Original Research Communications

Predicting body composition by densitometry from simple anthropometric measurements[1,2]

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ABSTRACT New equations have been developed to predict body fat (percent BF) calculated from body density measured by underwater weighing from simple anthropometric measurements, using stepwise-multiple-regression analysis in 63 men and 84 women. Log_{10} sum of four skinfold thicknesses explained 80.1% (SE = 3.8) of variance of percent BF in men and 76.4% (SE = 4.6) in women. Alternative equations using limb lengths instead of height may be valuable for epidemiologic and clinical work, with particular advantages for the chair- or bed bound, for whom no previous predictive equations existed. Five equations combining triceps-skinfold thicknesses with other anthropometric measurements explained > 80% (men) and 77% (women) of variance. The most powerful prediction was from waist circumference and triceps-skinfold thickness, which explained 86.6% (SE = 3.2) of variance of percent BF in men and 79.0% (SE = 4.0) in women. Percent BF for men = 0.353 waist (cm) + 0.756 triceps (mm) + 0.235 age (y) − 26.4; for women = 0.232 waist (cm) + 0.657 triceps (mm) + 0.215 age (y) − 5.5. The equations were tested in a separately studied validation sample of 146 men and 238 women aged 18–83 y. Skinfold-thickness measurements continued to give good predictions of mean body density, but with significant bias at extremes of body fat and age. The most robust prediction with the least bias was from waist circumference adjusted for age. Percent BF for men = 0.567 waist (cm) + 0.101 age (y) − 31.8; and for women = 0.439 waist (cm) + 0.221 age (y) − 9.4. *Am J Clin Nutr* 1996;63:4–14.

KEY WORDS Body composition, fat, anthropometry, body mass index, fat distribution

INTRODUCTION

Many techniques have been developed to assess body composition in humans. Direct measurement by chemical analysis, either by macroscopic dissection or by lipid extraction is of limited value because it cannot be done in vivo. The conventional standard is underwater weighing (UWW) for a two-compartment model, which measures body density from which fat and lean mass content are estimated by assuming standard figures for density of these components (1). Other robust methods include the total-body potassium method, measuring intracellular fluid by detecting the natural radioactive ^{40}K isotope (2), and measurement of total body water by dilution of a deuterium-labeled water dose (3). The principles for these techniques are described in detail by Brodie (4), Garrow (5), Gibson (6), and Shephard (7). More complicated multicompartment models of body composition that include bone mass are under development.

For routine clinical and epidemiologic use, simpler and cheaper anthropometric measurements have been used to predict body composition in relation to body density by UWW. Various combinations of anthropometric measurements have been used as independent variables. Shephard (7) reviewed the extensive literature and found few truly practical anthropometric approaches to predict body density or fat content. The most widely used method, that of Durnin and Womersley (8), used the log sum of four skinfold thicknesses to develop regression equations for males and females of different age groups. Jackson and Pollock (9) and Jackson et al (10) used the sum of three or seven skinfold thicknesses in combination with waist and forearm circumferences or gluteal circumference and age for generalized regression equations. These approaches have not been subjected to systematic validation in separate samples or populations. Recently, Deurenberg et al (11) suggested that body mass index (BMI) with age and sex can predict body density with an accuracy similar to that of skinfold-thickness methods in a large sample of the Dutch population. McNeill et al (12) observed the skinfold-thickness method to be as good as bioelectrical impedance and body water dilution, and better than ^{40}K-counting methods in relation to UWW in lean and overweight groups of women. Reilly et al (13) found the skinfold-thickness method to underestimate body fat in a small sample (n = 16) of 65–79-y-old women.

The present study was designed to develop regression equations from different combinations of simple anthropometric measurements, age, and sex to obtain the best equations to predict body density from UWW. Recognizing possible errors from the influence of fat distribution on the prediction of body composition (14) from the conventional skinfold-thickness method of Durnin and Womersley (8), we included waist and hip circumferential measurements because waist (15–19) or waist-hip ratio (15, 16) have been found to correlate with the ratio of visceral to subcutaneous fat. Alternative methods were considered for very obese subjects [ie, BMI (in kg/m^2) > 37]

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whose skinfold thicknesses exceed the size of the calipers, and arm span and lower-leg length were considered for subjects whose height cannot be measured. The equations developed were then tested in a validation study using a large data set obtained in a different population.

METHODS

1. Determination study (Glasgow)

Subjects and recruitment

Ethical approval was obtained from Glasgow Royal Infirmary's Ethical Committee. Healthy adult white volunteers (63 men and 84 women) were recruited from the greater Glasgow area by local advertisement. Volunteers with known diabetes were not included. Physical characteristics of subjects are shown in **Table 1**. Subjects were recruited to provide an even distribution by age (**Figure 1**), but were not selected for any other criteria.

Measurements of subjects were made in the morning after overnight fasting, with an empty bladder, and wearing a swimsuit. All measurements were made by the same investigator in every subject; thus, n = 147, or 63 men and 84 women in all analyses.

Densitometry by underwater weighing

A metal chair was suspended in a hydrotherapy pool, attached to a strain gauge (Mecmesin Ltd, Horsham, United Kingdom) with a 20-kg range and sensitivity to 0.01 kg. Subjects sat in the chair with water up to their necks, held the arm rests of the chair and put their feet on a bar attached to the chair. Their noses were sealed by a nose clip. In full expiration, subjects gently lowered their heads under water. Weight was recorded by using a pen recorder that was calibrated with known weights.

Residual lung volume

The residual lung volume was measured simultaneously with UWW by the three-breath-nitrogen technique modified from

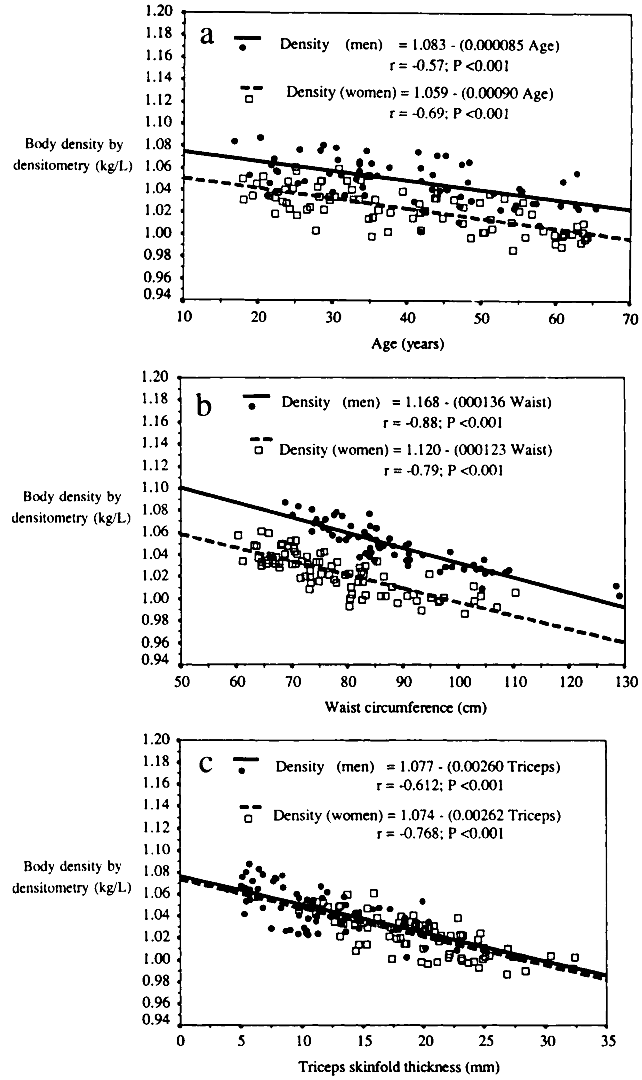

FIGURE 1. Relations between body density by underwater weighing and age (a), waist circumference (b), and triceps-skinfold thickness (c) in 63 males and 84 females in the determination study.

TABLE 1
Characteristics of men and women in the determination study[1]

	Men (n = 63)	Women (n = 84)
Age (y)	40.1 ± 13.1 (16.8–65.4)	39.9 ± 14.1 (18.0–64.3)
Height (m)	1.75 ± 0.06 (1.61–1.87)	1.62 ± 0.06 (1.43–1.78)
Weight (kg)	76.5 ± 13.1 (58.8–128.4	65.4 ± 11.9 (46.1–97.3)
BMI (kg/m^2)	24.9 ± 4.3 (18.9–41.2)	24.9 ± 4.3 (18.3–37.7)
Waist circumference (cm)	88.1 ± 12.5 (68.7–129.1)	78.3 ± 11.8 (60.4–116.1)
Hip circumference (cm)	98.0 ± 6.8 (87.6–125.5)	101.2 ± 9.3 (83.8–133.0)
Thigh circumference (cm)	55.3 ± 5.1 (45.8–70.2)	56.6 ± 4.6 (49.2–69.9)
MUAC (cm)	31.3 ± 3.1 (25.9–41.4)	29.5 ± 3.8 (23.4–43.8)
Waist-hip ratio	0.90 ± 0.08 (0.77–1.11)	0.77 ± 0.08 (0.62–0.99)
Lower leg length (cm)	53.6 ± 2.2 (48.3–57.9)	49.6 ± 2.9 (40.4–57.6)
Arm span (m)	1.76 ± 0.07 (1.60–1.90)	1.61 ± 0.08 (1.40–1.78)
Triceps-skinfold thickness (mm)	10.9 ± 4.6 (3.9–22.7)	19.1 ± 5.4 (6.1–32.4)
Σ_4Skinfolds (mm)	51.2 ± 25.7 (19.7–161.9)	63.2 ± 24.2 (23.4–126.1)
Body density (kg/L)	1.049 ± 1.003 (1.003–1.087)	1.024 ± 0.020 (0.987–1.061)
Percent body fat (% of body wt)	22.3 ± 8.9 (5.2–43.7)	33.75 ± 8.7 (16.4–51.7)

[1] $\bar{x}$ ± SD; range in parentheses. MUAC, midupper arm circumference; $\Sigma_4$skinfolds, sum of biceps-, triceps-, subscapular-, and suprailiac skinfold thicknesses.

TABLE 2
Correlation coefficients between body density and anthropometric measurements[1]

	Men (n = 63)	Women (n = 84)
Age	−0.572[2]	−0.687[2]
Height	0.104	0.182
Weight	−0.713[2]	−0.691[2]
BMI	−0.755[2]	−0.781[2]
Waist circumference	−0.878[2]	−0.790[2]
Hip circumference	−0.707[2]	−0.713[2]
Thigh circumference	−0.531[2]	−0.575[2]
MUAC	−0.586[2]	−0.790[2]
Waist-hip ratio	−0.841[2]	−0.536[2]
Waist-thigh ratio	−0.714[2]	−0.570[2]
Hip-thigh ratio	−0.015	−0.328
Lower leg length	−0.009	−0.011
Arm span	0.323[3]	−0.065
MLR	−0.745[2]	−0.727[2]
MAR	−0.768[2]	−0.747[2]
Biceps-skinfold thickness	−0.730[2]	−0.695[2]
Triceps-skinfold thickness	−0.612[2]	−0.768[2]
Subscapular-skinfold thickness	−0.678[2]	−0.661[2]
Suprailiac-skinfold thickness	−0.763[2]	−0.694[2]
Σ_4Skinfolds	−0.772[2]	−0.763[2]
$\text{Log}_{10}\Sigma_4$skinfolds	−0.809[2]	−0.781[2]

[1] MUAC, midupper arm circumference; MLR, ratio of body mass to lower leg length; MAR, ratio of body mass to armspan; $\Sigma_4$skinfolds, sum of biceps-, triceps-, subscapular-, and suprailiac skinfold thicknesses.
[2] $P < 0.001$.
[3] $P < 0.05$.

Womersley (20). Four 6-L anaesthetic bags (Ohmeda PLC, Hatfield, United Kingdom) were filled with a known volume of 100% oxygen measured with a dry rolling seal spirometer (PK Morgan, Kent, United Kingdom), ≈3 L for women and 4 L for men (21). On raising their heads from under water, a 35-mL mouthpiece connected to an anaesthetic bag was inserted into the subject's mouth. Subjects then breathed in and out deeply three times. After the last complete expiration, the bag was sealed and the gas mix obtained was immediately analyzed for oxygen (Polarographic, PK Morgan, Kent, United Kingdom) and carbon dioxide (Infra-red, PK Morgan) content. Nitrogen content of the gas mix was calculated from differences in oxygen and carbon dioxide. Residual lung volume was calculated as:

$$RV = F \times \frac{N \times (V + 0.035L)}{80\% - N\%}, \qquad (1)$$

where V is the initial volume of 100% oxygen in the gas bag, 0.035 L is the volume of the dead space in the mouthpiece, with the nitrogen content of alveolar air before the test assumed to be 80%. A correction factor (F) was included for standard temperature and pressure in dry condition (STPD):

$$F = \frac{273 + T_b}{273 + T_g} \times \frac{P_{atm} - P_s}{P_{atm} - P_A}, \qquad (2)$$

where T_b and T_g are the temperature of the body (37 °C) and gas in the spirometer, respectively; P_{atm} is atmospheric pressure, P_A and P_s are saturated vapor pressure of water in the lungs (assumed to be 47.1 mm Hg) and spirometer (assumed to be 18.63 mm Hg), respectively (20).

Subjects were allowed to practice the techniques for holding their breath, bending down and up, and breathing into the mouthpiece adequately outside the pool. They also practiced in the water to familiarize themselves with the environment. Fi-

TABLE 3
Explained variance (R^2) and SEE for predictions of body density and percentage body fat by regression equations from Tables 4 and 5 and by selected published equations[1]

Equation	Men (n = 63)			Women (n = 84)		
	R^2	SEE	SEE	R^2	SEE	SEE
	%	*kg/L*	*% of body wt*	*%*	*kg/L*	*% of body wt*
1. WC	77.8	0.0092	4.1	70.4	0.0100	4.7
2. Triceps	76.9	0.0094	4.3	75.1	0.0092	4.3
3. BMI	67.0	0.0113	5.0	74.5	0.0093	4.4
4. WC + triceps	86.6	0.0072	3.2	79.0	0.0085	4.0
5. BMI + triceps	84.5	0.0077	3.4	80.2	0.0082	3.9
6. $\text{Log}_{10}\Sigma_4$skinfolds	80.1	0.0088	4.0	76.4	0.0090	4.2
7. MAR	69.1	0.0109	4.9	73.0	0.0096	4.5
8. MLR	67.7	0.0111	5.0	72.2	0.0097	4.6
9. MUAC	57.3	0.0128	5.8	73.3	0.0095	4.5
10. MAR + triceps	84.4	0.0077	3.4	79.7	0.0083	3.9
11. MLR + triceps	83.5	0.0078	3.4	79.3	0.0084	4.0
12. MUAC + triceps	80.7	0.0084	3.8	77.0	0.0088	4.2
$\text{Log}_{10}\Sigma_4$skinfolds (D and W)[2]	81.0[3]	0.0084	3.8	81.0[3]	0.0102	4.6
$\text{Log}_{10}\Sigma_7$skinfolds + WC + FC (J and P)[2]	84.1	0.0073	3.2	—	—	—
$\text{Log}_{10}\Sigma_7$skinfolds + GC (J et al)[2]	—	—	—	75.2	0.0079	3.6

[1] $P < 0.001$ for all equations. $\Sigma_4$skinfolds, sum of biceps-, triceps-, subscapular-, and suprailiac skinfold thicknesses; MAR, ratio of body mass to arm span; MLR, ratio of body mass to lower leg length; MUAC, midupper arm circumference. WC, FC, and GC are waist, forearm, and gluteal circumferences, respectively.
[2] Figures obtained from other published equations are shown for comparison. D and W, reference 8; J and P, reference 9; J et al, reference 10.
[3] Highest value quoted.

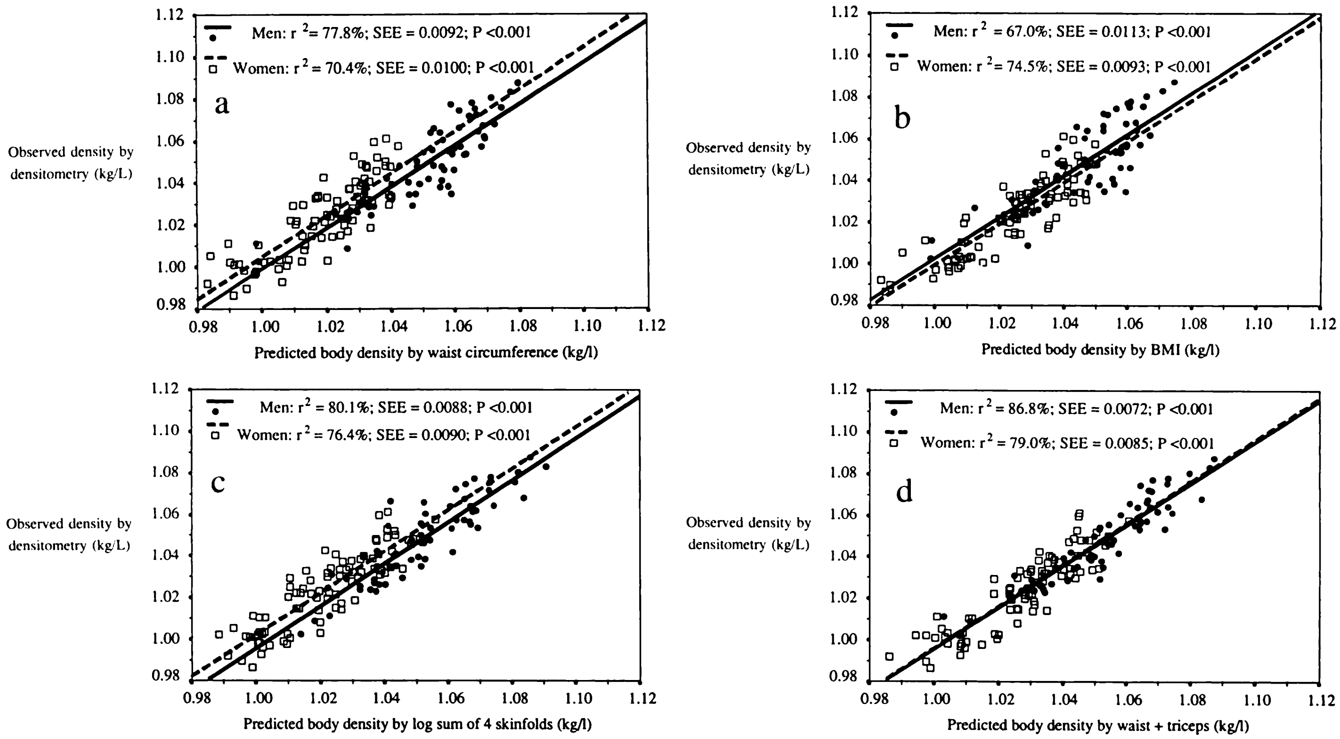

FIGURE 2. Relation between observed body density by underwater weighing and predicted body density by waist circumference (a), body mass index (b), log sum of four-skinfold thicknesses (c), and waist + triceps-skinfold thickness (d), adjusted for age, in 63 males and 84 females in the determination study.

nally, measurements were made after allowing the water to become absolutely calm. The temperature of the pool was kept at exactly 36.5 °C throughout the studies.

Anthropometry

Height was measured with the subject standing, back to a stadiometer, in bare feet. The head was adjusted so that the Frankfurt plane (the line from the auditory meatus to the lower border of the eye orbit) was horizontal. Feet were kept parallel with the heels together. The subject was encouraged to stretch upwards by applying gentle pressure at the mastoid processes (6). The moving arm of the stadiometer was lowered to touch the top of the head and height was measured to the nearest 1.0 mm.

Arm span was measured as the distance between the tips of the longest fingers in each hand, with arms stretched horizontally while in standing position and with the back against a wall. Lower leg length was taken from the mean of the two legs. The subject sat in a chair, with bare feet and lower legs vertical and parallel. Lower leg length was measured as the distance between the floor and the top of the patella.

Weight was measured to the nearest 0.05 kg with a beam balance, which was calibrated daily by using 10, 8-kg test weights. Waist, hip, thigh, and mid-upper arm circumferences (MUAC) and skinfold thicknesses were made with subjects standing, with intended sites marked on the skin, except for the hip and thigh circumferences. A flexible steel tape was used (Holtain Ltd, Crymych, United Kingdom). All measurements were made twice and the mean was used in regression equations. Waist circumference was measured midway between the lateral lower ribs and iliac crests (22). Subjects were asked not to tuck their stomachs in, and the measurement was taken in gentle expiration. Their clothes were loosened around the waist area. Hip circumference was taken at the widest part over the trochanters. Feet were kept 25–30 cm apart (22). Thigh circumference was measured for both legs 2 cm below the gluteal fold, with the weight on the nonmeasured leg, ie, the leg being measured relaxed. The average of the two legs was used in regression equations.

MUAC was measured on the right arm at the midpoint between the tip of the acromion and the tip of olecranon, elbow bent at 90°. Four skinfold thicknesses were measured according to the protocol described by Durnin and Womersley (8). All measurements were made on the right side of the body with calipers (Holtain Ltd). Biceps- and triceps-skinfold thicknesses were taken at the midpoint (*see* MUAC) of the upper arm. Subscapular-skinfold thickness was measured with the subject's shoulders relaxed. The measurement of suprailiac skinfold thickness was taken with the subject breathing gently. In some obese subjects whose skinfold thicknesses exceeded the range of the calipers (50 mm), an estimate was made with a ruler.

Statistics

Data were analyzed by using the MINITAB statistical program (Clecom, Birmingham, United Kingdom). Linear-regression equations were developed by using stepwise-multiple-regression analysis. Body density by UWW was used as the dependent (response) variable, and anthropometric measurements and age were used as independent (explanatory) variables for men and women separately.

TABLE 4
Regression equations predicting *a*) body density (BD) and *b*) the equivalent percentage body fat (BF%) in men[1]

Equation 1, waist circumference
a) BD = 1.1674 − (0.00125 × waist) − (0.000231 × age)
b) BF% = (0.567 × waist) + (0.101 × age) − 31.8
Equation 2, triceps-skinfold thickness
a) BD = 1.1181 − (0.00289 × triceps) − (0.000953 × age)
b) BF% = (1.31 × triceps) + (0.430 × age) − 9.16
Equation 3, BMI
a) BD = 1.1419 − (0.00290 × BMI) − (0.000527 × age)
b) BF% = (1.33 × BMI) + (0.236 × age) − 20.2
Equation 4, waist circumference and triceps-skinfold thickness
a) BD = 1.1554 − (0.000761 × waist) − (0.00170 × triceps) − (0.000532 × age)
b) BF% = (0.353 × waist) + (0.756 × triceps) + (0.235 × age) − 26.4
Equation 5, BMI and triceps-skinfold thickness
a) BD = 1.1414 − (0.00160 × BMI) − (0.00213 × triceps) − (0.000747 × age)
b) BF% = (0.742 × BMI) + (0.950 × triceps) + (0.335 × age) − 20.0
Equation 6, $\log_{10}$ sum of four skinfold thicknesses
a) BD = 1.1862 − (0.0684 × $\log_{10}\Sigma_4$skinfolds) − (0.000601 × age)
b) BF% = (30.9 × $\log_{10}\Sigma_4$skinfolds) + (0.271 × age) − 39.9
Equation 7, Ratio of body mass to arm span (MAR)
a) BD = 1.1425 − (0.167 × MAR) − (0.000529 × age)
b) BF% = (76.7 × MAR) + (0.237 × age) − 20.4
Equation 8, Ratio of body mass to lower leg length (MLR)
a) BD = 1.1471 − (0.0530 × MLR) − (0.000571 × age)
b) BF% = (24.2 × MLR) + (0.256 × age) − 22.6
equation 9, midupper arm circumference (MUAC)
a) BD = 1.1828 − (0.00333 × MUAC) − (0.000745 × age)
b) BF% = (1.52 × MUAC) + (0.336 × age) − 38.7
Equation 10, MAR and triceps-skinfold thickness
a) BD = 1.1407 − (0.092 × MAR) − (0.00205 × triceps) − (0.000746 × age)
b) BF% = (42.6 × MAR) + (0.917 × triceps) + (0.334 × age) − 19.6
Equation 11, MLR and triceps-skinfold thickness
a) BD = 1.1423 − (0.0280 × MLR) − (0.00209 × triceps) − (0.000777 × age)
b) BF% = (13.0 × MLR) + (0.933 × triceps) + (0.348 × age) − 20.4
Equation 12, MUAC and triceps-skinfold thickness
a) BD = 1.1613 − (0.00165 × MUAC) − (0.00238 × triceps) − (0.000882 × age)
b) BF% = (0.757 × MUAC) + (1.07 triceps) + (0.398 × age) − 29.0

[1] Units of measurements: waist circumference (cm); skinfolds (mm); BMI (kg/m^2); age (y); MUAC (cm); MAR and MLR (kg/cm). R^2 and SEE values are given in Table 3.

TABLE 5
Regression equations predicting *a*) body density (BD) and *b*) the equivalent percentage body fat (BF%) in women[1]

Equation 1, waist circumference
a) BD = 1.1145 − (0.000924 × waist) − (0.000465 × age)
b) BF% = (0.439 × waist) + (0.221 × age) − 9.4
Equation 2, triceps-skinfold thickness
a) BD = 1.0851 − (0.00200 × triceps) − (0.000586 × age)
b) BF% = (0.944 × triceps) + (0.279 × age) + 4.6
Equation 3, BMI
a) BD = 1.1088 − (0.00254 × BMI) − (0.000551 × age)
b) BF% = (1.21 × BMI) + (0.262 × age) − 6.7
Equation 4, waist circumference and triceps-skinfold thickness
a) BD = 1.1062 − (0.000482 × waist) − (0.00140 × triceps) − (0.000453 × age)
b) BF% = (0.232 × waist) + (0.657 × triceps) + (0.215 × age) − 5.5
Equation 5, BMI and triceps-skinfold thickness
a) BD = 1.1039 − (0.00148 × BMI) − (0.00122 × triceps) − (0.000505 × age)
b) BF% = (0.730 × BMI) + (0.548 × triceps) + (0.270 × age) − 5.9
Equation 6, $\log_{10}$ sum of four skinfold thicknesses
a) BD = 1.1622 − (0.0654 × $\log_{10}\Sigma_4$skinfolds) − (0.000574 × age)
b) BF% = (30.8 × $\log_{10}\Sigma_4$skinfolds) + (0.274 × age) − 31.7
Equation 7, Ratio of body mass to arm span (MAR)
a) BD = 1.1108 − (0.155 × MAR) − (0.000603 × age)
b) BF% = (73.6 × MAR) + (0.287 × age) − 7.6
Equation 7, Ratio of body mass to lower leg length (MLR)
a) BD = 1.1101 − (0.0466 × MLR) − (0.000630 × age)
b) BF% = (22.0 × MLR) + (0.300 × age) − 7.2
Equation 9, midupper arm circumference (MUAC)
a) BD = 1.1299 − (0.00291 × MUAC) − (0.000512 × age)
b) BF% = (1.38 × MUAC) + (0.243 × age) − 16.7
Equation 10, MAR and triceps-skinfold thickness
a) BD = 1.1047 − (0.0867 × MAR) − (0.00129 × triceps) − (0.000532 × age)
b) BF% = (41.3 × MAR) + (0.607 × triceps) + 0.253 × age) − 4.7
Equation 11, MLR and triceps-skinfold thickness
a) BD = 1.1040 − (0.0252 × MLR) − (0.00133 × triceps) − (0.000546 × age)
b) BF% = (12.0 × MLR) + 0.626 × (triceps + 0.260 × age) − 4.3
Equation 12, MUAC and triceps-skinfold thickness
a) BD = 1.1091 − (0.00139 × MUAC) − (0.00126 × triceps) − (0.000518 × age)
b) BF% = (0.676 × MUAC) + (0.582 × triceps) + (0.246 × age) − 7.1

[1] Units of measurements: waist circumference (cm); skinfolds (mm); BMI (kg/m^2); age (y); MUAC (cm); MAR and MLR (kg/cm). R^2 and SEE values are given in Table 3.

Measurements of UWW and residual lung volume were made three times for each subject, twice for body circumferences, and the mean taken. The experiment was repeated if the CV for the repeated measurements was > 1%. The SD of repeated measurements on the same subject was calculated by the equation given by Bland (23):

$$SD = \sqrt{\tfrac{1}{2}n \times \sum(x_i - y_i)^2}, \qquad (3)$$

where x_i and y_i are pairs of measurements for $i = 1$ to n. The CV was calculated as SD/overall mean.

2. Validation study (Wageningen)

Data were made available from earlier studies by Deurenberg et al (11) from 146 men and 238 women, including body density measured by UWW with residual volume estimated by simultaneous helium dilution; waist and hip circumferences; biceps-, triceps-, subscapular-, and suprailiac-skinfold thicknesses; weight; height; age; and sex. Anthropometric measurements used the same protocols as in the present study except

TABLE 6
Characteristics of 146 men and 238 women from the independent validation (Wageningen) sample

	Men	Women
Age (y)	45.9 ± 17.4 (18.0–82.0)	36.9 ± 17.5 (20.0–83.0)
Height (cm)	179.9 ± 7.7 (151.3–202.0)	167.7 ± 7.0 (150.7–185.9)
Weight (kg)	81.1 ± 11.7 (54.4–120.8)	67.8 ± 12.9 (43.7–109.6)
BMI (kg/m^2)	25.1 ± 3.4 (19.2–34.8)	24.2 ± 4.7 (17.4–40.9)
Waist circumference (cm)	93.3 ± 10.8 (70.5–115.0)	82.62 ± 12.0 (62.0–113.0)
Hip circumference (cm)	100.3 ± 6.1 (87.5–123.0)	101.3 ± 9.01 (85.0–138.0)
Waist-hip ratio	0.93 ± 0.07 (0.73–1.13)	0.81 ± 0.07 (0.68–1.04)
Triceps-skinfold thickness (mm)	13.6 ± 6.0 (4.0–35.5)	20.0 ± 7.7 (7.0–44.0)
Σ_4Skinfolds(mm)	57.8 ± 25.5 (18.8–152.7)	69.2 ± 30.5 (22.8–155.6)
Body density (kg/L)	1.034 ± 0.02 (1.008–1.079)	1.023 ± 0.02 (0.984–1.062)
Percentage body fat (% of body wt)	26.7 ± 7.7 (8.9–41.0)	34.1 ± 8.8 (16.3–53.1)

[1] $\bar{x}$ ± SD; range in parentheses. Σ_4Skinfolds, sum of triceps-, biceps-, subscapular-, and suprailiac-skinfold thicknesses.

that skinfold-thickness measurements were made on the left. This sample was used as an independent population to test the validity of the equations derived from the Glasgow determination study. Measurements of arm span, lower leg length, and MUAC were not available in the validation sample. Skinfold-thickness measurements were available in 143 men and 236 women.

Statistics

The Bland and Altman analysis (24) was used to assess the mean and 95% CIs of errors of body fat prediction as the difference in percent body fat estimated by regression equations from percent body fat measured by the reference UWW method.

TABLE 7
Mean percentage body fat predicted by equations derived from the determination study and by underwater weighing and their correlations, mean difference, and SEs and SDs of the difference in 146 men and 238 women from the validation study[1]

	Percentage body fat			Difference (Pre-UWW)		
	Pre	UWW	r	$\bar{x}$	SE	SD
Men						
Waist	25.71	26.65	0.839	−0.92[2]	0.35	4.20
Triceps	28.33	26.65	0.823	1.67[2]	0.55	6.64
BMI	24.01	26.65	0.843	−2.65[3]	0.34	4.13
BMI + triceps	26.87	26.65	0.850	0.22	0.46	5.55
Waist + triceps	27.55	26.65	0.861	0.89[4]	0.41	4.93
Log$_{10}\Sigma_4$skinfolds	25.88	26.65	0.867	−0.61	0.33	3.98
Log$_{10}\Sigma_4$skinfolds (D and W)	24.47	26.65	0.843	−2.01[3]	0.35	4.14
Women						
Waist	35.03	34.06	0.868	0.97[2]	0.28	4.38
Triceps	33.80	34.06	0.862	−0.26	0.33	5.12
BMI	32.19	34.06	0.879	−1.87[3]	0.28	4.28
BMI + triceps	32.67	34.06	0.883	−1.39[3]	0.31	4.77
Waist + triceps	34.76	34.06	0.883	0.70[4]	0.29	4.54
Log$_{10}\Sigma_4$skinfolds	33.88	34.06	0.882	−0.07	0.27	4.20
Log$_{10}\Sigma_4$skinfolds (D and W)	32.32	34.06	0.860	−1.63[3]	0.29	4.51

[1] Pre, predicted body fat from anthropometric equations derived from the determination study; UWW, underwater weighing. D and W, Durnin and Womersley equations (8).

[2,3,4] Significant difference between UWW method and predicted values (paired t test): [2] $P < 0.01$, [3] $P < 0.001$, [4] $P < 0.05$.

RESULTS

1. Determination study

Details of subjects and the anthropometric data are given as mean ± SD in Table 1. Sixty-three males aged 17–65 y and 84 females aged 18–64 y were studied under standard fasting conditions, with even distributions over wide ranges of weight, BMI, waist circumference, waist-hip ratio, skinfold thicknesses and body density. The mean height, weight, and BMI were similar to average figures for the British adult population (25).

Diurnal variations were studied for certain measurements made in the morning fasting and then in late afternoon for weight in 15 men, with mean age 25 y (range: 20–46 y) and 35 women, with mean age 25 y (range: 21–35 y) and height of 65 men, mean age 42.3 y (range: 16.8–65.4 y) and 69 women, mean age 43.1 y (range: 22.3–70.7 y). On average, there was a significant increase in body weight, + 0.26 (95% CI: 0.16, 0.35 kg, $P < 0.05$) and a decrease in height, mean −0.8 (95% CI: −1.0, −0.6 cm, $P < 0.001$) in the afternoon compared with the morning. These effects are compounded in estimates of BMI so on average, BMI (weight/height^2) would increase by 0.3 kg/m^2 (1.2%) during the day. The CVs for repeated measurements of

TABLE 8
Slopes of the difference between percentage body fat predicted by derived equations (adjusted for age) and body fat measured by underwater weighing, plotted against body fat measured by underwater weighing in 146 men and 238 women

	Men			Women		
	Slope	r	P	Slope	r	P
Waist	−0.787	−0.432	<0.001	−0.933	−0.464	<0.001
Triceps	0.288	0.249	0.002	−0.042	−0.024	0.710
BMI	−0.957	−0.515	<0.001	−0.651	−0.316	<0.001
BMI + triceps	0.277	0.200	0.015	0.056	0.030	0.642
Waist + triceps	0.191	0.123	0.134	−0.133	−0.069	0.292
Log$_{10}\Sigma_4$skinfolds	−0.446	−0.232	0.005	−0.616	−0.296	<0.001
Log$_{10}\Sigma_4$skinfolds (D and W)[1]	−0.859	−0.464	<0.001	−1.212	−0.624	<0.001

[1] D and W, Durnin and Womersley equations (8).

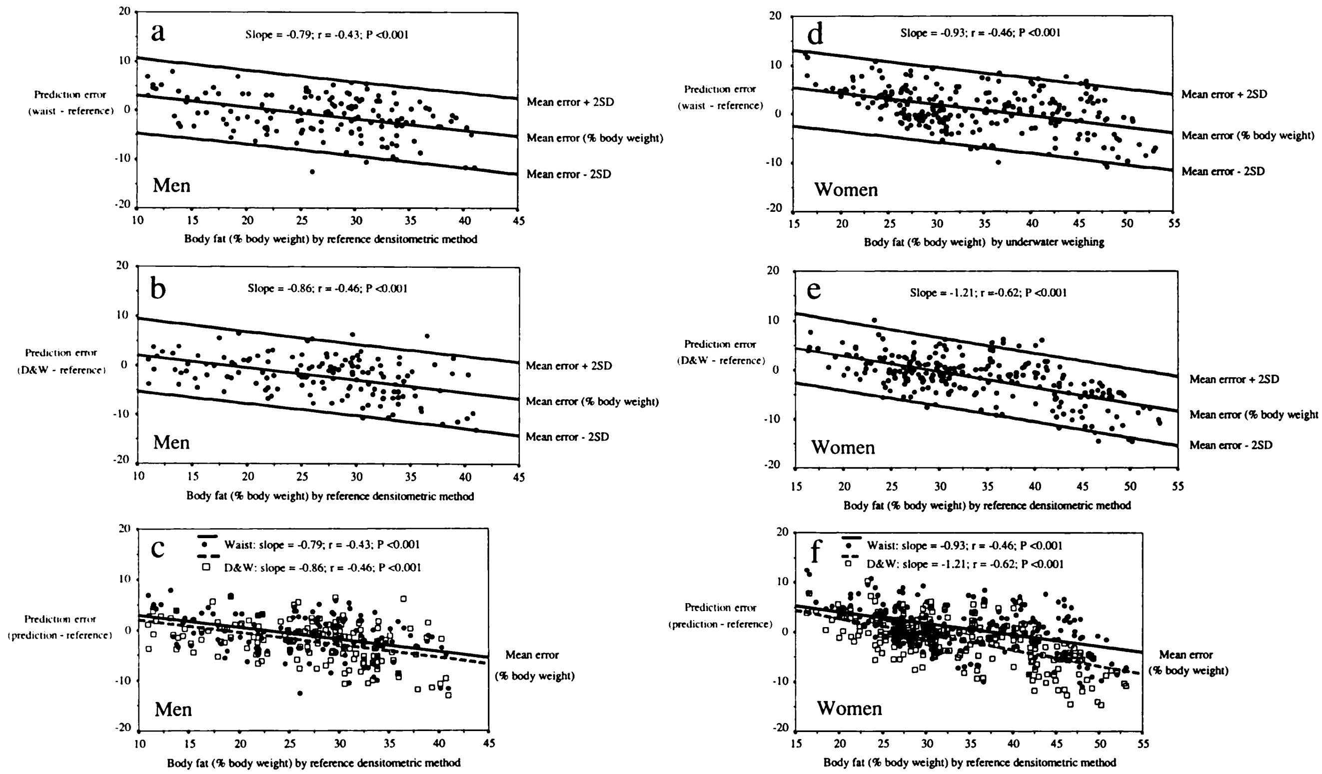

FIGURE 3. Plots of prediction errors of body fat (predicted − reference densitometric method) by waist circumference in 146 men (a) and in 238 women (d), and by the Durnin and Womersley (D&W) skinfold equations in men (b) and in women (e) against body fat measured by densitometry in the Wageningen validation sample. The errors of the two predictive methods are plotted against body fat by densitometry for comparison in men (c) and women (f).

UWW, and waist and hip circumferences were 0.16%, 0.44%, and 0.20%, respectively.

Figure 1a shows the age distribution, separately for men and women, in relation to body density. In general, body density decreased with increasing age. Females had consistently lower body density than males at a given age.

A plot between body density and waist circumference (Figure 1b) demonstrates an almost linear relation (men: $r = -0.88$ and women: $r = -0.79$). Both men and women showed approximately the same gradient, with a lower intercept in females. For a given waist circumference, the women tended to be less dense (fatter) than men, reflecting the greater central (visceral) fat deposition in men. Waist-hip ratio gave good prediction in men, but was no better than waist circumference alone.

A plot between body density and triceps-skinfold thickness (Figure 1c) shows the regression lines for males and females almost shared an identical intercept and slope, suggesting that triceps-skinfold thickness reflects proportionally the same amount of fat for the two sexes. Men tended to be leaner with smaller triceps-skinfold thicknesses (10.9 ± 4.6 mm) than women (19.1 ± 5.4 mm).

Linear regression: single variables

Table 2 shows the 17 significant ($P < 0.001$) correlations between body density and single anthropometric variables for men and women. Body density correlated most closely with waist circumference in both sexes ($r = -0.878$ in men and -0.790 in women). Thigh circumference correlated only moderately with body density, and was slightly higher in women ($r = -0.575$) than in men ($r = -0.531$). Correlation coefficients between body density and individual skinfold thicknesses ranged from -0.612 to -0.763 in men and from -0.661 to -0.768 in women. The sum of four skinfold thicknesses correlated with body density more closely than did single or combinations of two or three skinfold thicknesses in men ($r = -0.772$) but not in women ($r = -0.763$). A search was made for a better nonlinear relation (quadratic or logarithmic transformation) but no improvement in R^2 or SE was found, except for the relation with skinfold thicknesses. As in the study of Durnin and Womersley (8), logarithmic transformation of the sum of four skinfold thicknesses increased the correlations significantly ($P < 0.05$) with body density in both men ($r = -0.809$) and women ($r = -0.781$).

Stepwise-multiple-regression analysis

When all 20 anthropometric measurements or selected ratios (Table 2) were considered separately for each sex as possible explanatory variables, the best prediction (highest R^2) of body density for men was waist circumference + triceps-skinfold thickness + age. This equation accounted for 86.6% of variance of body density. The best prediction of body density in women was from BMI + triceps-skinfold thickness + age, explaining 80.2% of variance, but this equation was only slightly better than other simple equations, which included waist circumference + triceps-skinfold thickness + age (R^2 = 79.0%). Other anthropometric variables combined with triceps-skinfold thickness also gave good prediction of body density, explaining > 76.0% of variance (**Table 3**). Log_{10} sum of four skinfold thicknesses ($\log_{10}\Sigma_4$SF) gave a similar power of prediction of body density in the present study (men: R^2 = 80.1%;

TABLE 9
Slopes of the difference of percentage body fat prediction by derived equations (adjusted for age) and body fat measured by underwater weighing plotted against age in 146 men and 238 women[1]

	Men			Women		
	Slope	*r*	*P*	Slope	*r*	*P*
Waist	−0.226	−0.055	0.512	0.303	0.076	0.242
Triceps	1.515	0.579	<0.001	1.034	0.303	<0.001
BMI	0.439	0.104	0.210	0.653	0.160	0.013
BMI + triceps	1.344	0.430	<0.001	1.180	0.322	<0.001
Waist + triceps	1.163	0.330	<0.001	0.779	0.202	0.002
$Log_{10}\Sigma_4$skinfolds	1.214	0.276	<0.001	0.726	0.174	0.007
$Log_{10}\Sigma_4$skinfolds (D and W)	−1.003	−0.237	0.004	−1.355	−0.349	<0.001

[1] D and W, Durnin and Womersley equations (8).

women: R^2 = 76.4%) to the published equations (highest R^2 value of 81%) of Durnin and Womersley (8).

Figure 2a-d show the relations between the observed body density and predicted body density from some selected anthropometric variables. **Tables 4** and **5** contain six pairs of regression equations (nos. 1–6) that were validated in the Wageningen study to predict body density and equivalent percent body fat estimated from Siri's equation (1): percent body fat = 4.95/(body density − 4.5) × 100%.

For subjects whose height could not be measured, arm span and lower leg length were considered as possible alternatives. Height correlated with arm span (men: r = 0.76 and women: r = 0.81) and lower leg length (r = 0.85 for both men and women). These variables gave prediction of body fat as good as other commonly used variables (**Table 3**). Equations 7–12 incorporating these variables could not be validated in the Wageningen validation study.

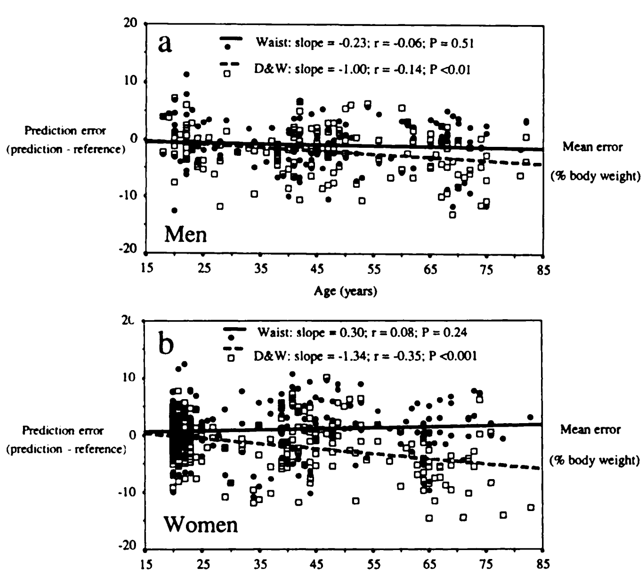

FIGURE 4. Plots of prediction errors of body fat (predicted − reference densitometric method) by waist circumference and by the Durnin and Womersley (D&W) skinfold equations in 146 men (a) and in 238 women (b) against age in the Wageningen validation sample.

2. Validation study

Subjects in the validation sample had a wider range of ages (18–83 y) than those in the determination study. Both samples had similar BMIs but the validation sample was fatter and had greater waist circumference and waist-hip ratio, indicating accumulation of abdominal fat mass associated with the older subjects in this sample (**Table 6**).

Percentage body fat was predicted by equations 1–6 derived from the determination study, and by that of Durnin and Womersley (8) for comparison. The prediction errors of each equation were calculated from the difference between predicted body fat and body fat measured by UWW.

Table 7 shows the mean body fat of the Wageningen validation sample predicted by equations derived from the Glasgow determination study correlated highly (r > 0.82; P < 0.001) with body fat by UWW. The mean difference (prediction errors) with its SE and SD for each of the derived equations and those of Durnin and Womersley (8) were similar, ranging from 4% to 5% of body weight, ie, 95% CI limits for errors of 8–10% of body weight about the mean errors. Body fat prediction from triceps-skinfold thicknesses in men gave the worst SD of 6.6% of body weight (95% CI limits of error: 13% of body weight). Although the mean errors of all equations were close to zero, almost all equations had significant positive or negative slopes for a plot of errors relative to body fat measured by the reference UWW method. This indicates systematic errors or bias in predicting body fat in individuals at extreme ends of the body fat spectrum (**Table 8**). Densitometry makes an assumption that the fat-free mass has a constant density of ≈1.1 kg/L (1); errors in the reference method may relate to the possibility that the density of the fat-free mass is lower than this in obese subjects and higher than this in very thin subjects because of different relative contribution of the organs (7).

Using waist circumference alone, adjusted for age, gave equally good prediction of body fat, with similar SEs and SDs to other equations using more than one variable or measurement, including the Durnin and Womersley equations (**Figures** 3a-f). The mean errors were close to zero in both men (−0.95% of body weight) and women (−0.93% of body weight), with a negative slope of errors almost identical to those found using Durnin and Womersley equations for men (Figure 3c). The slope was less steep for women (Figure 3f) indicating that body fat is less likely to be underestimated in fatter subjects using the waist circumference equations than those from Durnin and Womersley.

All equations containing triceps-skinfold measurement, including those from Durnin and Womersley had significant positive or negative slopes for a plot of errors in predicting body fat against age (**Table 9**). Negative slopes were observed for predicting errors with increasing age by the Durnin and Womersley (8) equations, but there was no systematic bias in percent body fat prediction with age using waist equations in both sexes (**Figures** 4a,b). The mean and 95% CIs of errors of percent body fat prediction in different age groups presented in **Table 10** shows that the skinfold-thickness method (8) gave good prediction of percent body fat in younger subjects (aged < 60 y), but underestimated percent body fat of subjects aged 60–83 y up to 15% of body weight, whereas the waist circum-

TABLE 10
Mean and 95% CIs of errors and body fat prediction by equations based on waist circumference and skinfold thicknesses from body fat measured by densitometry in different age groups of 146 men and 238 women aged 18–83 y[1]

Equation types and age groups	Men			Women		
	$\bar{x}$	95% CI	n	$\bar{x}$	95% CI	n
Waist circumference						
18–39 y	−0.5	−9.2, 8.2	48	0.6	−7.7, 8.9	138
40–59 y	−1.4	−9.0, 6.1	58	0.9	−8.7, 10.5	60
60–83 y	−0.7	−9.6, 8.2	40	0.9	−7.4, 9.3	40
Skinfold thicknesses						
18–39 y	−1.6	−8.7, 5.5	47	−0.9	−8.6, 6.7	138
40–59 y	−1.4	−9.8, 7.0	56	−0.5	−9.5, 8.5	58
60–83 y	−3.4	−12.0, 5.2	40	−5.7	−14.8, 3.4	40

[1] Skinfold-thickness measurements based on the equations of Durnin and Womersley (8).

ference equations from the present study continued to give good prediction of percent body fat in those aged 60–83 y.

DISCUSSION

The present study examined all the simple anthropometric measures currently in use in predicting body density in order to estimate percentage body fat. The number of subjects (63 men and 84 women) studied met the minimal number (n = 50) for generating prediction equations recommended by Katch (26), and allowed power of prediction at least equal to those currently used. The age distribution of subjects permits confidence over a wide range of ages. The validation sample had been studied under similarly rigorous conditions, but by other observers and in an entirely different white population.

The equations from the present study were derived from a healthy white population broadly representative of the adult UK population, including very few athletes or unusually thin individuals. Barata et al (27) recently found the equation of Jackson and Pollock (9) to be better than those of Durnin and Womersley (8) for athletes. Caution should be exercised when applying the equations to other population groups, or to subgroups with unusual physical characteristics.

Stepwise-multiple-regression analysis for the combination of single measurements found waist circumference and triceps-skinfold thickness, together with age, to provide the best prediction (highest R^2) of body density, explaining 86.6% and 79% of variance in men and women, respectively, in the population from which the equations were derived. This equation applied less well in the validation study, which probably reflects differences between observers in triceps-skinfold-thickness measurements. The prediction of body density from waist measurement alone, corrected for age (Table 3), is remarkably good (men: R^2 = 77.8%; women: R^2 = 70.4%). Age-adjusted BMI also showed good prediction of body density (men: R^2 = 67.0%; women: R^2 = 74.5%). Thus, for epidemiologic work, both waist circumference and BMI may be useful simple measurements. Several other combinations of body circumferences and skinfold thicknesses (biceps, triceps, subscapular, and suprailiac) also gave good correlation with body density, but no better than the combination of waist circumference and triceps-skinfold thickness. Age and triceps-skinfold thickness combined with BMI, the ratio of body mass to arm span, or the ratio of body mass to lower leg length gave similar prediction power for body density in both sexes. The classical equation of Durnin and Womersley (8) using $\log_{10}\Sigma_4$SF still gives a useful prediction, but BMI (with age and sex corrections) also demonstrated high predictive value (R^2 = 80.0%; not shown in tables) for body density, confirming previous observations from Deurenberg et al (11). Equations with BMI + triceps-skinfolds thickness gave better predictions of body density (men: R^2 = 84.5%; women: R^2 = 80.2%) than did $\log_{10}\Sigma_4$SF. The best four equations obtained from stepwise-multiple-regression analysis in the Glasgow determination study, which all included triceps skinfold-thickness measurements and either waist circumference or body mass, were significantly more powerful ($P < 0.05$) than $\log_{10}\Sigma_4$SF prediction equations in the population used to derive them (Table 3, equations 4, 5, 10, and 11).

A major advantage of waist circumference and triceps-skinfold methods lies in their practical use (Tables 4 and 5). The four-skinfold method requires a little practice to be reproducible, and may present some difficulties when subjects are clothed, or when skinfold thickness exceeds 50 mm (the limit of the calipers).

The equations based on waist circumference + triceps-skinfold thickness offer another advantage over skinfold-only methods by taking account of body fat distribution. For example, people with heart disease and with non-insulin-dependent diabetes mellitus have exaggerated central (visceral) fat distribution (28). In subjects in the highest quartile of waist-hip ratio, including subjects with diabetes, we found that equations using waist circumference are significantly better than methods based on subcutaneous-skinfold thicknesses or BMI (29). Waist circumference reflects intraabdominal fat, as distinct from the subcutaneous fat that is reflected in tricep-skinfold measurement, although both reflect total fat as well. Magnetic resonance imaging (15, 18, 19) and computed tomography studies (16, 17) showed that waist circumference correlated with fat from all sites, including intraabdominal fat (r range: 0.73–0.94; $P < 0.001$) and total body fat ($r > 0.94$; $P < 0.001$) in both men and women, although triceps-skinfold thickness correlated highly with subcutaneous fat (r range: 0.69–0.89; $P < 0.05$) and poorly with intraabdominal fat (r = 0.39; NS) in both men and women.

Equations using the simple measurement of waist circumference and age proved to be remarkably robust for body fat prediction, as good as the existing method of combining four-skinfold measurements in men and better in fatter women for whom the Durnin and Womersley equations systematically underestimate body fat. Figure 3c and f suggest some bias in predicting body fat with increasing body fatness. Measurement of residual lung volume by helium in Wageningen and nitrogen in Glasgow was the only methodologic difference, but this does not readily explain any bias. An alternative explanation for the bias could be the difference in body fat distribution in the Dutch population, possibly related to physical activity, smoking, and alcohol consumption. The equations based on waist circumference (Tables 4 and 5; equation 1) are also applicable to older subjects without the systematic underestimation of body fat shown by the four-skinfold method. This bias may indicate altered density of lean body mass with age (13), but there is little independent evidence for altered lean body mass in elderly people. Altered body fat distribution with aging is a more plausible explanation, which is taken into account by the waist circumference method.

Waist measurement is a highly practical method and its percentage measurement error is low due to its large circumference. Only a flexible tape is required, with minimal training to use bony landmarks. The only drawback would be in the very obese (BMI > 45 kg/m^2) when a large apron of abdominal fat would invalidate waist measurement. When waist circumference and skinfold measurements are not available, BMI from body mass and height could be used as an alternative method to predict body fat. The bias could be from one of the UWW protocols. The Glasgow method was tested against the earlier Durnin and Womersley tank as its replacement, showing no difference between the two methods on the same subjects. The Wageningen method is well established and has been used in many published studies (11). Because of their distance from one another, the Glasgow and Wageningen UWW methods could not be compared directly.

Alternatives to BMI were developed using the ratios of body mass to arm span in kg/cm or to lower leg length in kg/cm. These indexes were analyzed with other single anthropometric variables adjusted for age and sex. The best equations obtained were for the ratios of body mass to arm span ($R^2 = 80.0\%$) and body mass to lower leg length ($R^2 = 79.3\%$). There was no significant improvement when various powers were applied to variables. Triceps-skinfold thickness was added to these equations (separate sexes) resulting in improvement for the prediction of body density similar to other multiple-regression equations, for ratios of body mass to arm span, $R^2 = 84.4\%$ (men) and 79.9% (women) and body mass to lower leg length, $R^2 = 83.5\%$ (men) and 79.3% (women). These equations may be of value for elderly, chair-bound, and bedridden subjects, and use of lower leg length instead of height may occasionally be helpful clinically and in field work. To keep errors to a minimum in routine use, training of observers is urged, even for simple procedures.

The twelve equations for each sex group (Tables 4 and 5) use simple anthropometric measurements to predict body composition. All equations, except midupper arm circumference in men, gave acceptable accuracy and low error of prediction (Table 3), and thus can be used for clinical and epidemiologic purposes. The time, equipment, and skill required for these measurements vary. An equation using waist circumference adjusted for age, as well as giving a prediction with low error and freedom from bias with age or fatness, is also amongst the most convenient and avoids errors associated with altered fat distribution. Log sum of four skinfold thicknesses still gives very acceptable prediction of body composition, but with some underestimation in elderly subjects and in fat women, BMI can be used satisfactorily when these measures are unavailable. The most powerful prediction of body fat, from waist circumference and triceps-skinfold thickness, performed less well in a validation sample and is probably dependent on individual triceps-skinfold-thickness measurement technique. For elderly and chair-bound subjects and those with amputations, arm span or lower leg length can be used instead of height.

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