

How Useful Is Body Mass Index for Comparison of Body Fatness across Age, Sex, and Ethnic Groups?

Dympna Gallagher,¹ Marjolein Visser,² Dennis Sepúlveda,¹ Richard N. Pierson,¹ Tamara Harris,³ and Steven B. Heymsfield¹

This study tested the hypothesis that body mass index (BMI) is representative of body fatness independent of age, sex, and ethnicity. Between 1986 and 1992, the authors studied a total of 202 black and 504 white men and women who resided in or near New York City, were ages 20–94 years, and had BMIs of 18–35 kg/m². Total body fat, expressed as a percentage of body weight (BF%), was assessed using a four-compartment body composition model that does not rely on assumptions known to be age, sex, or ethnicity dependent. Statistically significant age dependencies were observed in the BF%-BMI relations in all four sex and ethnic groups (p values < 0.05–0.001) with older persons showing a higher BF% compared with younger persons with comparable BMIs. Statistically significant sex effects were also observed in BF%-BMI relations within each ethnic group (p values < 0.001) after controlling first for age. For an equivalent BMI, women have significantly greater amounts of total body fat than do men throughout the entire adult life span. Ethnicity did not significantly influence the BF%-BMI relation after controlling first for age and sex even though both black women and men had longer appendicular bone lengths relative to stature (p values < 0.001 and 0.02, respectively) compared with white women and men. Body mass index alone accounted for 25% of between-individual differences in body fat percentage for the 706 total subjects; adding age and sex as independent variables to the regression model increased the variance (r^2) to 67%. These results suggest that BMI is age and sex dependent when used as an indicator of body fatness, but that it is ethnicity independent in black and white adults. *Am J Epidemiol* 1996;143:228–39.

aging; body composition; body mass index; ethnic groups

The hallmark of obesity is excess adipose tissue. At present the quantification of adipose tissue mass in vivo requires costly equipment (1–3). Some methods involve radiation exposure (2–5), and many techniques are not practical for epidemiologic studies.

Body weight adjusted for stature is often used as an alternative to the measurement of adipose tissue mass in the evaluation of individuals or populations for obesity (6). One such measure now in widespread use is Quetelet's index, which is body weight (in kg) divided by stature (in m²) (6). Better known as body mass index (BMI), this measure was an attempt by the

19th century mathematician Lambert Adolphe Jacques Quetelet to describe the relation between body weight and stature in humans (7).

The recent use of BMI represents an effort to derive a measure of adiposity by adjusting body weight for individual differences in stature. Many studies have shown that BMI is a reasonable measure of adiposity (6, 8–12) given that body weight and stature are simple, inexpensive, safe, and practical measurements to acquire.

A major assumption is that BMI represents adiposity independent of age, sex, and ethnicity. In other words, the use of BMI assumes that after adjusting subjects' body weights for stature², all subjects have the same relative fatness regardless of their age, sex, or ethnicity. There have been few investigations of the validity of this assumption. Moreover, studies that examined the relations between BMI, fatness, aging, sex, and ethnicity usually relied on potentially biased methods for estimating fatness. Bias can be introduced into adipose tissue/fat measurements if a method makes assumptions related to body composition proportions and characteristics that are inaccurate across

Received for publication January 12, 1995, and in final form October 3, 1995.

Abbreviations: BMI, body mass index; TBBM, total body bone mineral mass; TBW, total body water.

¹ Department of Medicine, Obesity Research Center, St. Luke's-Roosevelt Hospital Center, Columbia University, College of Physicians and Surgeons, New York, NY.

² Department of Human Nutrition, Wageningen Agricultural University, Wageningen, the Netherlands.

³ National Institute of Aging, Bethesda, MD.

Reprint requests to Dr. Dympna Gallagher, Obesity Research Center, St. Luke's-Roosevelt Hospital Center, 1090 Amsterdam Avenue, 14th Floor, New York, NY 10025.

different populations. Among these methodological concerns are the following observations: hydration of fat free body mass changes with age and differs across ethnic groups (13–15); the density of fat free body mass changes with age and differs between men and women (16, 17); and total body potassium decreases with age (15) and fatness (18) and differs between blacks and whites (19, 20). These between-group differences influence the absolute accuracy of methods for estimating fatness such as the two-compartment total body water, underwater weighing, and total body potassium methods (21).

Another concern is that body weight may be associated with relative extremity length independent of total stature, and this is hypothesized to influence the association between fatness and BMI (22, 23). Due to kyphosis and osteoporotic degeneration of vertebral bodies, older subjects reportedly have a higher proportion of stature contributed by the lower extremities and pelvis than do young subjects (24–27). Similarly, the lower extremity to stature ratio is reportedly greater in blacks than in whites (14, 20).

This study used modern methodology to quantitatively test the hypothesis that BMI is representative of fatness independent of age, sex, and ethnicity in adult black and white men and women across a wide age spectrum. In addition, the influence of relative extremity length on the association between BMI and body fatness was investigated.

METHODS

Experimental design and protocol

Four studies were completed in each subject—anthropometry, hydrodensitometry, tritium dilution volume measurement, and dual photon absorptiometry. These studies provided the measurements needed to calculate BMI, total body fat, relative extremity length, and waist to hip circumference ratio. The ratio of waist to hip circumference was used as a measure of adipose tissue distribution (28). Fatness was examined in relation to age, sex, ethnicity, and waist to hip ratio after controlling first for BMI.

Body mass index is traditionally calculated as body weight divided by the square of total subject height. If a subject decreases in stature due to loss in vertebral bone with age, there would be a corresponding increase in BMI. A change in the relation between BMI and fatness would occur due to this loss in stature, assuming that body weight and fatness remained constant. The linear dimensions of appendicular bones such as the tibia do not change with aging as do vertebrae (24–27). We therefore explored the fatness-BMI relation with aging and also examined an alter-

native index not influenced by stature loss, the ratio of body weight to absolute tibia length squared.

Black and white subjects of similar age and stature differ significantly in relative extremity lengths (14, 20). We examined the proportion of total stature as tibia length in the current study and compared the tibia with stature ratio between black and white groups within each sex. The availability of the tibia to stature ratio also allowed us to examine the potential effects of relative lower extremity length on any observed black-white differences in the relation between body fat percentage and BMI.

All measurements were carried out on the same day with each subject clothed in a hospital gown and wearing foam slippers. After fasting overnight, subjects reported for testing to the Body Composition Core Laboratory of the New York Obesity Research Center. The four experimental studies were then completed over 4 hours.

Subjects

A total of 202 black and 504 white subjects who had participated in a larger (ongoing) multiethnic body composition investigation (20, 29) were included in this study. There were 312 men (98 black and 214 white) and 394 women (104 black and 290 white). Subjects with an empirically set BMI of ≥ 35 kg/m² were excluded from the present analysis due to methodological concerns such as ability to complete the underwater weighing procedure and technical limitations of dual photon methods in markedly overweight subjects (30). The subjects were recruited from 1986 to 1992 through advertisements in local newspapers, on radio stations, and in flyers posted in the community. Inclusion in the study required that subjects be ambulatory with no orthopedic problems or medical conditions known to affect any of the variables under investigation. Race was determined by self-report. Black subjects had to report both parents and all grandparents as non-Hispanic black. Likewise, white subjects had to report both parents and grandparents as non-Hispanic white. The study was approved by the Institutional Review Board of St. Luke's-Roosevelt Hospital, and all subjects gave written consent to participate.

Body composition

Anthropometry. Body weight was measured to the nearest 0.2 kg (Weight Tronix, New York, New York) and height to the nearest 0.5 cm using a stadiometer (Holtain, Crynych, Wales). Waist circumference was obtained with a measuring tape at the level of the narrowest part of the torso as viewed anteriorly. Hip

circumference was measured at the level of maximum extension of the buttocks as viewed from the side.

Hydrodensitometry. Body density and volume were determined by hydrodensitometry as previously described (31). The hydrodensitometry system requires that the subject kneel onto a platform supported by four force transducers (Precision Biomedical Systems Inc., University Park, Pennsylvania). Each subject wore a bathing suit and performed five to 10 submersions with maximal exhalation. The greatest weight recorded twice was considered the underwater weight. Prior to submersion, residual lung volume was estimated using the closed circuit oxygen-dilution technique (32), and body volume was adjusted accordingly. The within-person day-to-day coefficient of variation in our laboratory is 0.33 percent for body volume (33).

Tritium dilution. Total body water (TBW) was determined using 0.19 Bq $^3\text{H}_2\text{O}$ (32). Blood samples were collected before and 3 hours after an oral $^3\text{H}_2\text{O}$ dose. Tritium concentration in prepared blood samples was analyzed by scintillation counting. Loss of isotope in urine was accounted for, allowing for the calculation of dilution volume. A correction of 5 percent was made in the dilution volume for nonaqueous hydrogen exchange (2), and TBW was calculated as follows: $\text{TBW (in kg)} = ^3\text{H}_2\text{O dilution space (in liters)} \times 0.95 \times 0.99371$. The within-person day-to-day coefficient of variation for the TBW method is 1.5 percent (34).

Dual-photon absorptiometry. Total body bone mineral mass (TBBM) was measured by either a whole body ^{153}Gd dual-photon (44 and 100 KeV) absorptiometer (DP-4, Lunar Radiation Corporation, Madison, Wisconsin) or by a whole body dual-energy (40 and 70 KeV) x-ray absorptiometer (DPX, Lunar Radiation). Previous results from our laboratory showed a mean difference of 0.7 percent and a high correlation ($r = 0.98$) for TBBM measured by the DP-4 compared with the DPX system in 81 subjects (35). Total body bone mineral values derived from the DP-4 system were converted to DPX values using the following regression equation (31): $\text{TBBMDPX} = 0.0430 + (0.96 \times \text{TBBMDP-4})$. All DPX measurements were analyzed with Lunar software version 3.4. The within-person day-to-day coefficient of variation for TBBM is 1.0 percent by DP-4 and 0.5 percent by DPX (35).

Skeletal dimensions were measured in centimeters by a single reader using an engineering caliper (Staedtler Corporation, Frankfurt, Germany). The skeletal planogram generated by the dual photon scan was used to measure tibia length, from the lateral condyle to the medial malleolus, and total subject skeletal length, from the apex of the cranium (skull) to

the plantar surface of the feet. The ratio of tibia to total subject skeletal length was used as a measure of the proportion of total stature accounted for by the lower extremities. Absolute tibia length was calculated from the subject's tibia length to total length ratio measured in the dual photon scan and their actual height as $(\text{tibia}_{\text{scan}}/\text{length}_{\text{scan}}) \times \text{actual height}$.

Calculations and statistical analyses

Total body fat was quantified in all subjects using a four-compartment model (33) that requires measurements of body volume, TBW, TBBM, and body weight. The method provides fat estimates that are independent of major age-, sex-, and ethnicity-related assumptions (33). We used the following equation: $\text{fat mass} = 2.513 \times \text{BV} - 0.739 \times \text{TBW} + 0.947 \times \text{TBBM} - 1.79 \times \text{BW}$, where BV is body volume and BW is body weight (36). The propagated measurement error for this method is 3.0 percent of fat weight or <1 percent of body weight (36).

Differences between ethnic groups were tested using Student's *t* test. Pearson's correlation coefficients were calculated to investigate the relations between BMI, age, and body composition variables. Multiple linear regression analysis was used to investigate the possible influence of age, sex, and ethnicity on the relation between body fat percentage and BMI. Percentage of body fat was used as the dependent variable, and BMI, sex, age, ethnic group, and their interaction terms were used as independent variables. These analyses were repeated using body weight, stature, and fat mass instead of body fat percentage as dependent variables. Two-sided *p* values were considered significant at $p < 0.05$. Pooled subject data are expressed as the mean with standard deviation. Data were analyzed using the SAS statistical program (Statistical Analyses System, SAS Institute, Inc., Cary, North Carolina).

RESULTS

Baseline group characteristics

Baseline characteristics for the study population are presented in table 1 for women and in table 2 for men. Age and height were similar for black and white subjects within each sex. Body weight, BMI, fat mass, body fat percentage, and fat free body mass were all significantly greater ($p = 0.0001$) in black compared with white women. Black men had a greater waist to hip ratio than white men ($p = 0.0001$) but were similar for all other characteristics.

TABLE 1. Group characteristics of black and white women, New York City, 1986–1992

	Women				<i>p</i> value†
	Black (<i>n</i> = 104)		White (<i>n</i> = 290)		
	Mean	(SD*)	Mean	(SD)	
Age (years)	49.6	(16.2)	50.3	(18.7)	0.73
Body weight (kg)	71.2	(12.3)	61.8	(10.0)	0.0001
Height (m)	1.62	(0.06)	1.63	(0.07)	0.72
Body mass index (kg/m ²)	27.0	(4.3)	23.3	(3.7)	0.0001
Body fat					
%	35.6	(8.5)	30.3	(8.6)	0.0001
kg	26.0	(9.5)	19.3	(8.0)	0.0001
Fat free body mass (kg)	45.2	(6.0)	42.5	(5.2)	0.0001
Circumference (cm)					
Waist	83.4	(11.8)	74.8	(9.5)	0.0001
Hip	97.4	(11.5)	93.0	(9.4)	0.0008
Waist/hip	0.85	(0.06)	0.80	(0.05)	0.0001
Tibia/total body length	0.233	(0.011)	0.227	(0.012)	0.0001

* SD, standard deviation.

† For black vs. white women.

TABLE 2. Group characteristics of black and white men, New York City, 1986–1992

	Men				<i>p</i> value†
	Black (<i>n</i> = 98)		White (<i>n</i> = 214)		
	Mean	(SD*)	Mean	(SD)	
Age (years)	47.5	(16.1)	47.8	(18.0)	0.88
Body weight (kg)	79.6	(12.2)	77.4	(11.0)	0.11
Height (m)	1.75	(0.07)	1.75	(0.07)	0.91
Body mass index (kg/m ²)	25.8	(3.3)	25.2	(3.1)	0.08
Body fat					
%	21.7	(7.9)	21.2	(7.8)	0.65
kg	17.7	(8.1)	16.8	(7.7)	0.34
Fat free body mass (kg)	61.9	(8.6)	60.6	(8.0)	0.19
Circumference (cm)					
Waist	89.6	(10.1)	87.5	(9.2)	0.07
Hip	92.9	(9.5)	93.1	(8.7)	0.85
Waist/hip	0.96	(0.05)	0.94	(0.04)	0.0001
Tibia/total body length	0.233	(0.012)	0.229	(0.021)	0.02

* SD, standard deviation.

† For black vs. white men.

BMI relations

BMI versus age and body composition. The correlation coefficients for BMI versus age and body composition variables are shown in table 3. Body mass index increased significantly with age in black and white women and in black men. Body mass index was significantly correlated with height in white women only. Body mass index was highly correlated with body weight, body fat percentage, and fat mass in all four subgroups.

Percentage of body fat versus BMI. There was a significant linear correlation between body fat percentage and BMI in both black and white women (figure 1). Squaring body mass index did not contribute significantly to a model containing BMI as an indepen-

TABLE 3. Correlation coefficients for body mass index versus age and body composition, New York City, 1986–1992

	Women		Men	
	Black	White	Black	White
Age	0.23*	0.21***	0.25*	0.07
Height	−0.07	−0.19**	0.02	−0.04
Body weight	0.89***	0.87***	0.85***	0.84***
Body fat (%)	0.75***	0.72***	0.63***	0.58***
Body fat (kg)	0.89***	0.87***	0.78***	0.75***
Fat free body mass (kg)	0.42***	0.33***	0.48***	0.44***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

dent variable in women (p values = 0.34 and 0.08 for black and white women, respectively).

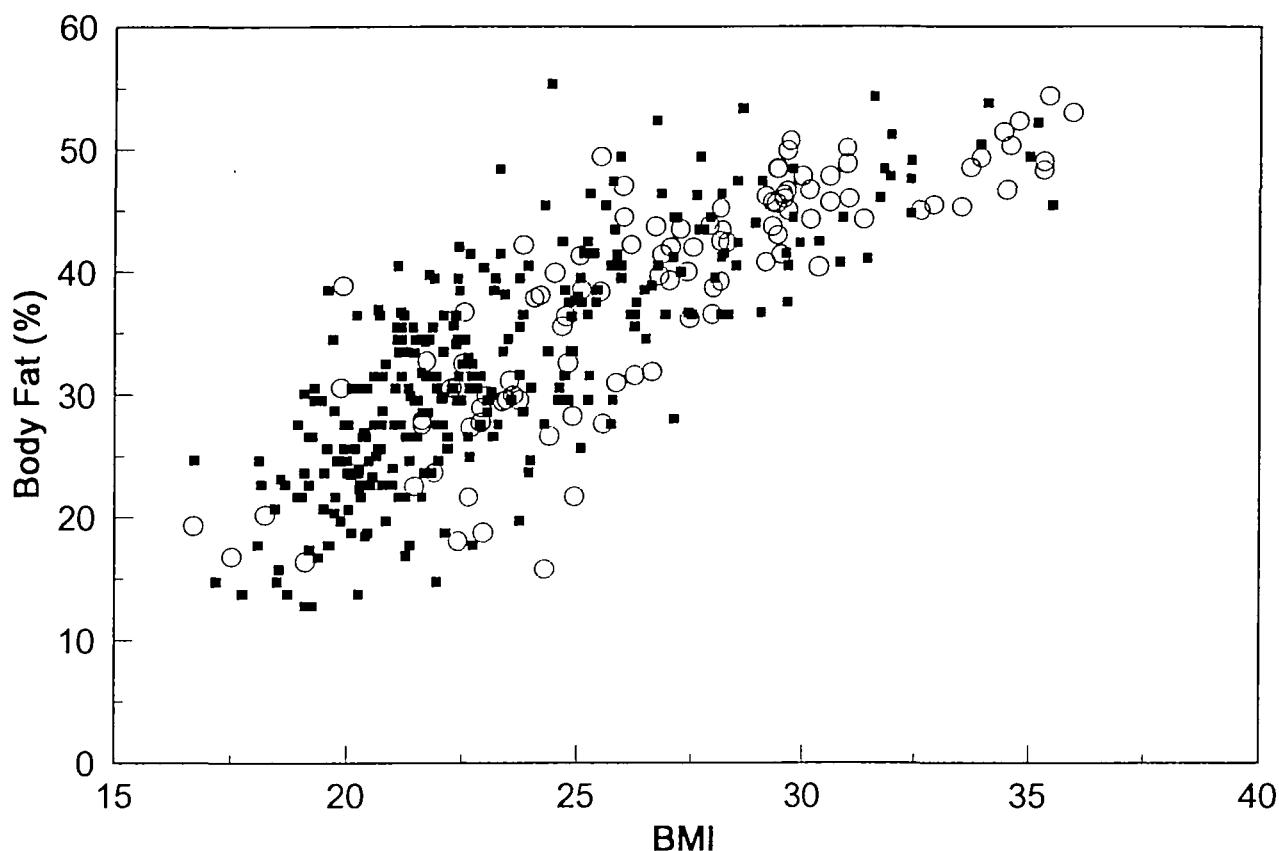


FIGURE 1. The relation between body fat percentage and body mass index (BMI, kg/m²) in black (○) and white (■) women ages 20–89 years.

In men, there was also a statistically significant linear relation between body fat percentage and BMI (figure 2). In addition, as with women, squaring BMI did not contribute significantly to the model (p values = 0.57 and 0.99 for black and white men, respectively).

Addition of age to the model. To investigate whether the relation between fatness and BMI was independent of age, multiple regression analyses were performed with body fat percentage as the dependent variable and BMI and age as independent variables. The analyses were performed separately for each sex and ethnic group (table 4).

Age contributed significantly to the model in all four subgroups, indicating a relatively greater body fat percentage in older versus younger persons of comparable BMI. The interaction term between BMI and age (and between BMI² and age for women) did not contribute significantly to the model (p values for the interaction terms were greater than 0.14) in the four sex/ethnic groups. The combination of body mass index and age explained 58 and 56 percent of the variance in body fat percentage in black and white women, respectively. In men, the explained variance was low-

er—44 and 52 percent for blacks and whites, respectively. The difference in the body fat percentage-BMI relation between young (<35 years) and older (>65 years) subjects is shown in figure 3 for women and figure 4 for men.

The ratio of tibia length to total stature tended to increase with age; however, none of the correlations were statistically significant within each sex and ethnic group. In addition, the strong influence of age on the relation between BMI and body fat percentage persisted in all subject groups when body weight/tibia length² was substituted for BMI. Age contributed significantly to the model with body fat percentage as the dependent variable and body weight/tibia length² as an independent variable ($p = 0.0001$ for white men and women, $p = 0.07$ for black women, and $p = 0.008$ for black men).

Addition of sex to the model. An analysis investigating whether the relation between body fat percentage and BMI is significantly different between men and women was carried out for each ethnic group (table 5). Because the association between fatness and BMI was shown to be age dependent, age was controlled for in the model prior to adding the sex term. A

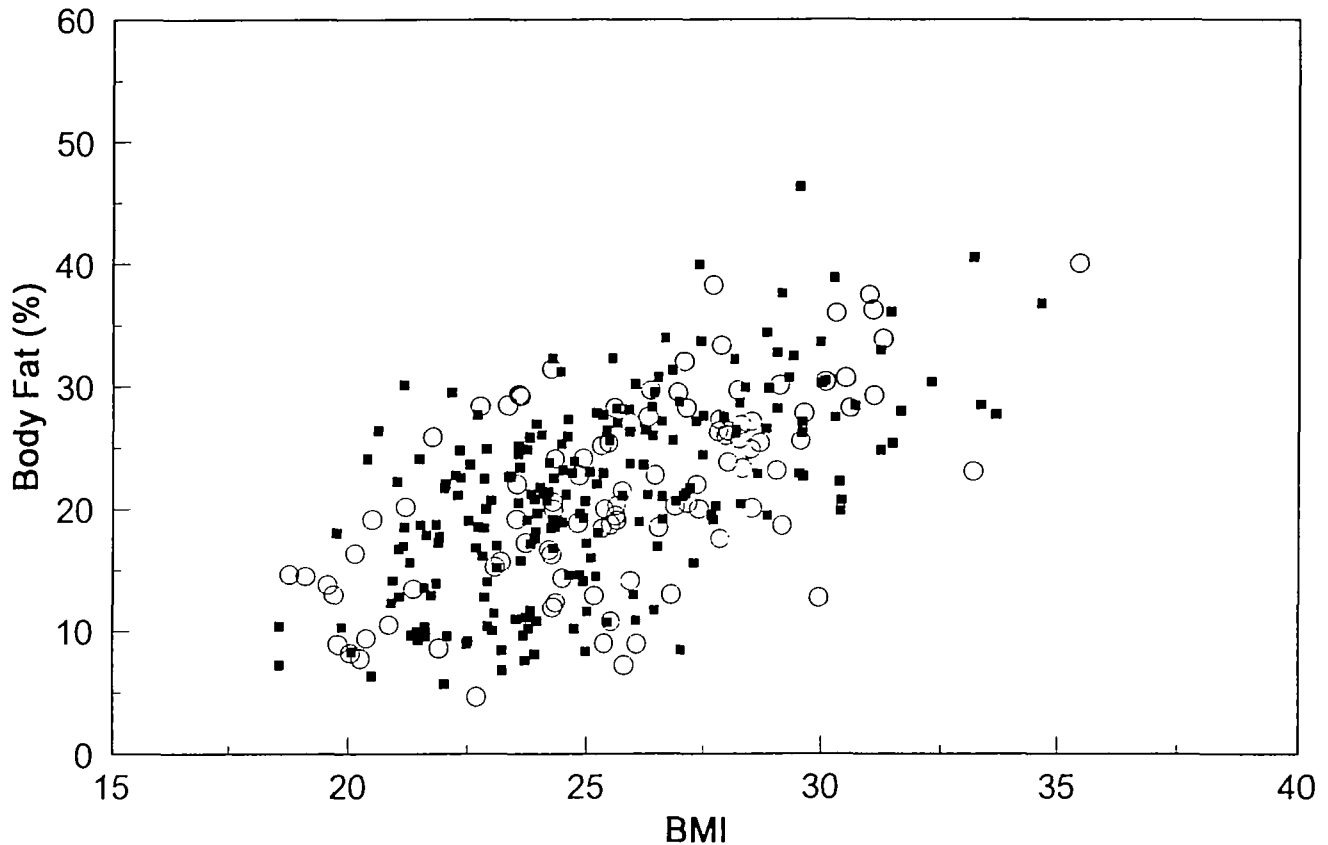


FIGURE 2. The relation between body fat percentage and body mass index (BMI, kg/m²) in black (○) and white (■) men ages 20–94 years.

TABLE 4. Multiple regression analysis of body fat percentage versus body mass index and age, New York City, 1986–1992

Coefficient	Women		Men	
	Black	White	Black	White
	Mean ± SE†	Mean ± SE	Mean ± SE	Mean ± SE
Intercept	-6.254 ± 3.595	-11.666 ± 2.229***	-18.624 ± 4.774**	-22.519 ± 3.145***
Body mass index	1.419 ± 0.131***	1.591 ± 0.095***	1.367 ± 0.187***	1.402 ± 0.121***
Age	0.072 ± 0.035*	0.096 ± 0.019***	0.105 ± 0.039*	0.177 ± 0.020***
r ² †	0.58 ± 5.53	0.56 ± 5.75	0.44 ± 5.95	0.52 ± 5.43

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

† SE, standard error; r², explained variance of the model.

significant negative regression coefficient was found for sex in both black and white subjects, thereby indicating that for the same BMI and age, men had a lower body fat percentage compared with women. The r^2 values for the body fat percentage model containing BMI, age, and sex as independent variables were 0.72 for black subjects and 0.64 for white subjects (table 5).

The ratio of tibia length to stature was not significantly different between men and women in either black ($p = 0.97$) or white ($p = 0.12$) subjects. Thus, the observed differences in the relation between fatness and BMI between men and women cannot be

explained by sex differences in lower extremity stature proportions.

Addition of ethnicity to the model. Multiple regression analysis was performed for all subjects pooled with body fat percentage as the dependent variable and BMI, age, sex, and ethnic group as independent variables (table 6). The r^2 values for the body fat percentage models that include BMI, BMI + age, and BMI + age + sex as independent variables are 0.26, 0.34, and 0.67, respectively. No significant additional variance was explained by the addition of ethnicity ($p = 0.66$) or its interaction terms to the model.

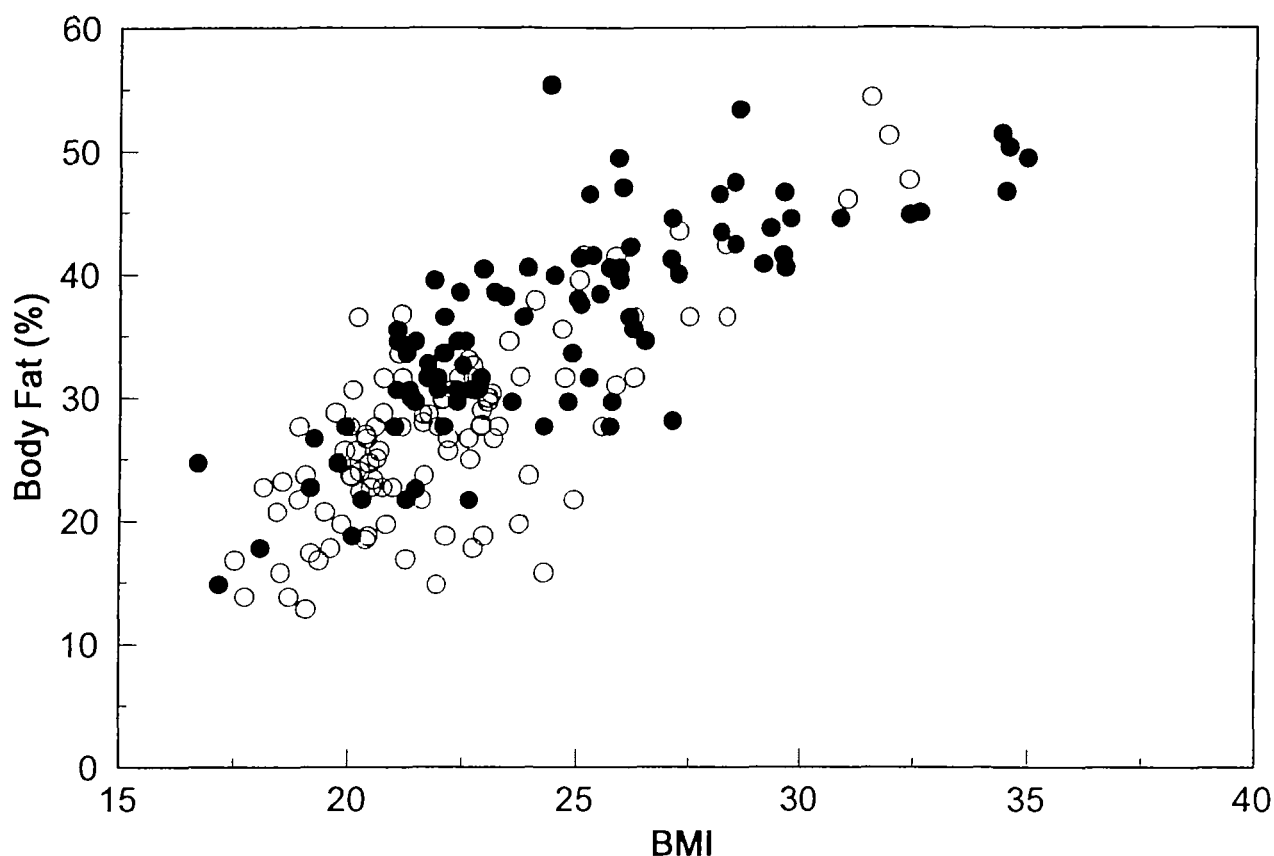


FIGURE 3. The relation between body fat percentage and body mass index (BMI, kg/m^2) in all young (<35 years, \circ) and elderly (>65 years, \bullet) women.

The ratio of tibia length to stature was significantly greater in blacks of both sexes relative to whites (tables 1 and 2; $p = 0.02$ for men and $p = 0.0001$ for women). Despite these skeletal differences, there were no significant ethnic differences in the fatness-BMI relation within each age and sex group.

Black subjects of both sexes had significantly ($p = 0.0001$) greater waist to hip circumference ratios than did white subjects (tables 1 and 2). Waist to hip ratio did not add significantly to the model in either black or white subjects (table 5). The addition of waist circumference to the model presented in table 5 (which included BMI, age, and sex) marginally increased the explained variance in black and white subjects (0.72–0.73 and 0.64–0.66, respectively). Thus, although black and white subjects clearly differed in adipose tissue distribution, waist to hip ratio and waist circumference did not influence the relation between body fatness and BMI between the two ethnic groups after controlling for age and sex.

Other analytical approaches

When body fat percentage was used as the dependent variable and body weight and height as separate

independent variables in the model, results were similar to those obtained when BMI was used as the independent variable. The influence of age and sex was very significant ($p < 0.001$) in the alternative model, and no ethnicity effect was observed. However, the explained variance of body fat percentage was lower when body weight and height were used as separate independent variables ($r^2 = 0.53$) compared with the model in which BMI was an independent variable ($r^2 = 0.67$). When fat mass (in kg) was used as the dependent variable, the relation between fat mass and BMI was comparable with those observed when body fat percentage was used as the dependent variable.

DISCUSSION

The present study investigated a cohort of adult subjects using a multicomponent body composition model to estimate total body fat. Results suggest that the relation between fatness and BMI is significantly influenced by age and sex but is independent of ethnicity in black and white adults of $\text{BMI} \leq 35 \text{ kg}/\text{m}^2$. These results have implications for the use of BMI as an index of body fatness.

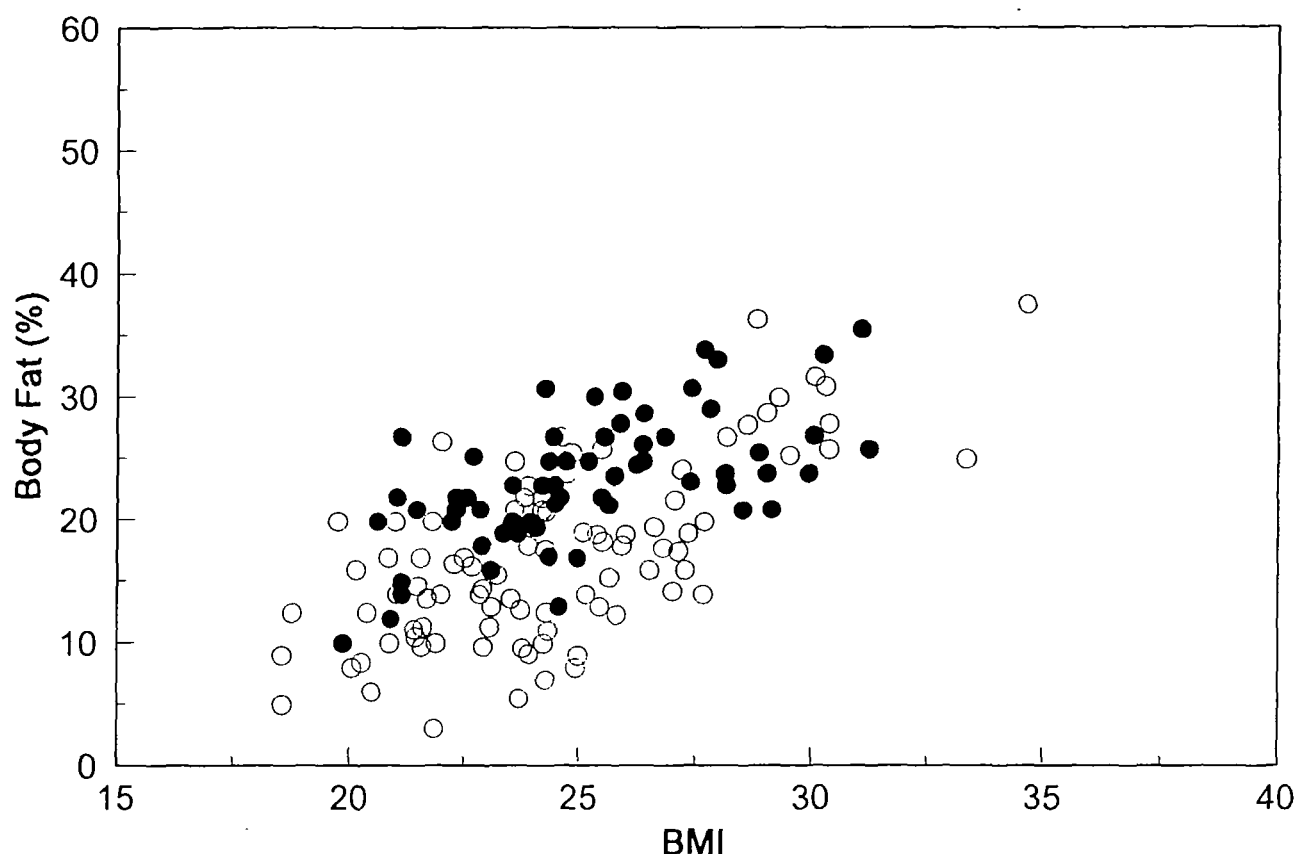


FIGURE 4. The relation between body fat percentage and body mass index (BMI, kg/m²) in all young (<35 years, ○) and elderly (>65 years, ●) men.

TABLE 5. Multiple regression analysis of body fat percentage versus body mass index, age, and sex, New York City, 1986–1992

Coefficient	Subjects	
	Black	White
	Mean ± SE†	Mean ± SE
Intercept	−6.489 ± 2.949*	−11.520 ± 1.799**
Body mass index	1.399 ± 0.108**	1.506 ± 0.075**
Age	0.088 ± 0.026**	0.133 ± 0.014**
Sex‡	−12.156 ± 0.814**	−11.481 ± 0.530**
r ² †	0.72 ± 5.71	0.64 ± 5.66

* $p < 0.05$; ** $p < 0.001$.

† SE, standard error; r², explained variance of the model.

‡ 0 = female; 1 = male.

BMI-age relations

Our findings indicate that when comparing young and old subjects who have similar BMIs, the older person will have a greater percentage of body weight as fat. Although other investigators have made similar observations (11, 37), our study is the first to use a method of estimating total body fat that is unbiased in providing body composition estimates in the elderly.

The findings indicate that in hypothetical cases of 23 kg/m² BMIs for men and women, there is an

increase in body fat percentage of approximately 1.0–1.1 percent and 0.7–1.0 percent per decade, respectively. The mechanisms of increasing relative fatness and corresponding reduction in lean tissue with aging are multifactorial and include such factors as disuse/physical inactivity (38), altered hormone/cytokine metabolism (39), protein-energy malnutrition (40), and other as yet not clearly identified factors. As the contribution of these factors may vary between subjects, our results should be considered population specific and generally applicable to healthy ambulatory persons who do not engage in extensive physical activity or exercise training.

Another aspect of our age analysis was to establish whether elderly persons had an increase in the lower extremity (i.e., tibia) to stature ratio due to osteoporosis-related decline in stature. Garn et al. (22), Quaade (23), and others have suggested that BMI fails to consider individual differences in skeletal proportions that in turn might influence BMI-fatness relations. As an example, Quaade hypothesized that solid extremities weigh more per unit length than does the partially air-filled trunk (23). According to this theory, an individual with relatively long

TABLE 6. Multiple regression analysis of body fat percentage versus body mass index, age, sex, and ethnicity for the total study population, New York City, 1986–1992

Body mass index	Regression coefficients				SEE	<i>r</i> ² †
	Age	Sex‡	Ethnic group§	Intercept		
Mean ± SE†	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE		
1.34 ± 0.07**				−6.07 ± 2.12*	8.48	0.26
1.23 ± 0.08**	0.15 ± 0.02**			−10.77 ± 2.07**	8.04	0.34
1.46 ± 0.06**	0.12 ± 0.01**	−11.61 ± 0.44**		−10.02 ± 1.46**	5.68	0.67
1.47 ± 0.06**	0.12 ± 0.01**	−11.61 ± 0.44**	−0.22 ± 0.49	−10.13 ± 1.48**	5.68	0.67

* $p < 0.01$; ** $p < 0.0001$.† r^2 , explained variance of the model; SE, standard error; SEE, standard error of the estimate.

‡ 0 = female; 1 = male.

§ 0 = white, 1 = black.

legs would have a greater body weight and BMI than a height-matched subject with short extremities.

In the current study, we examined these concepts using the tibia to stature ratio as a measure of lower extremity to trunk and total stature proportions. Although we found a small increase in the tibia/height ratio with age in some subgroups, particularly white women, the effects were small and not statistically significant. This may be partially explained by our subject selection as we eliminated patients with obvious diseases, including elderly subjects with clinical osteoporosis.

In a similar analysis, we examined in relation to fatness the body weight to tibia length² ratio as an alternative to BMI. Because stature decreases with age and tibia length does not, we considered the possibility that fatness might increase with age in relation to BMI but not body weight/tibia length². This alternative body mass index showed a relation to fatness (with age as a significant covariate) similar to that observed with BMI. This finding suggests that the observed increase in fatness in relation to BMI with age is independent of the senescence-related loss in stature.

Several population studies suggest that overall BMI increases with age up to the fifth or sixth decade after which BMI declines (41). We observed no obvious BMI reduction in elderly subjects in the present study, which suggests that our results may not be indicative of the population as a whole. The current findings therefore require confirmation in a large and representative cohort.

BMI-sex relations

The results of the current study indicate that BMI cannot be used as a comparable measure of fatness in men and women. Women have significantly greater amounts of total body fat than do men for an equivalent BMI. Although relative extremity length was not significantly different between men and women, it is unlikely that skeletal differences account for the sex

disparity in the relation between body fatness and BMI.

The difference in fatness between men and women of similar BMI was substantial and maintained throughout all adult age groups. For example, a 20-year-old man and woman of 23 kg/m² BMI would have 13.3 and 26.0 percent of body weight as fat, respectively. By age 80 years, this man and woman would have 23.9 and 32.6 percent of body weight as fat, respectively.

As women and men of similar BMI differ substantially in fatness, an important future consideration in population studies, if feasible, is to include body composition estimates. This practice, which is already being applied in a number of ongoing studies, will help to clarify the female to male relations between morbidity/mortality, body mass index, and fatness.

BMI-ethnicity relations

Our results suggest that BMI reflects the same relative level of fatness in black and white persons of the same age and sex. Therefore, BMI values of <35 kg/m² can be compared directly as a measure of relative fatness between black and white subjects. This observation applied in the current study even though both black men and women had relatively longer lower extremities than did white subjects. These ethnic differences in skeletal proportions confirm earlier studies in cadavers and in living subjects (14, 20, 42, 43).

Our findings differ from those of Kleerekoper et al. (44) who studied BMI and body fatness (measured by dual x-ray absorptiometry) in older black and white women. These investigators did not find a difference in percentage of body fat between black and white women, although BMI was significantly higher in the black women. These results suggest an influence of ethnicity on the relation between BMI and body fatness. Our two studies differ in several respects. First, the subjects in Kleerekoper et al.'s study were all older

women whose BMIs were greater than those of our subjects. Second, body fatness was measured using dual energy x-ray absorptiometry. There are at least two explanations (one subject-related and the other, technical) for these discrepant findings. First, it is possible that black and white women of greater body weights than studied in the current investigation differ in fatness after controlling for BMI. Second, the possibility exists that dual energy x-ray absorptiometry does not give reliable fat estimates in very obese subjects. We considered this latter possibility in the current study and enrolled subjects who had BMIs $<35 \text{ kg/m}^2$. There is considerable evidence that dual energy x-ray absorptiometry fat estimates are not reliable in very obese subjects due to attenuation artifacts caused by great body thickness (30) and by subjects exceeding the scanner study window. Thus, even though our study included a very large and carefully examined cohort of black and white subjects, there remains some question about BMI-fatness relations in very obese older subjects.

We also found significant differences in the waist to hip ratio, a measure of adipose tissue distribution, between black and white subjects in the current study even though the two ethnic groups had similar total body fat after controlling for age and sex. Others have also reported a greater waist to hip ratio in black versus white subjects (45). Some of the observed ethnic difference in adipose tissue distribution in the current study may be accounted for by greater total body weight and fatness in the black women.

Analytical issues

Linear versus curvilinear model. The relation between percentage of total body fat and BMI throughout the entire biologic range is curvilinear (9). Some suggestion of the curvilinear relation of body fat percentage to BMI is suggested in figure 1, although we found that a linear model fit the data equally as well as alternative models. The possibility exists, however, that a curvilinear model may have provided a better fit than a linear model if we had included subjects with higher BMIs. Our results and equations are therefore applicable only for $<35 \text{ kg/m}^2$ BMIs.

Design of regression equations

The results of the present study support the use of BMI as a means of adjusting body weight for height rather than using body weight and height separately in multiple regression equations for prediction of body fat percentage. No improvement in variance estimates was observed in body fat percentage regression equa-

tions when body weight and height were substituted for BMI as independent variables.

Similarly, we used absolute fat mass as an alternative to body fat percentage as the dependent variable in regression equations. In the present analyses, fat mass and body fat percentage had equivalent overall results. Although several previous studies have reported a stronger relation between absolute fat mass and BMI than between body fat percentage and BMI, the differences observed are relatively small (9, 46).

Correlation versus prediction equations

Although the explained variance of the regression model developed in all subjects combined (table 6) is high (~ 67 percent), this does not imply that the model can be used to predict percentage of body fat from BMI. No advanced model building techniques were used to develop the best prediction model. Furthermore, prediction models are likely to be population specific and should be externally validated before being applied to other populations.

Study design

Because our study was cross-sectional, there is clearly a need to explore the observed relations between BMI, fatness, age, sex, and ethnicity in longitudinally evaluated cohorts. We are subsequently re-examining some of the subjects in the current report with this goal in mind.

Comparison with earlier studies

Our study confirms and expands on several earlier investigations of BMI-body fat relations. These studies, including our own, are summarized in table 7 for a representative 45-year-old man and woman with BMIs of 27.8 kg/m^2 and 27.3 kg/m^2 , respectively.

TABLE 7. Predicted body fat percentage based on published body mass index (BMI) prediction equations*

Authorship (reference no.)	Men	Women
Womersley and Durnin (47)	24.8	34.0
Norgan and Ferro-Luzzi (48)	25.7† 27.3‡	
Garrow and Webster (9)	28.0	35.6
Heitman (49)	26.8	36.4
Deurenberg et al. (11)	27.5	37.7
Gallagher et al. (current data)	24.9	35.6

* The following obesity-defined BMI cut-off points and sex characteristics were used: Men—BMI, 27.8 kg/m^2 ; age, 45 years; weight 85.1 kg; height, 1.75 m. Women—BMI, 27.3 kg/m^2 ; age, 45 years; weight, 69.9 kg; height, 1.60 m.

† Equation based on BMI only.

‡ Equation based on BMI and age.

Body mass indices greater than these levels are usually considered diagnostic of obesity (41). The compiled studies using different fat estimation methods and including subjects in both Europe and the United States show remarkable concordance in the percentages of body fat that are indicative of obesity with levels greater than 25 percent in men and 35 percent in women at age 45 years.

Conclusion

The results of the present study demonstrate a strong influence of age and sex, but not of ethnicity, on the relation between BMI and body fatness. These findings should be considered when interpreting BMI results in population studies and when designing clinical trials in which body fatness is a main study variable.

ACKNOWLEDGMENTS

This research was supported in part by National Institutes of Health grant P01-DK37352 and a contract from the National Institute of Aging.

REFERENCES

- Lukaski HC. Methods for the assessment of human body composition: traditional and new. *Am J Clin Nutr* 1987;46:537-56.
- Forbes GB. Human body composition. New York: Springer Verlag, 1987.
- Jebb S, Elia M. Techniques for the measurement of body composition: a practical guide. *Clin Nutr* 1993;12:57-65.
- Pierson RN, Wang J, Heymsfield SB, et al. High precision in-vivo neutron activation analysis: a new era for compartmental analysis in body composition. In: Yasumura S, Harrison JE, McNeil KG, et al, eds. Basic life sciences. Vol 55. New York: Plenum Press, 1990:317-25.
- Sjöström L. A computer-tomography based multicompartiment body composition technique and anthropometric predictions of lean body mass, total and subcutaneous adipose tissue. *Int J Obes* 1991;15:19-30.
- Keys A, Fidanza F, Karvonen MJ, et al. Indices of relative weight and obesity. *J Chron Dis* 1972;25:329-43.
- Quetelet LAJ. A treatise on man and the development of his faculties. In: Comparative statistics in the 19th century. Edinburgh: William and Robert Chambers, 1842.
- Khosla T, Lowe R. Indices of obesity derived from body weight and height. *Br J Prev Soc Med* 1967;21:122-8.
- Garrow JS, Webster JD. Quetelet's index (W/H^2) as a measure of fatness. *Int J Obes* 1985;9:147-53.
- Smalley KJ, Knerr AN, Kendrick ZV, et al. Reassessment of body mass indices. *Am J Clin Nutr* 1990;52:405-8.
- Deurenberg P, Weststrate JA, Seidell JC. Body mass index as a measure of body fatness: age- and sex-specific prediction formulas. *Br J Nutr* 1991;65:105-14.
- Strain GW, Zumoff B. The relation of weight-height indices of obesity to body fat content. *J Am Coll Nutr* 1991;11:715-18.
- Cohn SH, Vaswani AN, Yasumura S, et al. Assessment of cellular mass and lean body mass by noninvasive nuclear techniques. *J Lab Clin Med* 1985;105:305-11.
- Gerace L, Aliprantis A, Russell M, et al. Skeletal differences between black and white men and their relevance to body composition estimates. *Am J Hum Biol* 1994;6:255-62.
- Mazariegos M, Wang Z, Gallagher D, et al. Differences between young and old females in the five levels of body composition and their relevance to the two-compartment chemical model. *J Gerontol* 1994;49:M201-8.
- Heymsfield SB, Wang Z, Baumgartner RN, et al. Body composition and aging: a study by in vivo neutron activation analysis. *J Nutr* 1993;123(suppl):432-7.
- Lohman TG. Advances in body composition assessment. Champaign, IL: Human Kinetics Publishers, 1992.
- Pierson RN Jr, Lin DHY, Phillips, RA. Total-body potassium in health: effects of age, sex, height, and fat. *Am J Physiol* 1974;226:206-21.
- Cohn SH, Abesamis C, Zanzi I, et al. Body elemental composition: comparison between black and white adults. *Am J Physiol* 1977;234:E419-22.
- Ortiz O, Russell M, Daley TL, et al. Differences in skeletal muscle and bone mineral mass between black and white females and their relevance to estimates of body composition. *Am J Clin Nutr* 1992;55:1-6.
- Heymsfield SB, Waki M. Body composition in humans: advances in the development of multi-compartment chemical models. *Nutr Rev* 1991;97-108.
- Garn SM, Leonard WR, Hawthorne VM. Three limitations of the body mass index. *Am J Clin Nutr* 1986;44:996-7.
- Quaade F. Nordisk forsikrings tidsskrift (in Finnish). Foredrag i Forsikringslægernes Forening 1963;24:37-46.
- Chumlea WC, Guo S. Equations for predicting stature in white and black elderly individuals. *J Gerontol* 1992;47:M197-203.
- Miller JAA, Schmatz C, Schultz AB. Lumbar disc degeneration: correlation with age, sex, and spine level in 600 autopsy specimens. *Spine* 1988;13:173-8.
- Prothro JW, Rosenbloom CA. Physical measurements in an elderly black population: knee height as the dominant indicator of stature. *J Gerontol* 1993;48:M15-18.
- Trotter M, Gleser GC. A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. *Am J Phys Anthropol* 1958;16:79-123.
- Seidell JC, Oosterlee A, Thijssen MAO, et al. Assessment of intra-abdominal and subcutaneous abdominal fat: relation between anthropometry and computed tomography. *Am J Clin Nutr* 1987;45:7-13.
- Pierson RN Jr, Wang J, Heymsfield SB, et al. Measuring body fat: calibrating the rulers. Intermethod comparisons of 389 normal Caucasian subjects. *Am J Physiol* 1991;261:E103-8.
- Jebb SA, Goldberg GR, Elia M. DXA measurements of fat and bone mineral in relation to depth and adiposity. In Ellis KJ, Eastman JD, eds. Human body composition: in vivo methods, models and assessment. New York: Plenum, 1993:115-19.
- Akers R, Buskirk ER. An underwater weighing system utilizing "force cube" transducers. *J Appl Physiol* 1969;26:649-52.
- Wilmore J. A simplified method for determination of residual lung volumes. *J Appl Physiol* 1969;27:96-100.
- Heymsfield SB, Lichtman S, Baumgartner RN, et al. Body composition of humans: comparison of two improved four-compartment models that differ in expense, technical complexity, and radiation exposure. *Am J Clin Nutr* 1990;52:52-8.
- Moore FD, Olesen KH, McMurrey JD, et al. The body cell mass and its supporting environment. Philadelphia: WB Saunders, 1963.
- Russell-Aulet M, Wang J, Thornton J, et al. Comparison of dual-photon absorptiometry systems for total-body bone and soft tissue measurements: dual-energy x-rays versus gadolinium 153. *J Bone Min Res* 1991;6:411-15.
- Heymsfield SB, Wang ZM, Withers R. Multicomponent molecular-level models of body composition analysis. In Roche A, Heymsfield SB, Lohman T, eds. Human body composition. Champaign, IL: Human Kinetics Publishers (in press).
- Visser M, Van den Heuvel E, Deurenberg P. Prediction equa-

- tions for the estimation of body composition in the elderly using anthropometric data. *Br J Nutr* 1994;71:823-33.
38. Bortz WM II. Disuse and aging. *JAMA* 1982;248:1203-8.
 39. Body composition: the measures and meaning of changes with aging. Proceedings from the USDA Conference at Tufts University, Medford, MA, November 6-7, 1991.
 40. Evans WJ. Exercise, nutrition and aging. *J Nutr* 1992;122:796-801.
 41. Kuczmarski RJ, Flegal KM, Campbell SM, et al. Increasing prevalence of overweight among US adults. *JAMA* 1994;272:205-11.
 42. Metheny E. Some differences in bodily proportions between American Negro and white male college students as related to athletic performance. *Res Q* 1939;10:41-53.
 43. Trotter M, Broman GE, Peterson RR. Densities of bones of white and Negro skeletons. *J Bone Joint Surg* 1960;42:50-8.
 44. Kleerekoper M, Nelson DA, Peterson EL, et al. Body composition and gonadal steroids in older white and black women. *J Clin Endocrinol Metab* 1994;79:775-9.
 45. Dowling HJ, Pi-Sunyer FX. Race-dependent health risks of upper body obesity. *Diabetes* 1993;42:537-43.
 46. Deurenberg P, Van der Kooy K, Hulshof T, et al. Body mass index as a measure of body fatness in the elderly. *Eur J Clin Nutr* 1989;43:231-6.
 47. Womersley J, Durnin JVGA. A comparison of the skinfold method with extent of "overweight" and various weight-height relationships in the assessment of obesity. *Br J Nutr* 1977;38:271-84.
 48. Norgan NG, Ferro-Luzzi A. Weight-height indices as estimators of fatness in men. *Hum Nutr Clin Nutr* 1982;36:363-72.
 49. Heitman BL. Evaluation of body fat estimated from body mass index, skinfolds and impedance: a comparative study. *Eur J Clin Nutr* 1990;44:831-7.