown in Figure 4. Impedance 7 is not a typical body impedance but was included to determine each bioelectrical impedance analyzer's ability to measure a pure reactance.

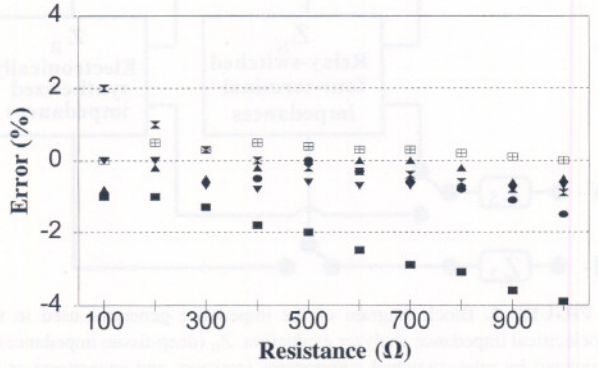

FIGURE 6. Errors for the six bioelectrical impedance analyzers tested as basic alternating-current resistance meters from 100 to 1000 Ω without series resistance.

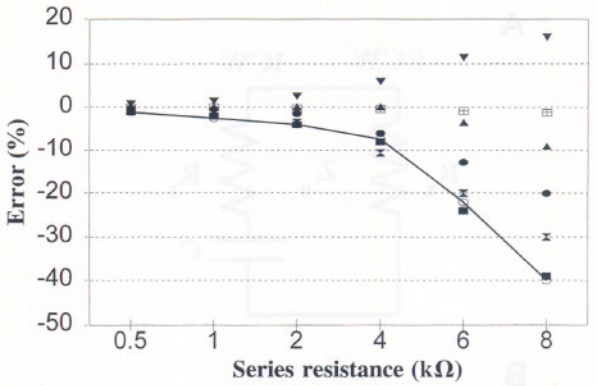

FIGURE 7. Errors for the six bioelectrical impedance analyzers tested in measuring a 500-Ω resistor with from 250 Ω to 4 kΩ in series with the current terminals only (Z_1 and Z_2 in Figure 3A). The solid curve shows the simulated error that would be caused by a current source shunt resistance of 64 kΩ (Z_I in Figure 3A) and a 2.5-V compliance voltage limit for a 0.5-mA test current. Z, impedance.

The results of measurements made without series impedance are shown in **Figure 9**. Errors were typically within a few percent for all but one of the analyzers. Impedance 7 caused a large error (84%) for one of the analyzers. Figure 9 shows only how well each of the analyzers can measure simulated deep tissue impedance with zero surface impedance.

A more realistic measure of performance is shown in **Figure 10**, for which an impedance to simulate the surface tissue was placed in series with each terminal. The typical human surface impedance is highly reactive. For this test a value of 345 Ω ($R = 65$ Ω and $X = 320$ Ω) was used. The components of this impedance are similar with those recommended by one of the bioelectrical impedance analyzer manufacturers for the model

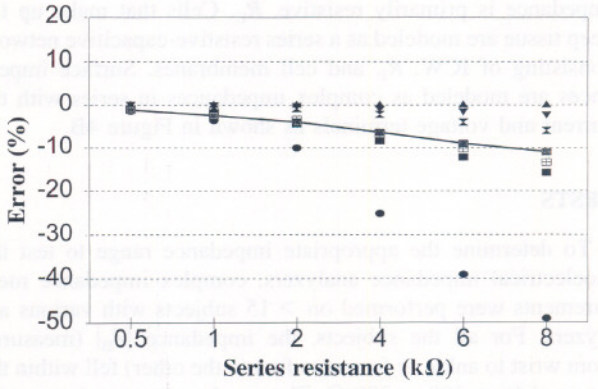

FIGURE 8. Errors for the six bioelectrical impedance analyzers tested in measuring a 500-Ω resistor with from 250 Ω to 4 kΩ in series with the voltage terminals only (Z_4 and Z_5 in Figure 3A). The solid curve shows the simulated error that would be caused by a volmeter shunt resistance of 64 kΩ (Z_V in Figure 3A). Z, impedance.

TABLE 1
Eight complex impedances used to test the bioelectrical impedance analyzers[1]

	1	2	3	4	5	6	7	8
				Ω				
Z	698	229	144	518	681	500	462	347
R	669	220	130	513	680	500	0	342
X	200	65	63	74	40	0	462	59

[1] *Z*, impedance; *R*, resistance; *X*, reactance.

shown in Figure 4B. Two of the analyzers appear to be insensitive to series impedance, showing errors < 3% at all of the test impedances. As expected, these are the same instruments that performed well in tests 1 and 2. As in Figure 9, impedance 7 led to a large error in one of the analyzers. Additionally, one of the other analyzers did not register on five of the eight impedances.

The results shown in Figures 9 and 10 are based on the mean of two or more independent measurements at each point with an associated standard uncertainty *A* (the SD of the mean). The total uncertainty U_T of the measurements includes the standard uncertainty *B* of the reference impedance meter. The components of uncertainty are then combined using the method described in reference 8 as follows:

$$U_T = 2(A^2 + B^2)^{1/2} \quad (7)$$

For the results shown in Figures 9 and 10, U_T ranges from 0.4% to 1.6%. In general, the analyzers with the smallest errors had the smallest SDs and thus the smallest measurement uncertainties.

Additional tests were performed at 500 Ω (resistive) with complex series impedances up to 4 kΩ to simulate higher surface impedances. At 3690 Ω (R = 1500 and X = 3330), errors ranged from −23% and 47% (for the two analyzers that performed best on all the above tests) to 140% for one of the others.

MULTIFREQUENCY TESTS

Two of the bioelectrical impedance analyzers submitted for evaluation were multifrequency units capable of measuring impedance at frequencies other than 50 kHz. These analyzers were tested over their operating range of frequencies by using a 500-Ω resistor with and without the 345-Ω series impedance used in test 3. Results of these tests are shown in **Figure 11** and **Figure 12**. At low frequencies the reactive component of the series impedance becomes quite large (X = 4 kΩ at 4 kHz), resulting in large errors, which are not shown in Figure 12. The uncertainty of these measurements, computed by using equation 7 is ≈ ± (0.2 + 2F)%, where F is the test frequency in MHz.

By making measurements at more frequencies than there are components in the body model, it should be possible to use an iterative-parameter optimization method to solve for the model components. Most methods involve minimizing the square of the difference between the measured and predicted impedances by increasing the parameters in increments until the mean-squared error is sufficiently small. Because of the limited scope of this evaluation, the analysis software available with the multifrequency analyzers was not tested. However, on the basis of limited attempts to solve for model components using real R and X data, it is recognized that this analysis is not trivial.

TEST PARAMETERS

The measured and observed test parameters for each of the six analyzers are given in **Table 2**. The waveform is the shape of the test current signal. The test frequency is the average of two or more measurements made on different days for a nominal 50-kHz signal. The maximum test current is the highest 50-kHz current observed for resistive loads ranging from 0 to 100 kΩ. The maximum currents for all the tested bioelectrical impedance analyzers were < 1 mA—well below the 20–30 mA threshold of perception (at 50 kHz) for children and adults, respectively, described by Chatterjee et al (9). The compliance voltage is the maximum voltage that the current source can generate in its attempt to deliver a constant current. The maximum body impedance is the highest value that can be dis-

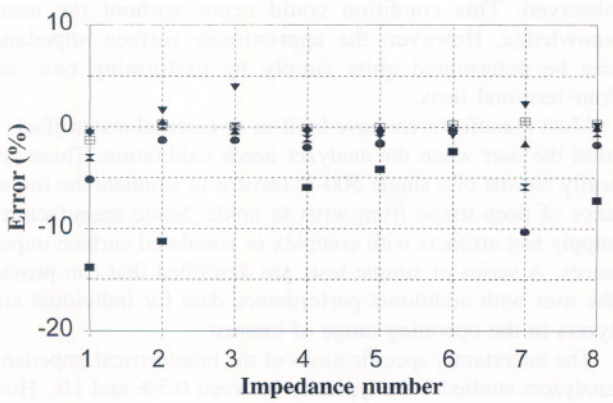

FIGURE 9. Errors for the six bioelectrical impedance analyzers tested in measuring eight complex impedances, which were selected to simulate a range of deep-tissue imedances without simulated surface impedance (Figure 4A).

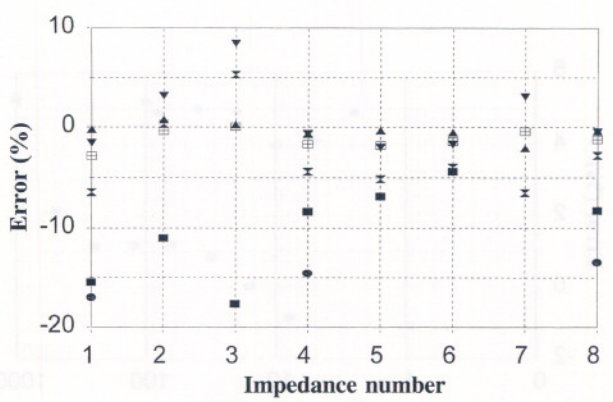

FIGURE 10. Errors in the six bioelectrical impedance analyzers tested in measuring the same eight complex impedances as in Figure 9, but with a 345-Ω simulated surface impedance in series with each terminal (*see* Figure 4B).

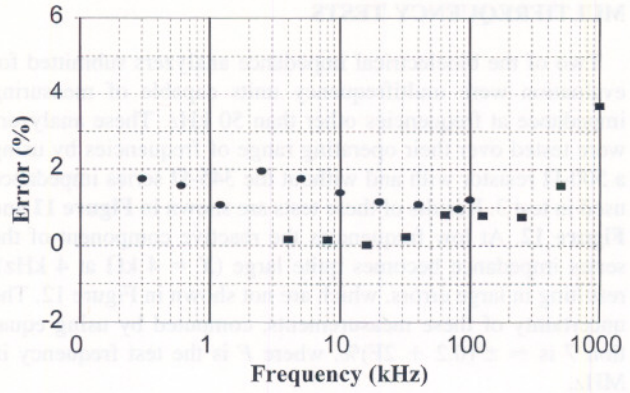

FIGURE 11. Error versus frequency of two multifrequency bioelectrical impedance analyzers measuring a 500-Ω resistor without simulated surface impedance.

played, independent of the applied impedance. The display represents the default impedance component or components shown on the bioelectrical impedance analyzer display screen. Two of the analyzers could provide several modes of display. The specified uncertainty is the figure given in the user's manual.

CALIBRATION

Five of the six bioelectrical impedance analyzers were supplied with internal or external artifacts for testing the accuracy of the analyzer. In general, the test procedures only verified that the instrument could measure a 500-Ω resistor, although one tester included series impedance and another had several switchable impedances. Variation of the tests described in this paper can be performed by the user to determine whether a particular bioelectrical impedance analyzer is appropriate for the task. Even without calibrated standards, these test procedures are useful for determining operating range and influence of surface impedance. *See* Appendix A for sample tests.

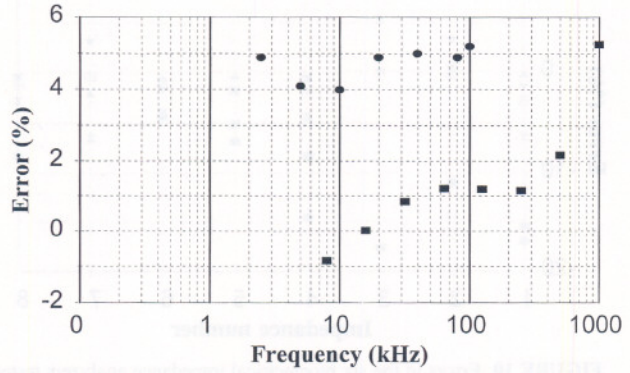

FIGURE 12. Error versus frequency of two multifrequency bioelectrical impedance analyzers measuring a 500-Ω resistor with a 345-Ω simulated surface impedance in series with each terminal.

TABLE 2
Test parameters of the six bioelectrical impedance analyzers tested[1]

	1	2	3	4	5	6
Waveform	Square	Sine	Sine	Sine	Sine	Sine
Test frequency (kHz)	46.6	50.2	50.0	50.2	50.6	49.6
Max test current (mA)	0.76	0.57	0.39	0.42	0.85	0.20
Compliance voltage (V)	4	4	1.7	3.5	3.5	1.5
Max body impedance (kΩ)	1.999	1.999	1.432	1.999	1.999	2.001
Display	Z	Z	Z	R, X	Z	Z, θ
Specified uncertainty (%)	—	1	—	0.5, 1	1	0.5

[1] Max, maximum.

CONCLUSIONS

An evaluation of six commercial bioelectrical impedance analyzers, as electrical impedance meters, was conducted at NIST. Some of the instruments tested are intended for a specific range of impedances, and display error messages if this range is exceeded. Others are more general-purpose research tools that operate over a wide range of complex impedances. The objective of this study was not to rate specific instruments, but rather to explore the accuracy limitations of these devices and the state-of-the-art of bioelectrical impedance measurements.

The analyzers tested pass an imperceptible current of < 1 mA (at 50 kHz) through the test subject with one set of electrodes. A second set of electrodes measures the voltage that is developed somewhere between the surface and deep tissue. This four-terminal (tetrapolar) measurement method minimizes the influence of contact and surface impedances; however, imperfections in the bioelectrical impedance analyzer current sources and voltmeters cause different errors for different analyzers. The ratio of complex voltage to current is the complex impedance, which is generally considered to be a measure of ECW. The algorithms used to relate impedance to body composition were not investigated in this evaluation.

For electrical impedances similar to those normally encountered in measurements of the human body, errors $< 1\%$ to 20% were observed. For extreme cases, in which the contact or surface impedances were as high as 4 kΩ (with large reactive components), errors of 25% to $> 100\%$ were observed. This condition could occur without the user's knowledge. However, the approximate surface impedance can be determined quite simply by performing two- and four-terminal tests.

Most manufacturers have built-in or external test artifacts to alert the user when the analyzer needs calibration. These typically consist of a single 500-Ω resistor to simulate the impedance of deep tissue from wrist to ankle. Some manufacturers supply test artifacts with complex or simulated surface impedances. A series of simple tests are described that can provide the user with additional performance data for individual analyzers in the operating range of interest.

The uncertainty specifications of the bioelectrical impedance analyzers studied were typically between 0.5% and 1%. However, the conditions under which these figures apply are not clearly stated. Of the 48 test points performed on stable electrical artifacts that simulate body impedance, only 25% were within $\pm$ 1%, with 60% $> 2\%$. Only one of the bioelectrical

impedance analyzers tested was consistently within ± 1%. Even instrumentation-grade impedance meters, with uncertainty specifications of ± 0.1% or better, degraded to ± 1% or worse when faced with simulated surface impedances in series with the current or voltage leads. Repeatability was typically better than 0.5% for the electrical artifact tests, although experience measuring actual body impedance suggests that repeatability better than ± 1% is difficult to achieve. The state-of-the-art error for bioelectrical impedance measurements of the human body appears to be between ± 1% and ± 2%, whereas uncertainties for measurements with commercial bioelectrical impedance analyzers are typically within ± 5%.

I thank Bryan Waltrip for developing the software simulator, Andrew Koffman for analyzing the multifrequency data, Robert Palm for constructing special adaptors, Di Wu for performing many of the follow-up tests, and the volunteers whose impedance data helped determine the range of test impedances.

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APPENDIX A

The following tests can be performed by the user to determine if a bioelectrical impedance analyzer is appropriate for a particular task:

1) Dynamic range

Connect three nominally equal (±10%) resistors R_1, R_2, and R_3 in series as shown in the top of **Figure A1**. (The plus and minus signs are used only to identify the two different sets of leads, not a particular polarity.) $I+$ is normally bundled with V+. If the current and voltage terminals are not identified, the I terminals are the ones that attach to the outer electrodes (those at the farthest extremity of the arm or leg). Measure each resistor by connecting the $I+$ and $V+$ terminals at one end and the $I-$ and $V-$ terminals at the other end. Also measure the

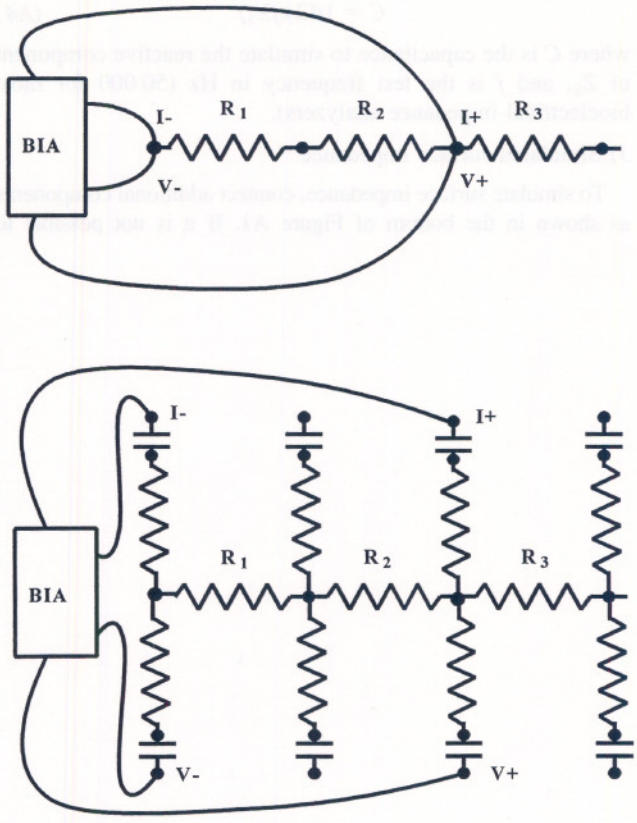

FIGURE A1. User tests to evaluate bioelectrical impedance analyzers for a particular task. The top part of the figure is a test to measure the dynamic range of an analyzer; the bottom part of the figure is a test to simulate surface impedance.

combinations of $R_1 + R_2$ (the connection shown in the top half of Figure A1), $R_2 + R_3$, and $R_1 + R_2 + R_3$. The combinations should equal the sums of the individual resistors. This test does not measure accuracy unless the resistors have been calibrated. However, it does provide a coarse measure of the dynamic range and linearity of the bioelectrical impedance analyzer. Choosing R_1 equal to 250 Ω gives a typical range of human body impedance (250–750 Ω).

2) Surface impedance

Surface impedance can be measured by using the procedure described in the Tests section of the text. Place one electrode at each end of the test path (eg, one on the wrist and one on the ankle). Connect $I+$ and $V+$ to one of the electrodes and $I-$ and $V-$ to the other and measure the two-terminal impedance. Add the second electrode at each site and perform a normal test. Estimate the surface impedance by using equation *5*. Because the surface impedance can be highly reactive, it is preferrable to use an analyzer that displays R and X or Z and ϕ, related by equations *2* and *3*. The resistive and reactive components for the surface impedance are given by the following formulas:

$$Z_S \approx (Z_{2T} - Z_{4T})/2 \qquad (A1)$$

$$R_S \approx (R_{2T} - R_{4T})/2 \qquad (A2)$$

$$X_S \approx (X_{2T} - X_{4T})/2 \qquad (A3)$$

$$C = 1/(2\pi f X_S) \quad (A4)$$

where C is the capacitance to simulate the reactive component of Z_S, and f is the test frequency in Hz (50 000 for most bioelectrical impedance analyzers).

3) Simulated surface impedance

To simulate surface impedance, connect additional components as shown in the bottom of Figure A1. If it is not possible to measure the surface impedance components, $R = 100\ \Omega$ in series with $C = 20$ nF represents the typical human surface impedance at 50 kHz. Measurements can be made with series impedance inserted into any node. An ideal impedance analyzer should respond only to R_1, R_2, and R_3, depending on the connections. In the example shown in the figure, the analyzer should read the same impedance for the connections in the circuits shown in both the top and bottom, ie, $R_1 + R_2$.