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Comparison of Dual-Energy X-Ray Absorptiometric and Anthropometric Measures of Adiposity in Relation to Adiposity-Related Biologic Factors

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Dual-energy x-ray absorptiometry (DXA) can provide accurate measurements of body composition. Few studies have compared the relative validity of DXA measures with anthropometric measures such as body mass index (BMI) and waist circumference (WC). The authors compared correlations of DXA measurements of total fat mass and fat mass percent in the whole body and trunk, BMI, and WC with obesity-related biologic factors, including blood pressure and levels of plasma lipids, C-reactive protein, and fasting insulin and glucose, among 8,773 adults in the National Health and Nutrition Examination Survey (1999–2004). Overall, the magnitudes of correlations of BMI and WC with the obesity-related biologic factors were similar to those of fat mass or fat mass percent in the whole body and trunk, respectively. These observations were largely consistent across different age, gender, and ethnic groups. In addition, in both men and women, BMI and WC demonstrated similar abilities to distinguish between participants with and without the metabolic syndrome in comparison with corresponding DXA measurements. These data indicate that the validity of simple anthropometric measures such as BMI and WC is comparable to that of DXA measurements of fat mass and fat mass percent, as evaluated by their associations with obesity-related biomarkers and prevalence of metabolic syndrome.

absorptiometry, photon; adiposity; body mass index; nutrition surveys; waist circumference

Abbreviations: AUC, area under the receiver operating characteristic curve; BIA, bioelectrical impedance analysis; BMI, body mass index; CT, computed tomography; DXA, dual-energy x-ray absorptiometry; MRI, magnetic resonance imaging; NHANES, National Health and Nutrition Examination Survey.

Excess body fat is an established risk factor for numerous chronic diseases and premature death (1–5). Among many methods for adiposity assessment, recently developed imaging methods, such as computed tomography (CT) and magnetic resonance imaging (MRI), can provide the most precise estimate of the location and amount of adipose tissue in various body regions (6). However, the use of these methods in large epidemiologic studies is limited because of high cost, complexity of operation, and lack of portability of equipment. In comparison with these methods, dual-energy x-ray absorptiometry (DXA) provides a more practical approach to directly measuring body fatness (7). Validation studies have demonstrated strong correlations between DXA and CT measures of body fatness (8, 9), indicating that DXA can serve as a reference method for adiposity measurement in epidemiologic studies. While this method has been increasingly used in relatively large surveys such as the National Health and Nutrition Examination Survey (NHANES) (10), anthropometric indices, such as body mass index (BMI) and waist circumference, remain the most commonly used measurements of adiposity in epidemiologic studies because of their simplicity. However, because these indices do not directly measure the amount of adipose tissue and cannot distinguish between fat mass and lean mass, their validity in measuring adiposity has been questioned (11).

Although several studies have consistently documented strong correlations between BMI and DXA measurements of adiposity in various populations (10, 12–14), studies

evaluating whether BMI and DXA measurements correlate similarly with obesity-related biologic factors have been inconsistent (15–24), and fewer investigations have compared waist circumference with corresponding DXA measurements of fat in the trunk and abdomen (15, 16, 22, 25–28). Comparison of previous studies is difficult because study populations have differed in many aspects, such as age, gender, ethnicity, body fatness, sample size, and other characteristics that might explain the inconsistent observations. Thus far, few studies have been conducted to systematically compare BMI and waist circumference with DXA measurements as correlates of a wide spectrum of obesity-related biologic factors in a single population. Therefore, we compared the validity of DXA measurements and anthropometric indices with respect to their correlations with obesity-related biologic factors and the metabolic syndrome using data from the NHANES.

MATERIALS AND METHODS

Study population

During 1999–2004, 3 representative cross-sectional samples of 31,126 US residents were selected through a complex sampling process using the most current census information (10). All participants provided written informed consent, and the study protocol was approved by the institutional review board at the Centers for Disease Control and Prevention (Atlanta, Georgia).

Anthropometric measurements

Body weight, standing height, and waist circumference were measured by trained study technicians following a standard protocol (10). BMI was calculated as weight in kilograms divided by the square of standing height in meters.

DXA measurements

Whole-body DXA scans were conducted by using a Hologic QDR 4500A fan beam x-ray bone densitometer (Hologic, Inc., Bedford, Massachusetts) (29). Original DXA scan results were analyzed using Hologic Discovery software, version 12.1 (Hologic, Inc.). Missing DXA values were imputed via a multiple imputation procedure (10, 30). Percentage of body fat for the whole body and each region was calculated as fat mass divided by total mass times 100.

Assessment of obesity-related factors

For the current analysis, we selected systolic blood pressure, diastolic blood pressure, serum total cholesterol, low density lipoprotein cholesterol, high density lipoprotein cholesterol, triglyceride, fasting blood glucose, fasting serum insulin, and serum C-reactive protein as biologic cardiovascular risk factors related to adiposity (31).

Definition of metabolic syndrome

In the current analysis, we used the modified National Cholesterol Education Program's Adult Treatment Panel III criteria (32) to define the metabolic syndrome. Any participants who met 3 or more of the following criteria were defined as having the metabolic syndrome: elevated waist circumference ($\geq$102 cm for men or $\geq$88 cm for women), elevated triglyceride level ($\geq$150 mg/dL), reduced high density lipoprotein cholesterol level ($<$40 mg/dL for men or $<$50 mg/dL for women), elevated blood pressure (systolic blood pressure $\geq$130 mm Hg or diastolic blood pressure $\geq$85 mm Hg), and elevated fasting blood glucose level ($\geq$100 mg/dL). When we examined the association between waist circumference and metabolic syndrome, we used BMI $\geq$30 to replace the waist circumference criterion.

Analytic sample

In the current study, we restricted our analysis to adult NHANES participants aged $\geq$20 years who were eligible for DXA assessments ($n = 14{,}213$). Of these participants, we excluded any participants with missing anthropometric measurements ($n = 868$) and participants for whom missing DXA values were not imputed (primarily because of pregnancy; $n = 764$). In addition, we excluded participants who reported currently using medications that lower blood pressure, blood lipid levels, or blood glucose levels, as these medications can obscure the correlations of interest ($n = 3{,}808$). After these exclusions, 8,773 (61.7%) participants remained in the analysis (1,574 of these participants had 1 or more missing DXA measurements imputed). Since the amount of missing data varied for blood pressure and other adiposity-related biologic factors, to preserve statistical power as much as possible, we utilized nonmissing data for each of these biologic factors in the current analysis.

Statistical analysis

In the current analysis, we calculated sample-weighted partial Pearson correlation coefficients, adjusted for age (20–39, 40–59, or $\geq$60 years), gender, ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, or other), education (high school or below, any college, and college graduate or above), regular moderate-to-vigorous physical activity (yes, no), smoking status (nonsmoker, past smoker, or current smoker), and alcohol consumption (nondrinker, 1–3 drinks/day, or $\geq$4 drinks/day) when appropriate, to evaluate the strength of correlations. We examined all continuous variables for outliers and log-transformed these variables to improve normality. In the current analysis, we calculated each correlation coefficient 5 times by using the 5 imputation data sets respectively and then used the mean of the 5 estimates as a combined single statistical summary (33). We compared BMI with whole-body fat mass and whole-body fat mass percent as measures of overall adiposity, and we compared waist circumference with trunk fat mass and trunk fat mass percent as measures of central adiposity, respectively. To compare correlation coefficients, we used Wolfe's method for comparing dependent correlation coefficients estimated in the same sample: The hypothesis that correlation between X and Z equals correlation between Y and Z is equivalent to the hypothesis that

correlation between $(X - Y)$ and Z equals zero (34). To minimize the influence of between-person variation of variables on correlation coefficients, the difference between standardized z scores of X and Y was used in estimating the sample-weighted correlation coefficients, which were then transformed by means of Fisher's z transformation (34). The variance for a transformed correlation coefficient is $1/(n - 3)$ (34). We used t tests to examine the significance of these statistics, for which we calculated combined variances by following the method introduced by Rubin and Schenker (33). Briefly, the total variance was calculated as $T = W + (6/5) \times B$. W is the within-imputation variance, which was calculated as the average of individual variance estimates. B is the between-imputation variance, which was calculated as

$$B = \sum_{i=1}^{5} \left(Q_i - \bar{Q}\right)^2 \Big/ 4,$$

where the Q_i's are the individual estimates and $\bar{Q}$ is the mean of the 5 individual estimates. The number of degrees of freedom was determined using the method introduced by Barnard and Rubin (35). We used 47 (the number of primary sampling units minus the number of sampling strata) as the degrees of freedom for complete data (10). In the current analysis, we compared correlations of anthropometric indices and corresponding DXA measurements within strata of age, gender, and ethnicity. To take into account multiple comparisons, we used a Bonferroni-corrected P value less than 0.05 (equivalent to $P < 0.000125$, corresponding to 0.05 divided by 400 comparisons) as the significance level. Following the same analytical approaches, in a secondary analysis we also evaluated the relative validity of bioelectrical impedance analysis (BIA) in comparison with BMI by using DXA indices as the reference measure. In another secondary analysis, we examined the misclassification of adiposity by anthropometric measurements when using whole-body fat mass as the reference measure.

To compare anthropometric measurements with DXA measurements with respect to their capabilities of discriminating between participants with and without the metabolic syndrome, we plotted a receiver operating characteristic curve and calculated a sample-weighted area under the receiver operating characteristic curve (AUC) that incorporated the NHANES sampling design. In these analyses, the metabolic syndrome was treated as a dependent variable, and individual anthropometric indices or DXA measurements, together with the covariates, were entered as independent variables in logistic regression. We followed the aforementioned approach to perform pairwise comparisons of AUCs between models. More specifically, the difference between AUCs was used as the statistic of interest. The variances for these statistics were estimated using a linearization approach (36). In a sensitivity analysis, we excluded the anthropometric measures from the metabolic syndrome diagnosis criteria and repeated the analysis. In these comparisons, we used a Bonferroni-corrected P value less than 0.05 (equivalent to $P < 0.00208$, corresponding to 0.05 divided by 24 comparisons) as the significance level. In a sensitivity analysis, we compared odds ratios for the metabolic syndrome in association with each increment of z scores of anthropometric and DXA measurements.

Data were analyzed with SUDAAN, version 10.0 (Research Triangle Institute, Research Triangle Park, North Carolina); SAS, version 9.2 (SAS Institute, Inc., Cary, North Carolina); and STATA, version 11.0 (Stata Corporation, College Station, Texas).

RESULTS

Table 1 shows the characteristics of the study participants by gender. As expected, women had higher absolute and relative fat mass than men. Men and women also differed with respect to BMI, waist circumference, and most obesity-related biologic factors. Web Table 1 (which is posted on the *Journal*'s Web site (http://aje.oxfordjournals.org/)) shows the prevalence of abnormal values of the biomarkers according to anthropometric measurements in men and women, respectively. In both men and women, higher BMI or waist circumference was correlated with increased prevalence of abnormal values for most of the biomarkers.

Within each subgroup of age, gender, and ethnicity, BMI was more strongly correlated with whole-body fat mass than with whole-body fat mass percent (Table 2). Similarly, waist circumference was more strongly correlated with trunk fat mass than with trunk fat mass percent. In both men and women, the strength of correlation coefficients between anthropometric measurements and fat mass or fat mass percent in the whole body or trunk was attenuated with increasing age. We observed weaker correlations of anthropometric indices with DXA measurements in Hispanic groups than in other ethnic groups. In a secondary analysis, we showed that BMI and waist circumference quintiles agreed more strongly with the quintiles of fat mass than with those of fat mass percent for the whole body and trunk, respectively (Web Tables 2 and 3). More than 97% and 98% of participants could be correctly classified within 1 category of whole-body and trunk fat mass quintiles, respectively, whereas these figures were 89% and 92% for fat mass percent.

Scatterplots illustrating the unadjusted correlations of anthropometric and DXA measurements with the biomarkers are shown in Web Figure 1. Partial Pearson correlation coefficients are shown in Table 3 for men and Table 4 for women, by age group. We made 2 observations that were consistent between men and women. The first observation was that different biologic factors were correlated with measures of adiposity with different strengths. Fasting serum insulin, C-reactive protein, high density lipoprotein cholesterol, and triglyceride levels were most strongly correlated with the adiposity measurements, whereas correlations for other risk factors were relatively weaker. The second observation was that for most biologic factors, correlations with BMI were not significantly different from correlations with whole-body fat mass or whole-body fat mass percent. For a few comparisons, BMI was significantly more strongly correlated with biologic factors than were the DXA measurements. For example, BMI was more strongly correlated with systolic blood pressure than was whole-body fat mass

Table 1. Characteristics of Study Participants, National Health and Nutrition Examination Survey, 1999–2004

Variable[a]	Men (n = 4,521[b])			Women (n = 4,252[b])		
	Mean (SE)	No.	Weighted %	Mean (SE)	No.	Weighted %
Gender			49.9			50.1
Age, years	41.0 (0.3)			42.3 (0.3)		
Body mass index[c]	27.3 (0.1)			27.2 (0.1)		
Waist circumference, cm	97.2 (0.3)			90.3 (0.4)		
Whole-body fat mass, kg	24.0 (0.2)			29.2 (0.3)		
Whole-body fat mass percent	27.1 (0.1)			38.8 (0.2)		
Trunk fat mass, kg	12.2 (0.1)			13.5 (0.2)		
Trunk fat mass percent	27.9 (0.1)			36.7 (0.2)		
Ethnicity						
Non-Hispanic white		2,202	71.2		2,120	71.9
Non-Hispanic black		850	10.0		769	10.3
Mexican-American		1,130	9.3		1,021	7.4
Other Hispanic		132	3.9		126	4.0
Other		207	5.7		216	6.4
Education						
High school or below		2,559	53.7		2,189	42.6
Any college		1,075	28.0		1,237	31.9
College graduate or above		887	25.7		826	25.5
Smoking status						
Never smoker		3,008	66.8		3,177	72.1
Past smoker		783	16.4		530	13.2
Current smoker		730	16.8		545	14.7
Alcohol use, drinks/day						
Nondrinker		2,297	48.9		2,544	55.6
1–3		1,408	33.2		1,471	38.4
4		816	17.9		237	6.0
Moderate-to-vigorous physical activity[d]		1,921	47.2		1,761	47.1
Obesity-related risk factors[e]						
Systolic blood pressure, mm Hg	121.9 (0.4)			117.8 (0.4)		
Diastolic blood pressure, mm Hg	73.6 (0.3)			71.0 (0.3)		
Total cholesterol, mg/dL	202.0 (0.9)			200.0 (0.9)		
Low density lipoprotein cholesterol, mg/dL	125.0 (1.2)			119.0 (1.0)		
High density lipoprotein cholesterol, mg/dL	47.2 (0.3)			57.4 (0.5)		
Triglyceride, mg/dL	156.4 (5.0)			121.0 (3.1)		
C-reactive protein, mg/dL	0.30 (0.01)			0.42 (0.01)		
Fasting blood glucose, mg/dL	98.4 (0.5)			94.4 (0.6)		
Fasting insulin, μU/mL	11.3 (0.3)			10.1 (0.2)		

Abbreviation: SE, standard error.

[a] For continuous variables, values are presented as mean (SE). For categorical variables, numbers and weighted percentages are presented.

[b] Unweighted number of participants.

[c] Weight (kg)/height (m)^2.

[d] Based on nonmissing data only.

[e] n = 8,459 for systolic blood pressure, 8,426 for diastolic blood pressure, 8,322 for total cholesterol and high density lipoprotein cholesterol, 3,811 for low density lipoprotein cholesterol, 4,080 for triglyceride, 4,131 for fasting blood glucose, 4,070 for fasting serum insulin, and 8,369 for C-reactive protein.

Table 2. Partial Pearson Correlations[a] of Anthropometric Measurements With Dual-Energy X-Ray Absorptiometry Indices, by Gender and Age Group and Ethnicity, National Health and Nutrition Examination Survey, 1999–2004[b]

Characteristic and Age Group, years	No. of Participants	Body Mass Index[c]		Waist Circumference, cm	
		Whole-Body FM, kg	Whole-Body FM%	Trunk FM, kg	Trunk FM%
Gender					
Male					
20–39	2,049	0.92	0.79	0.95	0.86
40–59	1,458	0.90	0.75	0.93	0.82
≥60	1,014	0.90	0.74	0.91	0.77
Female					
20–39	1,911	0.95	0.84	0.93	0.83
40–59	1,436	0.94	0.79	0.92	0.80
≥60	905	0.92	0.78	0.88	0.76
Ethnicity					
Non-Hispanic white	4,322	0.92	0.78	0.93	0.83
Non-Hispanic black	1,619	0.92	0.78	0.94	0.84
Hispanic[d]	2,574	0.91	0.74	0.92	0.78
Total	8,773	0.92	0.78	0.93	0.83

Abbreviations: FM, fat mass; FM%, fat mass percent.

[a] Pearson correlation coefficients were adjusted for gender, age (20–39, 40–59, or ≥60 years), ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, or other), education (high school or below, any college, and college graduate or above), regular moderate-to-vigorous physical activity (yes, no), smoking status (nonsmoker, past smoker, or current smoker), and alcohol consumption (nondrinker, 1–3 drinks/day, or ≥4 drinks/day) whenever applicable. For analysis within each age group, results were further adjusted for age (years) as a continuous variable.

[b] All comparisons of the correlation coefficients for body mass index or waist circumference with corresponding dual-energy x-ray absorptiometry measurements were significant at the Bonferroni-adjusted $\alpha = 0.05$ level (equivalent to $P = 0.000125$, corresponding to 0.05 divided by 400 comparisons).

[c] Weight (kg)/height (m)^2.

[d] Includes Mexican Americans and other Hispanic groups.

percent (for both men and women at ages 20–39 years) and more strongly correlated with high density lipoprotein cholesterol than was whole-body fat mass percent (for women of all age groups). In contrast, for women at ages 40–59 years, whole-body fat mass was more strongly correlated with C-reactive protein than was BMI. Similarly, most comparisons between waist circumference and trunk fat mass or trunk fat mass percent were not significant, except for the following: Waist circumference was more strongly correlated with systolic blood pressure for men at ages 20–39 years than was trunk fat mass percent, whereas trunk fat mass or trunk fat mass percent was more strongly correlated with serum total cholesterol (for men at ages 20–39 years and women at ages 40–59 years), low density lipoprotein cholesterol (for men at ages 20–39 years), and C-reactive protein (for women at ages 40–59 years). Nevertheless, for each obesity-related biologic factor, correlation coefficients for anthropometric and DXA measurements were similar in magnitude.

The results for various ethnic groups and the total population are shown in Table 5. More significant comparisons were observed within ethnic groups and the whole population than in age- and gender-specific groups because of increased statistical power, although for most of the biomarkers the differences between correlations of anthropometric indices and DXA measurements were fairly small. Within the whole population, in no instance was a biomarker significantly more strongly associated with whole-body fat mass or fat mass percent than with BMI, but BMI was significantly more strongly associated with 7 of the 9 biomarkers than was one or both of the DXA measurements. When we excluded participants with imputed DXA measurements and repeated the analysis, we observed similar results (data not shown).

In a secondary analysis, we compared BMI against BIA measurements using DXA indices as the reference (Web Table 4). In men and women, for all comparisons BMI was more strongly correlated with DXA indices than were BIA measurements, except for the comparison between BMI and BIA body fat percentage in women aged ≥40 years, which was not significant. In a separate secondary analysis, we further compared BMI with waist circumference in terms of their correlations with the biologic factors. In the overall

Table 3. Partial Pearson Correlations[a] Between Anthropometric and Dual-Energy X-Ray Absorptiometry Measures of Adiposity and Obesity-Related Risk Factors by Age in Men[b], National Health and Nutrition Examination Survey, 1999–2004

Age Group and Adiposity Measure	Obesity-Related Risk Factor								
	SBP, mm Hg	DBP, mm Hg	Total Cholesterol, mg/dL	LDL Cholesterol, mg/dL	HDL Cholesterol, mg/dL	Triglyceride, mg/dL	C-Reactive Protein, mg/dL	Fasting Blood Glucose, mg/dL	Fasting insulin, μU/mL
Ages 20–39 years									
Whole-body FM, kg	0.27	0.16	0.21	0.21	–0.32	0.32	0.40	0.16	0.60
Whole-body FM%	0.21*	0.15	0.25	0.26	–0.28	0.30	0.39	0.15	0.55
BMI[c]	0.30*	0.16	0.19	0.19	–0.32	0.32	0.38	0.15	0.59
Trunk FM, kg	0.28	0.18	0.25*	0.23*	–0.34	0.37	0.40	0.18	0.62
Trunk FM%	0.23*	0.17	0.29*	0.29*	–0.31	0.36	0.39	0.16	0.57
WC, cm	0.29*	0.16	0.19*	0.17*	–0.33	0.34	0.41	0.16	0.61
Ages 40–59 years									
Whole-body FM, kg	0.13	0.16	0.11	0.03	–0.34	0.25	0.40	0.16	0.60
Whole-body FM%	0.12	0.16	0.14	0.05	–0.31	0.22	0.41	0.15	0.55
BMI	0.16	0.15	0.10	0.02	–0.36	0.25	0.38	0.18	0.60
Trunk FM, kg	0.16	0.19	0.13	0.04	–0.38	0.28	0.43	0.18	0.61
Trunk FM%	0.16	0.19	0.17	0.08	–0.35	0.26	0.43	0.17	0.58
WC, cm	0.17	0.17	0.09	0.01	–0.35	0.25	0.42	0.18	0.59
Ages ≥60 years									
Whole-body FM, kg	0.07	0.02	0.05	0.11	–0.24	0.28	0.18	0.21	0.53
Whole-body FM%	0.11	0.01	0.07	0.13	–0.17	0.24	0.22	0.22	0.50
BMI	0.07	0.03	–0.01	0.05	–0.28	0.25	0.15	0.15	0.50
Trunk FM, kg	0.10	0.02	0.07	0.12	–0.27	0.33	0.19	0.22	0.55
Trunk FM%	0.14	0.02	0.11	0.16	–0.22	0.30	0.20	0.20	0.52
WC, cm	0.07	0.03	0.02	0.07	–0.26	0.29	0.20	0.18	0.51

Abbreviations: BMI, body mass index; DBP, diastolic blood pressure; FM, fat mass; FM%, fat mass percent; HDL, high density lipoprotein; LDL, low density lipoprotein; SBP, systolic blood pressure; WC, waist circumference.

* Bonferroni-corrected $P < 0.05$.

[a] All correlating variables were log-transformed. Pearson correlation coefficients were adjusted for age (years), ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, or other), education (high school or below, any college, and college graduate or above), regular moderate-to-vigorous physical activity (yes, no), smoking status (nonsmoker, past smoker, or current smoker), and alcohol consumption (nondrinker, 1–3 drinks/day, or ≥4 drinks/day).

[b] For men aged 20–39 years, $n = 1{,}994$ for SBP, 1,988 for DBP, 1,935 for total cholesterol and HDL cholesterol, 898 for LDL cholesterol, 960 for triglyceride, 966 for fasting blood glucose, 952 for fasting serum insulin, and 1,943 for C-reactive protein; for men aged 40–59 years, $n = 1{,}421$ for SBP, 1,417 for DBP, 1,395 for total cholesterol and HDL cholesterol, 597 for LDL cholesterol, 672 for triglyceride, 678 for fasting blood glucose, 672 for fasting serum insulin, and 1,399 for C-reactive protein; and for men aged 60 years or older, $n = 984$ for SBP, 970 for DBP, 960 for total cholesterol and HDL cholesterol, 465 for LDL cholesterol, 500 for triglyceride, 505 for fasting blood glucose, 499 for fasting serum insulin, and 965 for C-reactive protein.

[c] Weight (kg)/height $(m)^2$.

group, of 9 pairwise comparisons between BMI and waist circumference, 2 were significant and in favor of waist circumference (triglyceride and fasting blood glucose), although the correlations of waist circumference and BMI with these factors were similar in magnitude.

We further compared the ability of anthropometric indices and their corresponding DXA measurements to discriminate metabolic syndrome status. Figure 1 presents the receiver operating characteristic curves corresponding to the overall and central adiposity measurements for each gender. In both men and women, none of the comparisons among AUCs of BMI, whole-body fat mass, and whole-body fat mass percent were significant. With respect to the comparisons among waist circumference, trunk fat mass, and trunk fat mass percent, waist circumference demonstrated AUCs similar to those of trunk fat mass and fat mass percent. In a sensitivity analysis, when we excluded waist circumference and BMI from the metabolic syndrome diagnosis criteria and repeated the analysis, although the AUCs were somewhat weaker, we observed a similar pattern in comparisons (Web Figure 2). In addition, anthropometric and DXA measurements were associated with the metabolic syndrome with similar strength, except that in women the odds ratio for BMI was significantly stronger than that for whole-body fat mass percent (Web Table 5).

Table 4. Partial Pearson Correlations[a] Between Anthropometric and Dual-Energy X-Ray Absorptiometry Measures of Adiposity and Obesity-Related Risk Factors by Age in Women[b], National Health and Nutrition Examination Survey, 1999–2004

Age Group and Adiposity Measure	Obesity-Related Risk Factor								
	SBP, mm Hg	DBP, mm Hg	Total Cholesterol, mg/dL	LDL Cholesterol, mg/dL	HDL Cholesterol, mg/dL	Triglyceride, mg/dL	C-Reactive Protein, mg/dL	Fasting Blood Glucose, mg/dL	Fasting insulin, μU/mL
Ages 20–39 years									
Whole-body FM, kg	0.26	0.14	0.10	0.15	–0.36	0.32	0.52	0.19	0.57
Whole-body FM%	0.20*	0.13	0.14	0.19	–0.31*	0.32	0.51	0.14	0.51
BMI[c]	0.29*	0.13	0.10	0.14	–0.39*	0.33	0.51	0.20	0.58
Trunk FM, kg	0.27	0.15	0.12	0.18	–0.41	0.38	0.52	0.21	0.60
Trunk FM%	0.23	0.14	0.15	0.22	–0.38	0.38	0.51	0.16	0.55
WC, cm	0.25	0.14	0.10	0.14	–0.41	0.36	0.50	0.21	0.59
Ages 40–59 years									
Whole-body FM, kg	0.19	0.14	0.11	0.17	–0.34	0.24	0.54*	0.20	0.53
Whole-body FM%	0.17	0.13	0.17	0.20	–0.27*	0.25	0.52	0.18	0.49
BMI	0.22	0.14	0.10	0.18	–0.37*	0.24	0.51*	0.22	0.55
Trunk FM, kg	0.21	0.15	0.14	0.20	–0.39	0.31	0.56*	0.24	0.55
Trunk FM%	0.20	0.14	0.19*	0.24	–0.34	0.32	0.54	0.22	0.53
WC, cm	0.22	0.15	0.11*	0.18	–0.41	0.30	0.53*	0.26	0.53
Ages ≥60 years									
Whole-body FM, kg	0.02	0.02	0.06	0.10	–0.26	0.11	0.32	0.19	0.48
Whole-body FM%	0.01	–0.02	0.10	0.14	–0.17*	0.06	0.32	0.11	0.43
BMI	0.05	0.05	0.03	0.06	–0.31*	0.12	0.32	0.23	0.51
Trunk FM, kg	0.07	0.04	0.10	0.12	–0.32	0.19	0.34	0.26	0.57
Trunk FM%	0.07	0.01	0.14	0.17	–0.27	0.17	0.34	0.19	0.53
WC, cm	0.11	0.09	0.06	0.06	–0.33	0.20	0.32	0.33	0.53

Abbreviations: BMI, body mass index; DBP, diastolic blood pressure; FM, fat mass; FM%, fat mass percent; HDL, high density lipoprotein; LDL, low density lipoprotein; SBP, systolic blood pressure; WC, waist circumference.

* Bonferroni-corrected $P < 0.05$.

[a] All correlating variables were log-transformed. Pearson correlation coefficients were adjusted for age (years), ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, or other), education (high school or below, any college, and college graduate or above), regular moderate-to-vigorous physical activity (yes, no), smoking status (nonsmoker, past smoker, or current smoker), and alcohol consumption (nondrinker, 1–3 drinks/day, or ≥4 drinks/day).

[b] For women aged 20–39 years, $n = 1{,}816$ for SBP, 1,814 for DBP, 1,810 for total cholesterol and HDL cholesterol, 789 for LDL cholesterol, 842 for triglyceride, 851 for fasting blood glucose, 841 for fasting serum insulin, and 1,819 for C-reactive protein; for women aged 40–59 years, $n = 1{,}378$ for SBP, 1,376 for DBP, 1,362 for total cholesterol and HDL cholesterol, 643 for LDL cholesterol, 670 for triglyceride, 683 for fasting blood glucose, 671 for fasting serum insulin, and 1,374 for C-reactive protein; and for women aged 60 years or older, $n = 866$ for SBP, 861 for DBP, 860 for total cholesterol and HDL cholesterol, 419 for LDL cholesterol, 436 for triglyceride, 448 for fasting blood glucose, 435 for fasting serum insulin, and 869 for C-reactive protein.

[c] Weight (kg)/height $(m)^2$.

DISCUSSION

In this large, representative US population, BMI and waist circumference were more strongly correlated with total fat mass than with percentage of fat mass in the whole body and trunk, respectively. When we used adiposity-related biologic factors as objective references to evaluate the relative validity of BMI or waist circumference in comparison with DXA indices as measures of adiposity, these anthropometric indices were correlated similarly with the biologic markers compared with DXA measurements. Moreover, BMI and waist circumference discriminated between participants with and without the metabolic syndrome equally well in comparison with DXA measurements of fat mass in the whole body and trunk, respectively. These relations were largely consistent across different age, gender, and ethnic groups.

Our results are consistent with the previous observation by Spiegelman et al. (37) that BMI was more strongly correlated with fat mass than with fat mass percent as measured by densitometry in adults. Similarly, studies conducted in children and adolescents also demonstrated that although BMI was highly correlated with both fat mass and fat mass percent as measured by DXA, a stronger correlation with fat mass was observed (19, 23). In addition, our observations were also consistent with previous studies that used other reference methods to estimate fat mass and fat mass percent

Table 5. Partial Pearson Correlations[a] Between Anthropometric and Dual-Energy X-Ray Absorptiometry Measures of Adiposity and Obesity-Related Risk Factors by Ethnicity[b], National Health and Nutrition Examination Survey, 1999–2004

Ethnicity and Adiposity Measure	Obesity-Related Risk Factor								
	SBP, mm Hg	DBP, mm Hg	Total Cholesterol, mg/dL	LDL Cholesterol, mg/dL	HDL Cholesterol, mg/dL	Triglyceride, mg/dL	C-Reactive Protein, mg/dL	Fasting Blood Glucose, mg/dL	Fasting insulin, μU/mL
Non-Hispanic white									
Whole-body FM, kg	0.17*	0.15	0.17	0.18	–0.33*	0.31	0.43	0.19	0.59
Whole-body FM%	0.15*	0.14	0.21	0.21	–0.28*	0.29*	0.42*	0.18*	0.54*
BMI[c]	0.21*	0.14	0.15	0.17	–0.35*	0.30*	0.42*	0.20*	0.58*
Trunk FM, kg	0.20	0.17	0.20*	0.22*	–0.36	0.36*	0.45*	0.22	0.61*
Trunk FM%	0.18	0.16	0.24*	0.26*	–0.33*	0.36	0.44	0.20	0.57
WC, cm	0.21	0.15	0.16*	0.17*	–0.37*	0.33*	0.44*	0.22	0.59*
Non-Hispanic black									
Whole-body FM, kg	0.15*	0.08	0.17	0.21	–0.30	0.27	0.49	0.19	0.54
Whole-body FM%	0.12*	0.07	0.21	0.24	–0.26*	0.25	0.46*	0.19	0.49*
BMI	0.18*	0.08	0.14	0.16	–0.30*	0.26	0.48*	0.18	0.52*
Trunk FM, kg	0.17	0.10	0.19	0.21	–0.32	0.32	0.49	0.23	0.56
Trunk FM%	0.14*	0.10	0.23	0.25	–0.29*	0.30	0.48*	0.22	0.52*
WC, cm	0.17*	0.10	0.15	0.16	–0.33*	0.32	0.49*	0.22	0.54*
Hispanic[d]									
Whole-body FM, kg	0.16*	0.21	0.10	0.13	–0.33	0.25	0.47	0.12	0.49
Whole-body FM%	0.13*	0.19*	0.15	0.16	–0.27*	0.21*	0.44*	0.08*	0.43*
BMI	0.20*	0.21*	0.09	0.12	–0.34*	0.24*	0.46*	0.15*	0.48*
Trunk FM, kg	0.19	0.24	0.14*	0.16	–0.36	0.31	0.48	0.15	0.51
Trunk FM%	0.16	0.21	0.19*	0.20	–0.32*	0.27	0.44*	0.12	0.46*
WC, cm	0.19	0.22	0.09*	0.11	–0.35*	0.28	0.46*	0.16	0.49*
All participants									
Whole-body FM, kg	0.17*	0.15	0.15	0.17	–0.33*	0.29	0.45	0.18	0.57
Whole-body FM%	0.15*	0.13*	0.19	0.21	–0.28*	0.27*	0.43*	0.16*	0.52*
BMI	0.20*	0.14*	0.13	0.16	–0.35*	0.28*	0.44*	0.19*	0.56*
Trunk FM, kg	0.19	0.17	0.18*	0.20*	–0.37	0.34*	0.46*	0.21	0.59
Trunk FM%	0.17*	0.16	0.22*	0.24*	–0.33*	0.33	0.44*	0.19*	0.55*
WC, cm	0.20*	0.15	0.14*	0.16*	–0.37*	0.32*	0.45*	0.22*	0.57*

Abbreviations: BMI, body mass index; DBP, diastolic blood pressure; FM, fat mass; FM%, fat mass percent; HDL, high density lipoprotein; LDL, low density lipoprotein; SBP, systolic blood pressure; WC, waist circumference.

* Bonferroni-corrected $P < 0.05$.

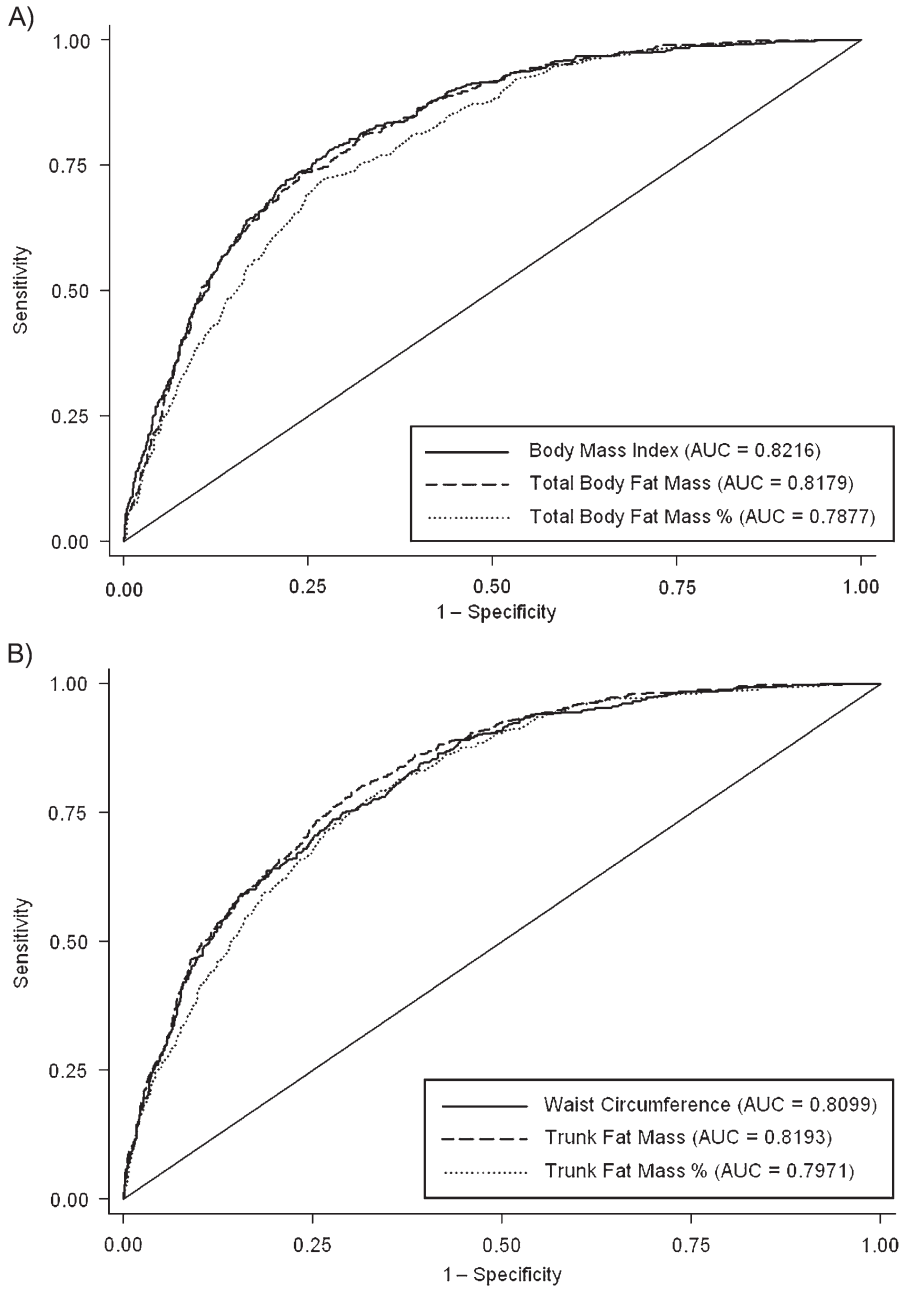
[a] Pearson correlation coefficients were adjusted for age (20–39, 40–59, and ≥60 years), gender (male, female), education (high school or below, any college, and college graduate or above), regular moderate-to-vigorous physical activity (yes, no), smoking status (nonsmoker, past smoker, or current smoker), and alcohol consumption (nondrinker, 1–3 drinks/day, or ≥4 drinks/day). For analysis utilizing all subjects, ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, or other) was further adjusted for.

[b] For non-Hispanic whites, $n = 4,208$ for SBP, 4,188 for DBP, 4,161 for total cholesterol and HDL cholesterol, 1,913 for LDL cholesterol, 2,033 for triglyceride, 2,043 for fasting blood glucose, 2,028 for fasting serum insulin, and 4,178 for C-reactive protein; for non-Hispanic blacks, $n = 1,538$ for SBP, 1,534 for DBP, 1,472 for total cholesterol and HDL cholesterol, 681 for LDL cholesterol, 740 for triglyceride, 759 for fasting blood glucose, 737 for fasting serum insulin, and 1,484 for C-reactive protein; for Hispanic groups, $n = 2,473$ for SBP, 2,464 for DBP, 2,453 for total cholesterol and HDL cholesterol, 1,108 for LDL cholesterol, 1,196 for triglyceride, 1,212 for fasting blood glucose, 1,194 for fasting serum insulin, and 2,468 for C-reactive protein; and for all participants, $n = 8,459$ for SBP, 8,426 for DBP, 8,322 for total cholesterol and HDL cholesterol, 3,811 for LDL cholesterol, 4,080 for triglyceride, 4,143 for fasting blood glucose, 4,070 for fasting serum insulin, and 8,369 for C-reactive protein.

[c] Weight (kg)/height $(m)^2$.

[d] Including both Mexican-American and other Hispanic.

(37–39). Interestingly, we observed that waist circumference was also a better measure of fat mass than of fat mass percent in the trunk. Because DXA cannot distinguish visceral fat from subcutaneous fat, we could not examine whether waist circumference was more strongly correlated with fat in a certain compartment of the trunk in the current analysis. Nonetheless, in studies that used CT or MRI to measure visceral and subcutaneous adipose tissue at



(Figure 1 Continues)

L4–L5 levels, waist circumference was more strongly correlated with total adipose tissue or subcutaneous fat than with visceral fat (40–43). Meanwhile, Kamel et al. (44) demonstrated that DXA measures of central adiposity were not superior to waist circumference with respect to measuring visceral fat accumulation assessed by MRI in men.

Because measurement error in the biologic factors and adiposity measurements are largely independent, obesity-related biomarkers can serve as objective references in evaluating relative performance of adiposity measurements (45). Our observation that BMI was correlated with obesity-related factors at least as strongly as DXA estimates of fat mass and fat mass percent was consistent with most of the previous studies that employed a similar study design (15–21, 23). Likewise, our observations of the relative validity of waist circumference and trunk fat mass or trunk fat mass percent were also consistent with previous studies (15, 16, 25, 27). Remarkably, in studies that compared BMI or waist circumference with overall or central adiposity assessed through other reference methods, such as CT, MRI, BIA, ultrasonography, or skinfold thickness, in general BMI or waist circumference correlated with obesity-related factors as well as these reference methods (17, 20, 23, 25, 28, 37, 46–55). Our study population consisted of US men and

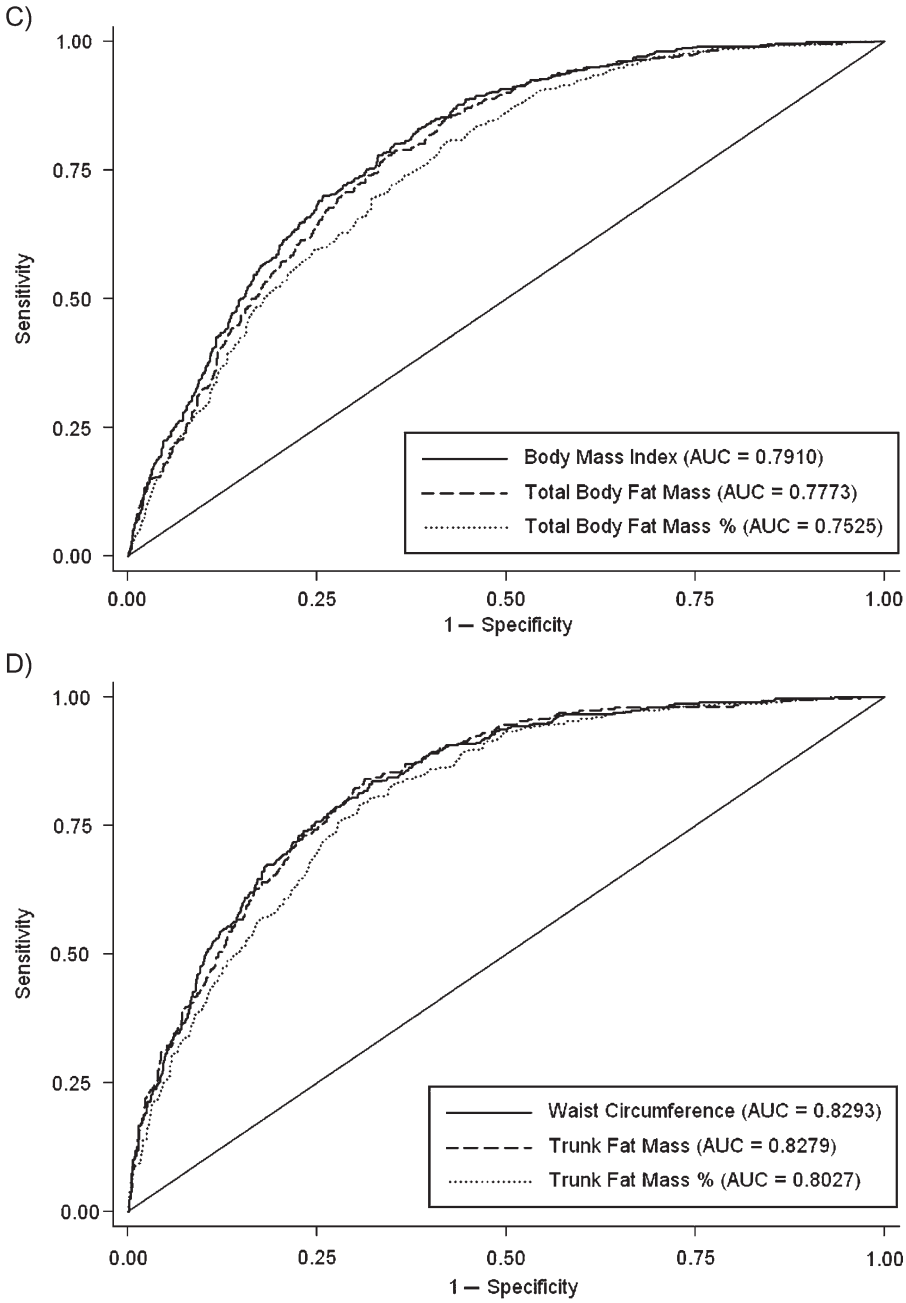


Figure 1. (continued)

Figure 1. Receiver operating characteristic curves for anthropometric measures and dual-energy x-ray absorptiometry measures in predicting the metabolic syndrome in US men and women, National Health and Nutrition Examination Survey, 1999–2004. A) Overall obesity measurements in men; B) central obesity measurements in men; C) overall obesity measurements in women; D) central obesity measurements in women. AUC, area under the receiver operating characteristic curve.

women of various ages and ethnicities, and we obtained similar results in subgroups defined by these characteristics. Previous studies conducted in other populations such as Pima Indian children and adolescents, Caucasian children, and Asians (16, 19, 20, 23) yielded similar results, suggesting that the validity of BMI or waist circumference with respect to correlations with obesity-related biomarkers is similar across different populations.

Each adiposity assessment method has its own strengths and limitations. CT and MRI can provide the most accurate estimates of body composition. They are especially valuable in that abdominal visceral and subcutaneous adipose tissue can be distinguished by means of these methods (31). However, high cost, lack of mobility, long measurement duration, and the need for sophisticated technical staff limit the use of these methods in large epidemiologic studies. In

contrast, DXA, which directly measures body fatness, is less expensive, relatively mobile, time-efficient, and easy to operate and exposes subjects to much lower levels of radiation than CT scans (31). However, this method cannot distinguish among fat in different body compartments. In addition, studies have documented some systematic measurement errors in DXA measurements (56, 57), emphasizing the necessity of calibrating DXA instruments to obtain the most accurate estimates of adiposity for individuals. Of all adiposity assessment methods, BMI and waist circumference are the cheapest, simplest, and most popular indices of body fatness in epidemiologic studies, although these indices have limited ability to distinguishing fat mass from lean mass. Flegal et al. (10) recently reported that anthropometric indices substantially misclassified body fatness at the individual level, by assuming that percent body fat by DXA is the true measure of fatness. However, when these indices were used to rank subjects according to their body fatness, anthropometric measures were highly accurate; more than 90% of NHANES participants could be correctly classified within 1 category defined by DXA fat mass percent (10). We further demonstrated that the degree of misclassification was even smaller when using DXA fat mass as the reference measure. These results indicated that simple anthropometric indices could accurately distinguish relatively lean subjects from those with higher body fatness. In addition, because the findings of the current analysis strongly suggest that DXA is not superior to BMI as a measure of body fat, the misclassification suggested by Flegal et al. would have been overstated for anthropometric indices. Therefore, for large epidemiologic studies consisting of thousands of participants, the accuracy of anthropometric measurements is sufficient for ranking participants' body fatness and evaluating associations between adiposity and disease risk. On the other hand, for studies that require more precise estimates of fat mass in certain compartments of the human body or studies that primarily consist of participants for whom anthropometric measurements are known to perform poorly in assessing adiposity, such as older adults and muscle builders (58), more accurate methods such as DXA, CT, or MRI should be used.

Our analysis had some limitations. In the current analysis, we could not compare waist circumference with DXA measures of fat in different regions of the trunk because only trunk fat mass data were available. We were unable to compare other anthropometric indices, such as waist-to-hip ratio, with corresponding DXA measures because of lack of hip circumference data. In addition, depending on the validity of imputation models and the assumption regarding missing data, including imputed data may introduce systemic bias into the analysis. However, when we restricted analysis to participants with measured DXA data only, we observed essentially similar results, which argues against this possibility. Strengths of the current study included national representativeness, a large sample size, standardized protocols for DXA and anthropometric measurements, and rich biomarker data allowing comprehensive analysis.

In summary, these data indicate that the validity of simple anthropometric measures such as BMI and waist circumference is comparable to DXA measurements of fat mass and fat mass percent as assessed by their correlations with obesity-related risk factors for cardiovascular disease. Low cost, simplicity, wide availability, and good validity make these anthropometric measures particularly valuable for epidemiologic studies that aim to investigate the role of excess adiposity in the development of chronic diseases in large populations.

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