Application of bioelectrical impedance to sports science

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Abstract Bioelectrical impedance analysis (BIA) involves passing a weak, high-frequency current through the body in order to measure variables such as tissue volume, or the volume of blood, on the basis of electrical resistance. Biometric measurements using BIA date back to the beginning of the 20th century; and since then there have been many technical refinements. BIA is non-invasive, it excels in terms of cost and safety, and it does not require any special measurement skills. It has therefore become an outstanding measurement tool for a range of body composition assessments in areas such as large-scale population studies or sports science. There have already been numerous reports of studies of BIA, and its contribution to sports science is well recognized, so that many researchers have demonstrated an interest in using BIA. However, while BIA is easier to operate than other measurement tools, it requires basic knowledge and precise methodology in order to properly interpret the data. This review summarizes the theory of measuring tissues related to exercise, the method of measuring cardiac output, and the method of estimating skeletal muscle mass. First, while the measurement, by BIA, of cardiac output (CO) at rest yields stable results, previous measurements during dynamic exercise had several limitations. CO measurement during intense exercise has recently become possible as a result of improvements to fast Fourier transform (FFT) and the algorithms. Moreover, the water content and fat mass of the body can now be calculated in terms of electrical models in which resistors and capacitors are arranged in series or in parallel, and cells and tissues have been simplified as far as possible. Finally, new estimation equations using single-frequency BIA and multi-frequency BIA have been developed for measurement of skeletal muscle mass in the limbs, and each are reported to have high reliability and high reproducibility. Development of simple, highly accurate measuring instruments and methods for vital observation, utilizing BIA, and that can contribute to sports science, is expected.

Keywords : bioelectrical impedance, muscle volume, cardiac output, tetra-polar impedance method, fat free mass

Introduction

At present, the results of numerous studies, utilizing bioelectrical impedance analysis (BIA), extend to various fields such as basic medicine, clinical medicine, nutrition and sports medicine. The history of using electrical impedance is fairly old, dating back to the early 20th century. Bioelectrical impedance (BI) is a method of determining changes in blood volume or tissue in the living body, based on measurements of electrical impedance at the body surface. Initial attempts at using the electrical properties of the living body were to obtain diagnostic information of the circulatory system, such as seen in the work of Nyboer¹⁾. Systematic research has led to the development of impedance plethysmography.

The method was eventually applied to basic physiology and clinical medicine about 50 years ago based on the

research of Kubicek et al²⁾. Since then, various types of research have been performed, including studies that used bi-polar electrode and tetra-polar electrode methods, and single-frequency and multi-frequency methods. Segmental BIA, or whole-body BIA, in states of altered hydration and the estimation of muscle mass have also been developed. Since these measurements are relatively inexpensive, noninvasive and have high accuracy, they have been applied in various research fields, including sports medicine^{3,4)}. Herein, the merits and limitations of the BIA method are discussed, and research introduced which has been performed in the field of sport sciences.

Considerations of measurement method

Impedance measurements are relatively simple compared with other methods. Researchers are required, however, to have basic knowledge about the proper interpretation of this measurement method. Although measurement

is relatively easy using the BIA method, it is important to comply with standardized measurement techniques as discussed below⁵.

Essentially, the diurnal variation in impedance for normal healthy subjects is nearly 1 to 2%⁶. This value is very small compared to the effects of exercise, dehydration, or eating. Generally, BIA is measured using standard procedures while the subject lies in a supine position in a relaxed state on a measurement bed. The time spent in the supine position on a bed before measurement must be unified, since postural changes affect the tissue fluid and blood movement from the limbs to the trunk. This faster body fluid movement can alter impedance measurements within the first 10 minutes⁷. However, because tissue fluid continues to move immediately after lying down, the measurement should be delayed. Conversely, there are also many studies that have started measurements after 10 min when the movement of tissue fluid has subsided. The time that subjects spend in the supine position for measurement appears to differ according to the aim of the study. During an actual measurement, the arms are opened slightly so that they do not touch the sides of the trunk, and the ankles are apart at least 20 to 30 cm, so that the feet do not touch. Care must be taken when measuring impedance at frequencies higher than 1 MHz using multi-frequency devices. Using electrical current at very high frequencies may result in current leakage. Thus, a frequency of 1 MHz or less is recommended to obtain physiological and histological information on a living body. Impedance measurement should not be performed after heavy exercise, water or food intake which changes

hydration levels⁸. Actions such as exercise and eating obviously decrease resistance and reduce the reliability of measurements. The factors that can influence fluid balance should be excluded whenever possible⁹. BIA is dependent on temperature, so remarkable changes in body temperature or ambient temperature will affect the measurements¹⁰. Maintenance of the ambient temperature is particularly important when performing continuous measurements¹¹. It is well known that both resistance and resistivity show a reverse correlation with temperature. In our experiments using pork meat, a continuous decrease in impedance was observed as the surface temperature rose from 14.3 to 18.2°C (Fig. 1). At this time, the temperature coefficient (temperature variation/impedance variation) of the impedance was -1.6% at 5 kHz, -2.4% at 50 kHz, -2.6% at 100 kHz, -2.6% at 200 kHz and -2.6% at 500 kHz, and rate of temperature coefficient change also increased with the increase in frequency. Although the measurements were taken from pork meat rather than a living human, a rise in tissue temperature of 1°C decreased electrical resistance by approximately 1 to 3%.

In addition to the elevation of body temperature during exercise, the electrolyte concentration and water loss, due to sweating, strongly affects the impedance. More fundamentally, there is strong muscle tissue anisotropy. Since skeletal muscle is made from a myriad of fibers, muscle resistance depends on the measurement direction^{12,13}. Skeletal muscle fibers in human limbs run parallel along the long axis direction, but the orientation of skeletal muscle fibers in the trunk is complex. Specifically, there

Fig. 1 Change in impedance for each frequency accompanying the rise of the surface temperature of pork. Shows the time-dependent changes of the impedance from 5 kHz to 500 kHz frequency. Decrease in the impedance was observed with increasing temperature of the surface of pork.

are large differences between conductivities in directions perpendicular and parallel to the muscle fibers, especially when attempting to extract information from deep underlying structures. Even if it is measurement of the same part, resistance measured transversely to the muscle fiber direction is remarkably greater than resistance measured longitudinally¹³⁾. The orientation of the muscle fibers must be taken into consideration when recovering the electrodes before and after the exercise. Although it is quite troublesome, the BIA method is insufficient to quantify small physiological changes in vivo, if these measurement procedures are not followed.

Measurement of cardiac output

Impedance has been widely used to measure cardiac output (CO) in studies on exercise physiology. Measurement of CO is the most basic means of assessing cardiac function and hemodynamics¹⁴⁾. Noninvasive measurement of CO is very important in exercise physiology, and has been advanced by extensive research. The gold standard for measuring cardiac function is considered the direct Fick method. The Fick method has been widely shown to give accurate and reliable determinations of CO during mild whole-body exercise or submaximal local exercise conditions. This method, however, has many technical problems and is not without risk to the subject. Moreover, to measure CO during exercise and in a variety of body positions is extremely difficult, and the conventional measuring method is cumbersome and complex. In that respect, the BIA method is a simple and potential method for noninvasive and continuous monitoring of stroke volume (SV) and CO by detecting the electrical impedance of the thorax. A BIA method has been developed by Kubicek et al.²⁾ to measure SV from the change in electrical impedance of the thorax due to the cardiac cycle. In this method, called impedance cardiography (ICG), one electrode is placed around the abdomen and the other is placed around the upper part of the neck. For the sensing electrode pair, one electrode is placed around the thorax between the xiphoid and the sternum, at the xiphisternal joint, and the other is placed around the lower part of the neck. This measurement is a noninvasive method for estimating SV based on changes in transthoracic electrical resistivity that occurs during the ejection of blood into the ascending aorta. For this measurement, the impedance measurement is generally made by introducing an electrical current, in the frequency range of 10 to 100 kHz and a constant current range of 300 μ A to 2 mA, into the volume conductor. The frequency often used is a single frequency of 50 kHz, which is selected partly for engineering and safety considerations. In this case, the impedance signal obtained from ICG is comprised of three elements¹⁵⁾. The largest component is the thoracic impedance (Z_0), which reflects the conductance of the entire thorax. The second element is respiratory activity,

which accounts for the change in thoracic impedance by a small percentage. The third element is the activity of the heart, which is less than 1% of the reference impedance. Kubicek et al.²⁾ developed the equation for calculating SV based on his experience with the measurement. Usually, ICG is measured simultaneously using the electrocardiogram (ECG), the phonocardiogram (PCG), the magnitude of change in thoracic impedance ΔZ , and the waveform of its first time derivative (dZ/dt). The equation developed by Kubicek et al.²⁾ has been widely used:

$$SV = \rho(L/Z_0)^2 (dZ/dt \max)(LVET),$$

where ρ is the resistivity of blood in ohms, L is the anterior chest distance in centimeters between sensing electrodes, Z_0 is the measured mean thoracic impedance in ohms, dZ/dt is the first derivative of change in thoracic impedance in ohms/second, and LVET is the left ventricular ejection time in seconds.

The waveform of dZ/dt has been used in the measurement of SV because it is less susceptible to baseline drift due to respiration. Because Z_0 depends on the relative amount of tissue in the thorax and air, it is determined by the fluid in the thorax and lung capacity. In addition, reference Z_0 has a large effect on changes in dZ/dt at the time of blood ejection, if reference Z_0 is small, dZ/dt decreases; thus, Z_0 is proportional to dZ/dt . Thoracic impedance changes according to the respiratory cycle as well as SV ¹⁵⁾. To date, many articles and publications have focused on the accuracy of ICG at rest. Measurement during exercise is difficult compared to at rest. There are physiological restrictions on breathing and body movement for measuring cardiac output during exercise. Generally, in order to avoid the effect of breathing on dZ/dt , the measurement has been performed in the state of apnea. To stop breathing during exercise, however, is difficult and dangerous. Because the baseline of the Z wave is distorted by body movements, measurements have usually been limited to during rest and light exercise. Therefore, to accurately measure SV during heavy exercise remains very difficult.

Temporarily stopping physical activity and breathing do not accurately reflect SV by a decrease in heart rate during exercise. Even if SV was obtained during exercise, it would be underestimated. In order to obtain an accurate SV during exercise, it is essential to measure it during exercise. To solve such problems, a method that can measure CO accurately, during exercise, must be developed. In recent years, newly developed spot electrodes have replaced the original tape electrodes, and a more appropriate arrangement of the electrodes, considering the baseline drift, has been determined¹⁶⁾. Moritani¹⁵⁾ enabled continuous recording of cardiac output using signal processing and a computer. First, the method carried out fast Fourier transform (FFT) of the ECG signal and Z -wave, leaving a signal ranging from 1.25 to 32 Hz. Then, after setting other frequency components to zero, the inverse

Fourier transform was performed and baseline drift was removed. After confirming the ECG, and the Z-wave as a secondary treatment, the ECG-R wave was selected as the trigger. A cumulative average was obtained every 8 sec (s), and dZ/dt was calculated. Ono et al.¹⁷⁾ assessed the validity of an adaptive filter, the scaled Fourier linear combiner (SFLC), for ICG. The SV and CO measured by ICG, during constant-load bicycle exercise at different intensities from unloaded to near maximal intensity, were compared with those measured by the CO₂ rebreathing method or technique. They found that the noise was significantly reduced in the impedance waveform, and that the inflection points, so-called B- and X-points, were clearly detected even during heavy exercise using the SFLC¹⁷⁾. Here, the B-point seemed to appear just after the first heart sound (S1), and the X-point just at the onset of the second heart sound (S2) in the PCG, respectively. Although a high correlation was observed in CO measured by the two methods, the mean values of CO for each method differed, and the regression line differed significantly from the identity line. Similarly, a significant correlation was observed between SV values obtained by the two methods. Although this high correlation was observed in two measurement results, it seems to overestimate the value of the impedance method. It was reported that the use of SFLC for ICG improves performance in eliminating noise and in detecting the inflection points in the waveform, thereby contributing to beat-to-beat measurements of SV, especially during exercise. In recent years, Charloux et al.¹⁸⁾ compared CO determined simultaneously by two methods, the direct Fick and Physio Flow methods using a new algorithm and improved electrodes. CO measurement by the Physio Flow device is based on the following equation¹⁸⁾:

$$CO = fc \times SV \text{ index} \times BSA,$$

where fc is the heart rate (beats/min), BSA is the body surface area (m²), calculated according to the Haycock formula ($BSA = 0.024265 \times BM^{0.5378} \times H^{0.3964}$, where BM is body mass, in kg and H is height in cm), and SV index (ml/m²; i.e. the SV divided by the BSA)¹⁸⁾.

Normally, ICG can be measured continuously. It is necessary, however, to have electrodes with high conductivity, and it is important to attach the electrodes precisely for measuring the baseline impedance. On the other hand, Charloux's method¹⁸⁾ does not require measurement of the baseline impedance; the position of the electrodes should not be a prerequisite for measurement accuracy. Accurate CO during maximal exercise in healthy adults was obtained using this method, a high correlation was observed between the Physio Flow method and direct Fick method.

Measurement of CO during exercise was difficult, and the measurement of CO during exercise was made possible by technological advances brought about by new research^{19,20)}.

Measurement of body composition

Over the past 20 years, the study of the BIA method for the measurement of body composition, such as fat-free mass (FFM) and percent body fat (%FAT), has been developed rapidly. In the early 1960s, the basic BIA principles were established by Thomasett²¹⁾. In the BIA method, low-level electrical current is passed through the human body using a BI analyzer, and the impedance is derived. Previously, the electrical information obtained from the impedance method ignored individual cells, estimating the living body from only a macroscopic perspective. In recent years, the structure of cells has been modeled theoretically, analysis developed rapidly, and BIA eventually applied to various fields.

Usually, regardless of single- or multi-frequency impedance, the frequency range for in vivo BIA measurement is approximately 1 kHz to 1 MHz. When dealing with the electrical information in this frequency range, except for special cases, it is sufficient to consider the cellular level. The cell encapsulates intracellular fluid within the cell membrane and the outside of the cell is surrounded by extracellular fluid, with each cell regularly arranged. Extracellular fluid is electrolytic, and the electrical properties are similar to those of intracellular fluid. Because the intracellular components differ based on the type of cell, resistance is different for each cell. Moreover, because the electrical properties of tissue exhibit anisotropy and nonlinearity, electrical measurement of tissue is complex in a living body. Therefore, it is difficult to measure resistance accurately for each type of tissue. In such cases, electrical properties can be considered based on a simplified electrical model. Body composition analysis with the BIA electrical model is necessary for the basic knowledge of electrical theory. Each cell and tissue are expressed as a simplified model and explained using the equivalent electrical circuit. In the cell, resistance and capacitance elements are connected either in parallel or in series (Fig. 2).

The muscle tissue can be regarded electrically as an equivalent consisting of extracellular resistance (R_e) and intracellular resistance (R_i). The capacitive effect of the cell membrane is indicated by capacitance C_m , and the intracellular fluid, a liquid electrolyte, is represented by capacitance C_i . Next, the electrical equivalent circuit of the tissue becomes slightly more complex. Although the cells which constitute the tissue are homogeneous, electrical properties are not necessarily constant, and cell sizes differ. Cell membrane resistance (R_m), C_m , extra-intracellular capacitances (C_i and C_e), R_i , and R_e are greatly affected by the shape and size of the cells. Therefore, when energizing the current of two or more frequencies, resistance and reactance are distributed in a semicircle around a certain value. This electrical distribution is called the Cole-Cole distribution²²⁾. Using the Cole-Cole distribution model, R_i and R_e can be derived. Although

resistance differs substantially by tissue, intracellular resistance is high and extracellular resistance, i.e., electrolytic solution, is very low. The plasma membrane is an insulator and has both a high resistance and a large C_m . Therefore, the electrical equivalent circuit, of the cells that form the tissue, is simplified. The electrical current does not penetrate the cell membrane at the low-frequency domain, which acts as an insulator; and, therefore, the current passes through the extracellular fluid.

Fig. 2 Equivalent electrical circuit of a cell. In the cell, the equivalent electrical circuit is represented by the series-parallel circuit of resistance and capacitance. R_i , intracellular resistance; R_e , extracellular resistance; C_m , membrane capacitance; C_i , intracellular capacitance.

If tissue impedance is measured using a low-frequency current, the cell is regarded as an insulator, and only extracellular resistance is measured (Fig. 3-A). Information from R_i , R_e and C_m is obtained in the middle frequency domain; and this phase is called the β dispersion²³ (Fig. 3-B). It is appropriate for blood or extracellular fluid to be measured at frequencies lower than the β dispersion. On the other hand, it is appropriate for muscle to be measured at frequencies higher than the β dispersion. In the high-frequency domain, the impedance of the cell membrane decreases substantially, and the electrical current flows into the cell. For this reason, the intra- and extracellular resistance is measured in parallel when using high-frequency current (Fig. 3-C).

In addition, the β dispersion and the impedance of tissues have frequency properties particular to the tissue - the β dispersion of muscle is tens of kHz, and that of blood is 2 MHz. When tissue impedance is measured, in consideration of the frequency characteristics or β dispersion, the measurer should select the frequency according to the tissue type. Frequency properties of BIA are closely related to intra- and extracellular fluid volume. Accordingly, it is possible to clarify the status of edema of the body or local muscle groups by considering the frequency properties. Based on these electrical theories, measurement of the total body water (TBW) and amount of body fat is explained. TBW can be measured electrically because the electrolytes, in the water of the human body are good conductors of electrical current. If the volume of TBW is large, since resistance is small, the electrical current flows more easily into the body. Because adipose tissue contains little water, the resistance to electrical current is greater in obese individuals with large amounts of body fat. Measurements of BIA are a significant predictor of

Fig. 3 Equivalent electrical circuit of the tissue in the case of using low frequency, middle frequency and high frequency currents. R_i , intracellular resistance; R_e , extracellular resistance; C_m , membrane capacitance. A: low frequency, B: middle frequency, C: high frequency.

the variables of FFM; and the volume of the body's FFM or TBW is indirectly estimated from measures of BI. Therefore, certain basic assumptions about the geometric shape of the body and the relationship of impedance to the length and volume of the conductor are made.

Individuals with a small FFM and TBW have high resistance to current flowing through the body, compared to a person who has a large FFM. There is a strong relationship between whole-body impedance and TBW; thus, the BIA method may be an accurate measuring device for analyzing body composition and assessing TBW in the sports and clinical fields. This method was used by Lukaski et al.²⁴⁾ and Baumgartner et al.²⁵⁾ to estimate FFM and %FAT. Several studies revealed that FFM or %FAT could also be accurately predicted in various people using the BIA methods²⁶⁾. Additionally, with multi-frequency BIA, it is possible to estimate extracellular water and intracellular water compartments, along with TBW. BIA measurement, which has been used to estimate body composition, is possible due to the conductivity of various tissues. Conductivity and resistance of the tissue are closely related to intracellular and extracellular fluid volume, and tissues that contain an abundance of water, such as muscle, are highly conductive, whereas fat, bone and tendon are highly resistive tissues. Applied electrical current always passes through the passage of least resistance between cells in tissues. This low-resistance passage will include mainly extracellular fluid of muscle and blood that configure most of the FFM. Based on electrical theory, impedance (Z) is composed of two components, resistance (R) and reactance (X_c). R has the role of actual opposition to the flow of the current through the cylindrical conductor, and the role of X_c is imaginary opposition. Measurement of Z is composed of the sum of two factors, R and X_c , and is described mathematically by the equation $Z^2 = R^2 + X_c^2$. The resistance between two arbitrary points in the human body as a cylindrical conductor is represented using Ohm's Law:

$$R = E/I,$$

where R is resistance in ohms, E is the voltage, and I is the current in amperes.

The curves of resistance and reactance versus frequency are quite different. The Cole-Cole²²⁾ impedance model is used to calculate the intracellular and extracellular resistance by multi-frequency impedance (Fig. 4). In this Cole-Cole model, R is represented on the abscissa and X_c on the ordinate. Here, R_0 theoretically representing the R of the extracellular fluid and R_∞ representing the R of intracellular and extracellular fluid are predicted using the Cole-Cole model. Total body water and extracellular fluid were derived using the resistance and reactance components of impedance²⁷⁾. At low-frequency currents, the electrical current cannot pass through the cell membranes. With an increase in frequency, the electrical current passes through the cell membrane, and penetrates

the cell. At the same time, while it is possible to tell the intra- and extracellular resistance with multi-frequency BIA, specialist knowledge is needed for measurement and interpretation of the results. For these reasons, a single-frequency impedance device can be used. Many of the single-frequency BIA analyzers use 50 kHz primarily for safety reasons.

When a frequency of 50 kHz is used, whether or not electrical current passes completely through the inside of a cell remains problematic. Although some electrical problems persist, the use of BIA has spread rapidly in various fields. The BIA method is widely used in population studies as well as basic exercise research²⁸⁾. The use of BIA in recent obesity studies has also been very effective. The specific resistivity of the trunk is significantly greater in obese than normal-weight subjects. BIA measurements tend to reduce the FFM prediction of extreme obesity²⁹⁾.

On the other hand, it is well known that L^2/Z correlates highly with FFM²⁵⁾. After reports on L^2/Z were made known, FFM research developed dramatically using the so-called impedance index (IPI). The IPI method for the estimation of body composition has been applied to sports medicine successfully. IPI can evaluate FFM accurately before and after exercise. Unfortunately, the current BIA equipment does not have the capability of detecting a small change in body composition. Nevertheless, the BIA method has merits as a measurement method. For instance, the BIA method can be applied to any subject regardless of age, sex, and race. BIA has been used frequently in the management of athlete FFM and weight control during exercise therapy for mildly obese subjects. However, accurate impedance measurements for extreme obesity may be difficult. Extreme obesity does not apply to the model equation obtained from samples of the general population. Single- and multi-frequency BIA have been used as an electrophysiological means for assessing the abnormal fluid distribution associated with exercise-induced dehydration and leg edema³⁰⁾. This could enhance the clinical application of BIA to assess changes and

Fig. 4 Impedance plot curve of resistance and reactance with frequency. Resistances extrapolated at zero (R_0) and infinite (R_∞) frequency.

shifts between the intracellular water and extracellular water compartments associated with sports-related edema. On the other hand, single-frequency BIA is a powerful assessment tool for body composition in field studies. Further research results are expected in the near future.

Measurement of muscle mass

Skeletal muscle in the human body represents approximately 30 to 40% of the body weight of a healthy person, and is primarily concentrated in the legs^{31,32}. Skeletal muscles located in the lower legs play an important role in physical activities such as standing, jumping, walking and running in sports and daily life. Recently, many researchers have become interested in the effect of exercise on increases in muscle mass. Sports doctors and trainers need to estimate muscle mass in order to evaluate its effect on the prognosis of patients undergoing treatment. The reliability of the BIA method for evaluating the muscles of the limbs is still under investigation.

When measuring muscles using BIA, it is necessary to know the characteristic electro-physiological properties of muscle tissue. The spectra of muscle multi-frequency impedance values plotted against frequency for each individual follow a similar set of curves, as demonstrated in Fig. 5. Muscle resistance varies with frequency, i.e., it is high at low frequencies and low at high frequencies. Therefore, it is necessary to use an optimal frequency and electrode arrangement when measuring muscles. Normally, the human body is expressed as five cylinders, which consist of the arms, legs and trunk, instead of one cylinder; and these cylinders are connected in series³³. The trunk and extremities can be represented as cylinders of uniform length and cross-sectional area. Therefore, the

muscle volume of each part is calculated as a cylinder, respectively. In practice, it is easier to measure height than the conductive length, which is usually from the wrist to the ankle. Because the body segments are not uniform in length or cross-sectional area, resistance to the flow of current through these body segments will differ. Based on electrical theory, the impedance (Z) to current flow through a cylindrical conductor is related to the length (L) of the conductor, and inversely related to its cross-sectional area (A). The equation of the impedance (Z) is as follows:

$$Z = \rho L/A,$$

where ρ (ohms-cm) is the specific resistivity of the tissues and is assumed to be constant. Consequently, whole-body or segmental muscle mass may be determined by using Z obtained from BIA measurement in the formula $V = \rho L^2/Z$.

Usually, whole-body impedance is measured in terms of body height (L) as an index of the length of the conductor. In fact, the impedance is measured between the wrist and ankle. For measurement of whole-body impedance, body height (L) is used as an indicator of the length of the conductor. Therefore, FFM of the body is directly proportional to the square of the height, or the square of the length of the conductor, and indirectly related to the impedance. Thus, the volume of a cylindrical conductor can be calculated from the length and impedance of the conductor. Many reports to determine muscle volume of the limbs use L^2/Z as IPI, and all are now conducted using the tetra-polar electrode method. L^2/Z is also used for whole-body measurement; however, measurement of the trunk is more complex than measurement of the limbs because the trunk contains several organs³⁴.

Alternatively, take into consideration that careful at-

Fig. 5 Resistance and Reactance spectrum curve against frequency in gastrocnemius muscle. A: Resistance; B: Reactance.

tention must be paid to the difference in each part of the body when measuring the limbs and trunk simultaneously. When measuring the whole-body resistance, a conductor with a small cross-sectional area, such as an arm or a leg, can strongly affect the whole-body resistance. A cylindrical conductor with a small cross-sectional area, such as an arm or a leg, will have a higher resistance than a cylindrical conductor that has a large cross-sectional area such as trunk. Comprehensive studies of single- and multi-frequency analyzers to evaluate muscle mass have been examined.

Miyatani et al.³⁵⁾ developed a BIA system that uses an 800-mA alternating current at 50 kHz and measures upper arm and lower leg impedance. Salinari et al.³⁶⁾ proposed a new approach for BIA, based on a mathematical model, that accurately predicts lower limb muscle mass. Stahn et al.³⁷⁾ reported that arm and leg muscle volumes were estimated based on a multi-frequency BIA method and a mathematical model, and compared the technique to conventional segmental BIA. Komiya et al.³⁸⁾ evaluated two multi-frequency methods to measure thigh muscle volume. In his first method, the thigh was divided into three parts, proximal, center, and distal, and the volume of each was totaled. In the second method, the volume of the entire thigh was measured as one cylindrical conductor. Although the bone and muscle composition of the thigh differs by site, the values of the two measurement methods were in agreement, and impedance could still be measured simultaneously without dividing the thigh. The range of frequencies used were from 4 kHz up to 1.02 MHz, and the optimum frequency for the measurement of muscle volume was verified.

Because 50 kHz gave the best performance in the study by Komiya et al.³⁸⁾, it is suggested that muscle mass can be estimated at the conventional single frequency of 50 kHz. In addition, the estimation of whole-body muscle mass was actively carried out by applying the segmental BIA method³⁹⁾. Tanaka et al.⁴⁰⁾ reported that a segmental BIA can predict whole-body skeletal muscle volume more accurately than a whole-body BIA. Oshima et al.⁴¹⁾ attempted to estimate the whole-body skeletal muscle mass by BIA in the standing position. The volume of the skeletal muscle obtained using MRI was made into a reasonable standard, and the measurement which deduces skeletal muscle volume simply was examined by using various kinds of anthropometric variables and impedance values or IPI (L^2/Z) as an independent variable. These results were verified by the Bland and Altman model⁴²⁾, and methodical evaluation was performed⁴³⁻⁴⁵⁾. According to previous reports, results from BIA of the limbs and whole body correlated closely with the muscle volume determined by MRI.

When applying any predictive equation, examining the accuracy of the estimated muscle mass is very important. An estimated equation obtained from multiple regression analysis generally shows relatively good performance.

Even if high consistency is obtained in an independent sample, the accuracy of an equation decreases when it is adapted to other samples, and this discrepancy may be significant. Thus, the factors that influence the reliability of a predictive equation should be explored when adapted to separate samples, and the criteria should be evaluated in terms of maximum accuracy. Verification is then required for the generalized equation obtained. It is necessary to apply a predictive equation to a sample independent of the original data to cross validate the equation. Even if high consistency is observed in independent samples, obtained by multiple regression analysis, the conditions are limited, and reliability is reduced by differences in factors such as race, age, gender, body type and the actual measuring device. It is recognized, however, that, as an alternative to CT or MRI, BIA is useful for estimating the muscle volume noninvasively. In addition, it is desired that BIA will provide new diagnostic information related to muscle, and muscular diseases such as sarcopenia and muscular dystrophy. In the near future, based on these studies, it is hoped that developed predictive equations, that are cross-validated, will be more generally applicable in sports science research. Accordingly, the development of further BIA research is expected.

Future prospects

Extensive research on BIA has been reported in terms of electrical theory, frequency and electrode arrangement. And it has been highly evaluated in estimating regional blood flow, cardiac output, muscle volume, and visceral fat area; currently, it is being applied to the study of sports science. Concerning metabolic syndrome, measurement of visceral fat area^{46,47)}, by the impedance method, has been investigated, and new measuring devices have been developed. The methodology for impedance measurement has largely been established, and possible future studies, applying electrical theory, include the use of impedance to identify areas of damaged muscle or to estimate the temperature inside muscle during icing. The future development of a simple and high-precision measuring method, which can contribute to sports science, is desired.

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