Bioelectrical impedance analysis measurements as part of a national nutrition survey\textsuperscript{1,2}

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ABSTRACT  Since 1960 the National Center for Health Statistics has conducted seven national health examination surveys. All surveys included anthropometry. As the relations between various chronic diseases and body composition have been recognized, there has been considerable interest in assessing body composition in health examinations on the basis of nationally representative probability samples. I focus on considerations that influenced the decision to include bioelectrical impedance analysis (BIA) in a national nutrition survey. Tetrapolar, single-frequency (50 kHz) BIA was included in the third National Health and Nutrition Examination Survey (1988–1994) for persons aged \( \geq 12 \) y, resulting in \( > 17000 \) resistance and reactance measures in non-Hispanic white, non-Hispanic black, and Mexican American subjects. The usefulness of these data in producing national reference distributions for lean body mass and fat mass, however, is currently limited by the uncertain availability of generalizable, valid, reliable, cross-validated prediction equations for various age, sex, and racial-ethnic groups. \textit{Am J Clin Nutr} 1996;64(suppl):453S–8S.

KEY WORDS  Nutrition surveys, body composition, bioelectrical impedance, BIA, anthropometry, skinfold thickness, NHANES, National Health and Nutrition Examination Surveys, prediction equations

INTRODUCTION: SURVEY OVERVIEW

The National Health and Nutrition Examination Survey (NHANES) is only one of the many data collection systems of the National Center for Health Statistics, but is unique in that it collects data on the health and nutritional status of Americans through detailed interviews and direct physical examinations. Operating from mobile examination centers, the NHANES staff travels across the country to reach people selected to participate in the survey. A team of skilled interviewers administers extensive interviews in the household, capturing a wide variety of information, including information on health status and medical care. A team of specially trained health technicians conducts standardized examinations and laboratory tests in the mobile examination centers.

SURVEY CONTENT

Numerous examination tests and procedures in NHANES III were age dependent; these included a physician’s examination, a gallbladder ultrasound for gallstones, spirometry tests for pulmonary function, bone densitometry to examine risk factors for osteoporosis of the hip through use of dual-energy X-ray absorptiometry, an electrocardiogram. X-rays to examine arthritis of the joints, a complete dental exam, allergy tests, fundus photography to detect diabetic retinopathy and macular degeneration, physical function tests for the elderly, and various other procedures that have been described in the NHANES III plan and operation manual (3). For some of these procedures, to examine cause and association, data analysts may find

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it highly desirable to have more detailed body-composition information that goes beyond anthropometric measurements.

Nutritional status

NHANES includes a thorough nutritional status assessment. In addition to collecting comprehensive socioeconomic and demographic information, the NHANES staff administers food-frequency questionnaires and a detailed 24-h recall. Clinical measures focus on selected chronic conditions and not on acute nutrient deficiencies. An extensive list of the biochemical measures included in NHANES III can be found in an article by McQuillan et al (4). In all the national health examination surveys, various anthropometric measurements were included for several reasons (5). In the 1960s, some body measures were included from the standpoint of a human engineering interest. Beginning with NHANES I, however, when major nutritional-assessment components were added, more attention was focused on anthropometric measures as indicators of nutritional status and predictors of chronic disease and health outcomes.

Anthropometry

When NHANES III was being planned in the mid 1980s, decisions had to be made regarding which anthropometric measures as indicators of body composition would be included. The desire was, of course, to use procedures considered to be state-of-the-art at the time the survey was being planned for all examination components, but also to project to the future to when the survey would come out of the field (in 1994) and when the data would realistically be available for public use (around 1995 or 1996). Other factors that influenced the decision to include a measure were the time required for completion of the measurement procedure, respondent burden, practical utility, and public health importance (6).

It was certain that measures such as height and weight would be included because body mass index has widespread utility in epidemiologic analyses and continues to be useful for tracking trends in the prevalence of overweight (7–9). It was thought highly desirable to be able to obtain estimates of fat mass (FM) and lean body mass (LBM) for use in analyses of other health status indicators and outcomes measured in the survey. In the mid 1980s, increasing numbers of reports were appearing in the literature on so-called "higher technology" methods for assessing body composition (10). Infrared interactance was intriguing but did not seem to be well developed or sufficiently tested (11). Total-body electrical conductivity exceeded the size limitations of the mobile examination centers and was costly (12). Ultrasound appeared to be a promising approach for estimating subcutaneous fat, perhaps somewhat more accurately than with skinfold calipers, but time constraints alone ruled out that procedure (13). Remaining among the potential higher technology procedures not restricted to the laboratory was bioelectrical impedance analysis (BIA).

There were a few other options for assessing body fat, one of which was the use of skinfold calipers. Measurements at four skinfold sites (triceps, subscapula, suprailium, and midthigh) were ultimately included, partly for some limited potential of estimating total body fat but more to provide current national reference estimates for skinfold thicknesses and additional data points for monitoring population trends. The limitations of using skinfold thicknesses were recognized.

Because skinfold-thickness measurements have been relied on for many years for the estimation of body fatness, it is worthwhile to briefly review some of their well-known limitations to emphasize the desire to seize on an attractive and alternative method such as BIA. In the environment of a complex national survey, the technical limitations of obtaining reliable skinfold values either within or between observers are magnified as subcutaneous fat amounts and the number of observers increases. This is true regardless of efforts to standardize training, as indicated by reliability analyses (14). Tissue compression is problematic, especially with increasing amounts of subcutaneous fat (15). This has been observed in both the young and the elderly (16, 17). Skinfold thicknesses do not directly measure total body fat, but rely instead on regression equations to predict total body fat. The numerous prediction equations available for skinfold thicknesses tend not to be generalizable to groups with characteristics that do not closely match those of the group in which the equations were derived (18). This limitation is related in part to distribution of body fat. There are age, sex, and racial-ethnic differences in the distribution of body fat (19) and skinfold sites that work well for one group may not perform as well for another group. There are also technician differences across labs both in the skinfold assessment procedures and in criterion procedures such as densitometry (20). In addition, skinfold thicknesses measure subcutaneous adipose tissue and do not directly measure or even necessarily have a constant relation with internal body fat. Especially in the regions where there is a greater tendency to accumulate internal fat, notably on the lower trunk in the abdominal, buttocks, and thigh areas, circumference measurements may yield a better relative estimate of adipose tissue accumulation. In NHANES III, abdominal and buttocks circumferences were measured on examined persons aged ≥ 2 y.

INCLUSION OF BIOELECTRICAL IMPEDANCE ANALYSIS

The decision to incorporate tetrapolar BIA in NHANES III was made, as already indicated, in part because of a general dissatisfaction with the reliability of skinfold thicknesses, especially in subjects with increasing amounts of subcutaneous fat, and the inability to otherwise obtain estimates of FM and LBM. Although the terms lean body mass and fat-free mass are often used interchangeably, the term lean body mass is preferentially used in this article recognizing the observation by Malina (21) that “LBM is an in vivo concept based on water, organic matter and mineral components, while FFM [fat-free mass] is an in vitro concept appropriate for carcass analysis.
The two differ in the amount of essential lipids, which is variously estimated from 2% to 10% of the fat free weight.

For anthropometric measures to predict total body composition, the “correct” combination of measurements and body sites must be selected. In a national population survey in which these indexes may vary for age, sex, and racial-ethnic groups, in which time constraints for measurement procedures are imposed to control respondent burden, and in which anthropometry must be balanced with other competing needs of the survey, it is not feasible to include extensive batteries of group-specific anthropometric measurements. BIA offered an enticing possibility to measure body water and subsequently estimate whole-body composition with the simple “flip of a switch.”

In 1986 there was evidence that the impedance method may provide meaningful estimates of body composition in surveys of healthy populations (22). However, the decision to include BIA in NHANES III was a difficult one. A consultant from outside the National Center for Health Statistics initially made a recommendation against the inclusion of BIA in NHANES III, primarily because at the time, appropriate valid, age-, ethnicity-, and sex-specific prediction equations were not available. Furthermore, in 1986 it was believed that BIA had not been sufficiently validated or thoroughly tested, and it was difficult to know which manufacturer’s instrument to use. On the other hand, impedance was determined to be safe, it required minimal respondent burden (which was a major consideration in the 3.5-h examinations), it was noninvasive and had no associated discomfort, it required only a few minutes to connect the electrodes and run the test, and the procedure was highly reliable, relatively inexpensive, and could potentially give valid predictions of major body compartments, specifically, body water, LBM, and FM. Given these characteristics, it became difficult not to recommend the use of BIA in NHANES III.

The position of the National Center for Health Statistics on the use of BIA in NHANES III established and maintained that resistance and reactance should be collected, along with the other pertinent variables necessary for analysis, and that the data should be archived until valid, cross-validated prediction equations, derived through empirical research and recommended and endorsed by the scientific community, became available. There was optimism that such equations would become available, and it appeared to be worth the effort of including the procedure in a national survey. At the very least there would be national reference distributions for resistance and reactance, measured at a fixed frequency of 50 kHz. In addition, for purposes of monitoring nutritional status, we did not want to miss an opportunity to obtain what could prove to be important baseline data. Overweight and body fatness are issues of public health importance; the BIA data had scientific merit and the procedure was feasible and therefore met basic criteria for inclusion in the national survey (23).

SUBJECTS, EQUIPMENT, AND METHODS

Hydrostatic weighing was still the so-called gold standard for body composition in the mid 1980s. The paucity of studies in which this procedure was used in young children, however, led to the decision that impedance not be measured in children < 12 y of age because it was thought to be unlikely that future prediction equations based on the criterion procedure of hydrodensitometry would be available for this age group. In NHANES III the BIA procedure was not administered to persons < 12 y of age, pregnant women, or persons with cardiac pacemakers.

To minimize measurement errors, the NHANES data collection process used well-defined protocols, trained observers, and calibrated equipment for BIA and all other health examination procedures that were administered in the standardized environment of the mobile examination center. With regard to the choice of machinery, all models of BIA analyzers available in the mid-1980s were regarded as being essentially biological ohmmeters, so the major decision was to select a reputable company known for quality instrument construction. It was desirable to use a machine that would give both resistance and reactance values. Although reactance accounts for only a small part (< 3%) of bioelectrical impedance (24), it was measured and entered into the database to enhance predicted estimates of total body water (TBW), LBM, and FM. In addition to the standardized training, equipment, and environment, two calibration procedures were used. The first was an internal calibration built into the BIA machine by the manufacturer. The second was an external calibration of the machine, using a standard resistor and capacitor. The two calibration procedures were done once each day at the beginning or the end of an examination session. Daily logs were kept for both calibrations.

Because the decision to use BIA was based on knowledge that appropriate valid, age-, ethnicity-, and sex-specific prediction equations were not available at the time, choosing a BIA machine on the basis of the equations programmed into its software was irrelevant. Manufacturer-supplied equations built into the machines were reported to systematically overpredict TBW (25). A body-composition analyzer manufactured by Valhalla Scientific (model 1990B; San Diego) was the instrument used for the measurement of whole-body electrical resistance and was connected to a grounded alternating current power outlet.

During the BIA procedure, subjects lay in a supine position on a nonconductive exam table without a pillow under their head. Because BIA has to be performed with the subject in a recumbent position, a decision was made to have the procedure done by the physician in the physician’s examination component of the mobile examination center, where an examination table was available. By choosing and training physicians to administer the BIA procedure, the number of observers was minimized over the course of the 6-y survey. The physicians received standardized training to minimize potential errors associated with improperly placed electrodes. A review of the literature indicated that one source electrode displaced by only 1 cm can result in an underestimate of resistance by 2.1%; two displaced electrodes can reduce measured resistance by 4.1% (24). Attempts were made to minimize this potential error through training, periodic retraining, and field observations, and by limiting the number of technicians.

The contact area on the body for electrode attachment was cleaned vigorously with alcohol and gauze to clear it of excess body oils and dirt. Disposable foil-gum type electrodes were attached to the right wrist, hand, ankle, and foot. On the wrist, the center of the electrode was placed in the middle of an
imaginary line on the dorsal surface, bisecting the styloid processes of the ulna and radius. On the hand, the electrode was placed on the knuckle of the middle finger. On the ankle, the center of the electrode was placed in the middle of an imaginary line on the dorsal surface of the foot bisecting the medial and lateral malleoli of the ankle. On the right foot, the electrode was placed $\geq 4-5$ cm away from the electrode on the ankle at the knuckle of the middle toe.

The lead wires from the unit were attached to the electrode with the sense or detection leads attached to the wrist and ankle and the current or source leads to the hand and foot. The subject was instructed to remain motionless and relaxed, with arms and legs slightly apart and not touching any other part of the body. If the examinee’s arms and legs could not be spread properly, the procedure was still completed and a note made in the exam comments. The paper gown and pants separated the arms from the trunk or the legs from each other. As long as there was no skin contact there should have been no interference with the proper flow of current. Resistance and reactance values ($\Omega$) were recorded from the BIA unit.

Because BIA measures body water, some equipment manufacturers now recommend that subjects fast overnight and abstain from alcohol or exercise for 24 h before being tested (25). In NHANES III, persons 12 y and older were requested to report to the mobile examination center in a fasting state, although the fasting rules varied on the basis of which of the three daily exam sessions the subject was scheduled for. For the morning session, persons aged 12-19 y were asked to fast for $\geq 8.5$ h and adults aged $\geq 20$ y for $\geq 12$ h. For the afternoon and evening sessions, persons aged $\geq 12$ y were asked to fast for 6 h. All fasting subjects were requested not to eat or drink anything except water during the fasting period. There were no restrictions on physical activity or alcohol consumption before the fasting period (3).

Because the sequencing of examination components through the mobile examination center was random, some people had the BIA procedure done before their blood was drawn, whereas others had the BIA procedure done afterward. Blood samples ranged from 70 to 150 mL for persons aged $\geq 12$ y. In addition, each subject was requested to contribute a urine sample at the beginning of the examination session. All the above may have an effect on body fluid levels, but such effects would probably be negligible. Other investigators found that time of day, interval since subjects had anything to eat or drink, oral contraceptive use, or timing within the menstrual cycle did not have a significant effect on results of the BIA procedure (26).

Nevertheless, in the NHANES III database, information can be recovered on the time of day each examination component was performed on the subjects, whether or not the subjects were fasting at the time of the BIA procedure, and even everything they had to eat and drink in the 24 h before midnight before the day of their exam. Data can also be recovered on persons who received the 75-g oral glucose solution for the oral-glucose-tolerance test before the BIA procedure and on the use of vitamin and mineral supplements and medications such as diuretics in the 30 d before the home interview was administered.

**RESULTS**

NHANES III has shown that it is possible to collect total body resistance and reactance measurements by using a single-frequency BIA device in a nationally representative sample of the US population aged $\geq 12$ y. The approximate number of people, by sex and race or ethnicity, for whom both resistance and reactance values were recorded in NHANES III is shown in Table 2. Not only does NHANES III include measures for males and females in a wide age spectrum, it also includes large samples that vary by race or ethnicity. These subjects are not from a homogeneous sample as one might recruit or expect in a more restricted laboratory setting. They are representative of the entire US, civilian, noninstitutionalized population. Accordingly, their body compositions, at least as indicated by body mass indexes and skinfold thicknesses and circumference measurements, range from very low to very high values.

**DISCUSSION**

For researchers more familiar with traditional anthropometry and hydrodensitometry, BIA is truly remarkable. A method that can free investigators from the frustrations of taking skinfold caliper measures, maintaining underwater weighing tanks, coaching people to exhale, and measuring residual lung volumes is indeed exciting. With BIA, subjects do nothing more than lie on a table for 3 min and relax. The technician taking the measurements simply needs to place the electrodes correctly and press a few buttons.

BIA appears to fulfill the long-awaited desire for a simple, inexpensive, quick, reliable instrument that can be used in population surveys to assess body composition. However, challenges remain. The limitations of BIA lie in the uncertainties associated with currently available prediction equations. In fact, the initial hesitation in using the BIA procedure in NHANES III focused on the uncertainties associated with the availability and choice of valid equations to predict LBM and to calculate FM. In 1985 the literature indicated that in obese subjects, BIA systematically overestimated LBM with increasing obesity (27). Since then, there has been a move toward investigating the use of multifrequency machines (28, 29). Others have investigated the potential of simply adding height squared divided by resistance (Ht$^2$/R) in regression analyses, together with selected anthropometric variables, to explore whether the prediction of percentage body fat is improved significantly (30). There is considerable merit to that research, but the attractiveness of BIA lies in its potential as a standalone procedure to free us from anthropometry. The use of BIA, however, requires reliable, valid prediction equations to

**TABLE 2**

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
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<tbody>
<tr>
<td>Non-Hispanic white</td>
<td>3289</td>
<td>3714</td>
</tr>
<tr>
<td>Non-Hispanic black</td>
<td>2406</td>
<td>2686</td>
</tr>
<tr>
<td>Mexican American</td>
<td>2553</td>
<td>2374</td>
</tr>
<tr>
<td>Other</td>
<td>338</td>
<td>435</td>
</tr>
<tr>
<td>Total</td>
<td>8586</td>
<td>9209</td>
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at least estimate LBM from the resistance and reactance data so that FM can be calculated.

Valid equations that can be applied with confidence to the various age, sex, and racial-ethnic groups for which there are national data have not been identified, although the proliferation of equations continues and does include data for minority groups (31). A search of an electronic literature retrieval database, such as MEDLINE (National Library of Medicine, Bethesda, MD), would reveal additional equations for different ethnic groups and more recent articles on BIA and ethnicity, but there is still lack of agreement on which equations are most valid for the population groups to which they are applied. Several outstanding questions remain:

1) Do appropriate equations exist for any or all of the age-race-sex groups in NHANES III for calculating national, statistically weighted estimates of the major body compartments of interest in epidemiologic research (LBM and FM)? Any existing equations that might potentially be recommended should have been tested and validated in laboratory settings for their applicability to white, black, and Mexican-American groups; to males and females; to various age groups; and perhaps to various body mass index or fat distribution ranges.

2) Ideally, new research would meet some minimal criteria for developing prediction equations. What should these criteria be for the criterion measure or dependent variable in the equation (eg, hydrodensitometry or dual-energy X-ray absorptiometry), for the minimum cross-validation specifications, for the choice of BIA analyzer, and for the minimum sample population size and characteristics?

3) At this time, should others continue to be cautioned against applying various and perhaps numerous versions of equations to the NHANES III data? The use of various equations may yield various and inaccurate estimates and potentially confusing and spurious results in nationally representative reference distributions as well as in epidemiologic analyses of other risk factors and conditions or diseases.

4) Should journal reviewers follow specific guidelines in recommending articles containing NHANES III data for publication, on the basis of minimal criteria for BIA equations? What recommendations should be followed for these criteria? Up to now, a conservative approach has been taken that dictates waiting to use the NHANES III data to estimate distributions of LBM or FM in the US population until acceptable equations are available.

Statistical measures of central tendency and various percentile distributions for resistance and reactance measured in NHANES III by selected demographic characteristics may be useful to other researchers as reference data for determining where their sample values fall in relation to the national distribution. A similar approach could be taken to produce distributions for other variables, such as $H^2/R$.

It has been known for some time that $H^2/R$ is a significant predictor of TBW. Kushner and Schoeller (32) showed that $H^2/R$ had an $r^2$ of 0.94 in predicting deuterium dilution space ($D_2$)-TBW. Assuming that TBW constitutes 73% of the FFM, it is tempting to simply estimate TBW from $H^2/R$, and subsequently FFM as FM = TBW/0.73. This approach might be compelling if it were supported by empirical evidence from diverse populations. However, as pointed out by Houkooper et al (33) and by Deurenberg (34) in the present proceedings, there are deviations in the assumed hydration constant of FFM that are associated with changes in body composition during growth, aging, and obesity and other disease processes that occur in cross-sectional population surveys. Furthermore, impedance measured at 50 kHz is primarily a measure of extracellular water; in persons with a shift in water distribution, FFM may be under- or overestimated by prediction equations developed in population samples with normal water distribution.

In summary, I have given a brief overview of NHANES III, hinting at its wealth of information. For more complete details on all of the NHANES III variables in which BIA data may have analytic utility, the NHANES III plan and operation manual is a useful reference (3). NHANES III has shown that tetrapolar, whole-body, single-frequency resistance and reactance data can be collected in a nationally representative sample of males and females, aged $\geq 12$ y. Furthermore, contingent on valid prediction equations that are developed under specific conditions and endorsed by the scientific community, national reference distributions for body water, LBM, and FM (ie, percentage fat and total body fat) can be generated. Until such equations are developed and widely recognized, it is recommended that the NHANES III BIA data, if used at all, be used cautiously and conservatively in estimating LBM or FM for the NHANES participants.

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