Body-composition assessment by dual-energy x-ray absorptiometry in subjects aged 4–26 y[1–3]

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ABSTRACT This cross-sectional study describes the body composition of 265 normal subjects (137 males and 128 females) aged 4–26 y determined by dual-energy x-ray absorptiometry (DXA). Lean tissue mass (LTM) and bone mineral content (BMC) increased with age in females until 13.4 and 15.7 y, respectively, and in males until 16.6 and 17.4 y, respectively. A strong relation between LTM and BMC was found for each sex ($r = 0.98$, $P = 0.0001$ for males; $r = 0.98$, $P = 0.0001$ for females). DXA percent body fat ($\%BF_{DXA}$) increased with age in females ($r = 0.52$, $P < 0.001$) but not in males and was higher in females than in males at all ages. Trunk to leg fat ratio (TLFR) was calculated as DXA trunk fat/leg fat. In post-pubertal age the TLFR was higher in males than in females (1.01 ± 0.23 and 0.75 ± 0.16, $P = 0.001$), but there was no sex difference in younger children. DXA weight underestimated scale weight by a mean of 0.83 kg. $\%BF_{DXA}$ correlated with %BF by skinfold thickness measurement with good agreement for males but overestimated %BF by skinfold thickness for females. These normative data for body composition demonstrate significant sex differences in all body compartments after the pubertal years. *Am J Clin Nutr* 1995; 61:746–53.

KEY WORDS Body composition, dual-energy x-ray absorptiometry, DXA, childhood, obesity

Introduction

Dual-energy x-ray absorptiometry (DXA) has been shown to be a precise method for assessing body composition in adults (1, 2), correlating highly with methods such as underwater weighing (3, 4), deuterium dilution (3), and total body potassium (2, 4). It provides a three-compartment model of body composition: fat, lean tissue mass (LTM), and bone mineral content (BMC). The procedure is ideal for children, being simple and exposing them to minimal radiation. However, there are few reports of its use in this group. Recently DXA was shown to compare well with chemical analysis in body-composition assessment of pigs weighing 35–95 kg (5), a weight range that overlaps those of older children and young adults. We evaluated DXA in a cross-sectional study of young normal Australian subjects. The study aimed to describe the body composition of this population by sex for the three-body compartments of fat, LTM, and BMC, and to compare the agreement of DXA results with those derived from skinfold anthropometry.

Subjects and methods

Two hundred sixty-five subjects (137 males and 128 females) aged 4–26 y were studied. The subjects were siblings of hospital outpatients, children of staff or their friends, and medical students. Children were selected if their height and weight were within 2.33 SD scores (SDS) (ie, 1st to 99th centile) of the median (*see* below) and they were healthy and without known medical disease.

Height was measured with a stadiometer to the nearest 1 mm and weight with electronic scales to the nearest 20 g. Derived values for auxological variables were calculated based on the US National Center for Health Statistics reference data (6). Height and weight SDS for age were calculated for ages 4–18 y from data derived from the study of Hamill et al (7). If the subject's age was >18 y, height SDS and weight SDS were calculated as for an 18-y old. Body mass index (BMI) was calculated as weight/height^2, where weight is expressed in kg and height in m. BMI SDS for age were calculated for ages 6–26 y ($n = 248$) from data derived from Cronk and Roche (8). The study was approved by the institutional Ethics Committee, and informed consent was obtained from all subjects and families.

A DPX (Lunar Corp, Madison, WI) total body scanner with adult software (version 3.4) was used to perform DXA measurements on all subjects. This method was previously described (1–4). Daily quality-assurance tests were performed according to the manufacturer's directions. The entire body of each subject was scanned, beginning at the top of the head and moving, in a rectilinear pattern, down the body to the feet. Subjects were all scanned in the "fast" scan mode—a scan speed of 12.5 cm/s, with a sample size of 4.8 × 9.6 mm, sample interval of 0.03 s, and source collimation of 1.68 mm.

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The total scan time is ≈10 min and the radiation dose is ≈0.2 μSv (product information from Lunar Corp).

During analysis, output is provided for the total body and four anatomical regions: trunk, arms, legs, and head plus neck. Head and neck values were determined by subtraction of all other regions from the total. The output in grams is divided into a three-compartment model: fat tissue mass, BMC, and LTM, where LTM represents the non-BMC LTM. Percent body fat by DXA ($\%BF_{DXA}$) for the total body was calculated with this formula:

$$\%\ BF_{DXA} = \text{fat mass}/(\text{fat mass} + \text{LTM} + \text{BMC})$$

In addition, trunk and leg fat were defined by using standard regional settings as previously described by Ley et al (9). The trunk region was delineated by an upper horizontal border below the chin, vertical borders lateral to the ribs, and a lower border formed by oblique lines passing through the femoral necks (9). The leg region was defined as the tissue below the oblique lines passing through the femoral necks. The oblique lines form an angle of 65° to a horizontal line drawn above the pelvis and meet at the central line of the body at approximately midthigh. The angle of the oblique lines cannot be altered in software version 3.4. The TLFR was calculated by dividing truncal fat (g) by leg fat (g).

The performance of DXA was assessed by using a total body phantom, constructed of aluminium strips and rice bags. These materials were recommended by the manufacturer because their attenuation properties are similar to those of human bone and soft tissue. The CVs from 47 scans on consecutive days on the total body phantom were 0.4% for soft tissue and 1.2% for BMC. The in vivo performance of DXA was also assessed by scanning one adult female on 6 consecutive days. The CVs were 1.59% for $\%BF_{DXA}$, 0.82% for LTM, and 0.74% for BMC. These are comparable with published data (1, 2). Ethical approval was not available to perform multiple scans on a child. Bone mineral density is reported separately (10).

Skinfold thickness was measured to the nearest 0.1 mm on the left side of the body at the triceps, biceps, subscapular, and suprailiac sites by using Holtain (London) calipers (n = 232). Midupper-arm circumference (MUAC) was also measured (n = 230). The percent body fat from skinfold anthropometry ($\%BF_{SKINFOLD}$) was calculated by using the method of Slaughter et al (11) for ages 8–26 y (n = 232). This method uses a multicomponent approach to body composition that accounts for the chemical immaturity of children (11). Upper-arm muscle area (UAMA) and upper-arm fat area (UAFA) were calculated from the MUAC according to standard formulas:

$$\text{UAMA} = [\text{MUAC} - (\text{triceps skinfold} \times \pi)]^2/(4 \times \pi)$$

$$\text{UAFA} = [(\text{MUAC})^2/(4 \times \pi)] - \text{UAMA}$$

where MUAC and triceps skinfold are in cm (12). UAMA in this formula includes bone mass, as discussed by Frisancho (12). Ethical approval for pubertal staging was not obtained. Postpubertal age was defined as ≥15 y for females and ≥17 y for males.

Statistics

Data were analyzed by using MINITAB statistical software (version 8.0; Minitab Inc, State College, PA). Pearson product-moment correlations (r) were calculated. Agreement between scale and DXA weight and between $\%BF_{DXA}$ and $\%BF_{SKINFOLD}$ were assessed by using the technique of Bland and Altman (13). Pair-wise comparisons between %BF derived by the two different methods were conducted by using paired t tests. Data are presented as mean ± SD and the significance level was set at $P < 0.05$.

STATISTICAL ANALYSIS SYSTEM (SAS) software (version 6.04; SAS Institute, Cary, NC) was used for curve-fitting procedures. Nonlinear-regression procedures by least squares (SAS) were used with segmented polynomial models to detect the inflection points of the age-dependent changes in total body BMC, total body LTM, and regional LTM. We used a segmented polynomial function of degree two with only one inflection point (I). Thus the model is expressed as

$$y = \beta_0 + \beta_1 \cdot x + \beta_2 \cdot x^2 + \beta_3 \cdot (x - I) + \beta_4 \cdot (x - I)^2$$

The position of inflection point is estimated by inspection of the data and then verified by an iterative process. The iterative process of the nonlinear-regression procedure for detection of the inflection point starts with parameters (β_0, β_1, β_2, β_3, and β_4) computed from the segmental polynomial model with the estimated inflection point. The iterative process does not stop until successive values for each of the five parameters differed by <0.01% (convergence). The association between the TLFR and age for both sexes and between $\%BF_{DXA}$ and age for females is linear ($y = a + bx$).

Results

Population characteristics

The mean ages of the males (n = 137) and females (n = 128) were similar, being 14.4 y (range 4.2–26.1 y) and 14.6 y (range 4.6–26.1 y), respectively. There were no significant differences in the mean weight SDS, height SDS, and BMI SDS between males and females, so they were analyzed as one group (**Table 1**). The anthropometric characteristics of the study population were similar to those of the population from which the SDS were derived, with the exception of the BMI SDS, which had a significantly lower mean SDS (Table 1). There was a weak inverse relationship between BMI SDS and age in males (r^2 = 0.04, P = 0.02) but not in females.

Body composition

The DXA values for the three compartments (LTM, BMC, and fat) are shown in **Figure 1.**

Lean tissue mass. LTM increased steadily in males and plateaued at 16.6 y (95% CI: 15.7 y, 17.5 y). In females, LTM increased steadily before plateauing at 13.4 y (95% CI: 12.5 y,

TABLE 1
Population characteristics[1]

	Males (n = 137)	Females (n = 128)
Age (y)	14.4 ± 6.3	14.6 ± 6.1
Weight SDS	0.03 ± 0.91	0.08 ± 0.92
Height SDS	0.06 ± 1.09	0.09 ± 1.02
BMI SDS	−0.31 ± 0.81	−0.28 ± 0.79

[1] $\bar{x}$ ± SD. SDS, standard deviation score.

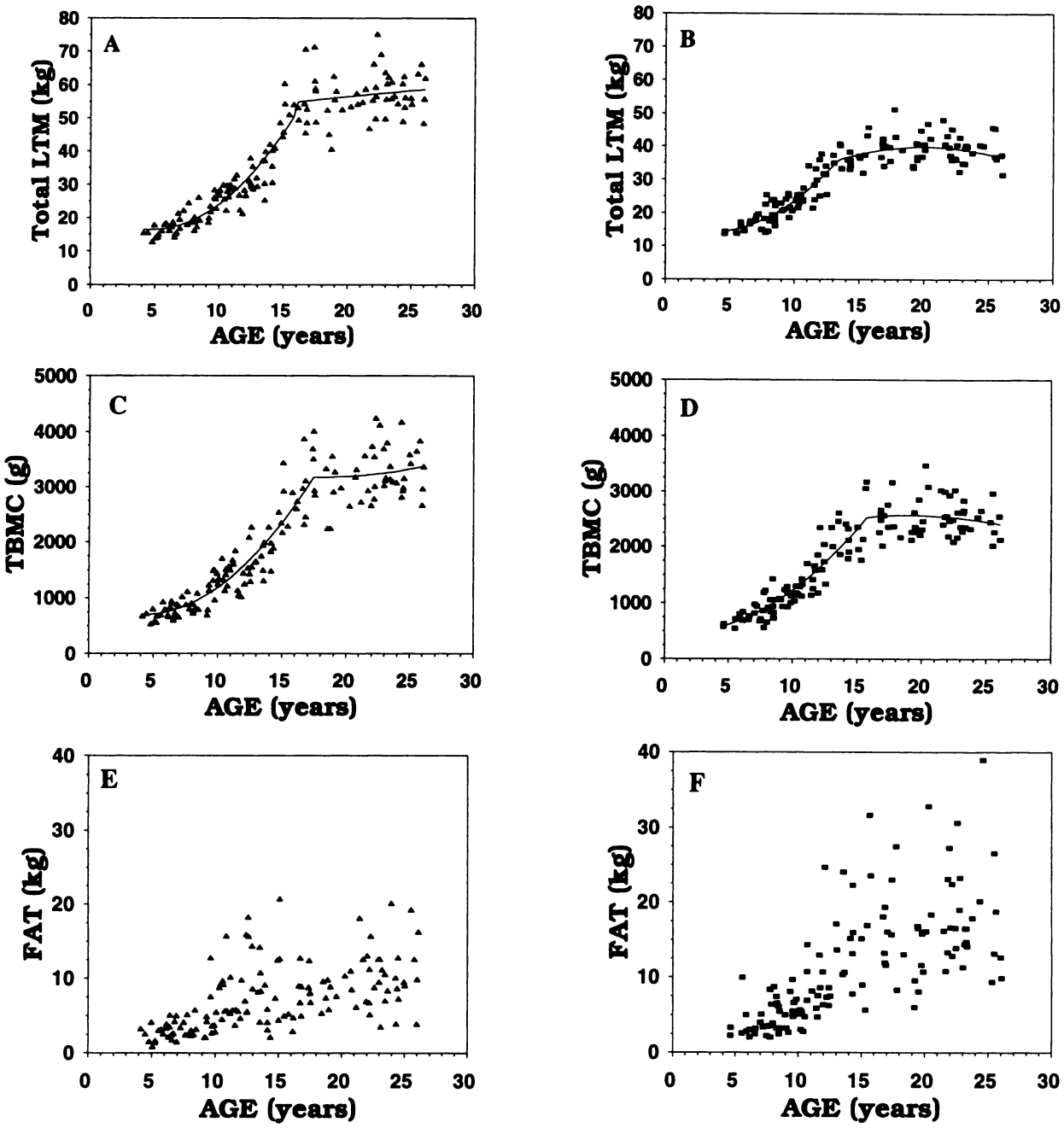

FIGURE 1. Dual-energy x-ray absorptiometry (DXA)–derived lean tissue mass (LTM) for males (A) and females (B), total body bone mineral content (BMC) for males (C) and females (D), and total body fat for males (E) and females (F), by age.

14.3 y). There was almost no overlap for LTM in males and females after age 17 y (Figure 1 and **Figure 2**A).

Bone mineral content. The changes for BMC with age are similar to those for LTM, but the plateau occurred 1–2 y later (Figures 1 and 2). For males, BMC increased until the late teens with the inflection point occurring at age 17.4 y (95% CI: 16.6 y, 18.4 y). Peak BMC was attained at age 15.7 y (95% CI: 14.4 y, 17 y) in females. There was almost no overlap in BMC values between the sexes after puberty.

The relation between BMC and LTM by sex is demonstrated in **Figure 3.** There was considerable overlap between males and females particularly in the prepubertal years but the slope of the regression lines differed. Although the linear relationship was strong between BMC and LTM, there was a wide range of BMC values for LTM between 35 and 65 kg, corresponding with the pubertal years for females and males. This variability in the relation between BMC and LTM may in part provide the explanation for the difference in timing within each sex for the plateau of these variables.

Fat. The absolute values for fat (g) are shown in Figure 1. For males, there is a small increase with age but the range of values is much less than for females, except for a peripubertal increase in the range between 10 and 15 y. The $\%BF_{DXA}$ for males ranged from 4.8% to 34.1% (median 14.4%), and for females from 10.4%

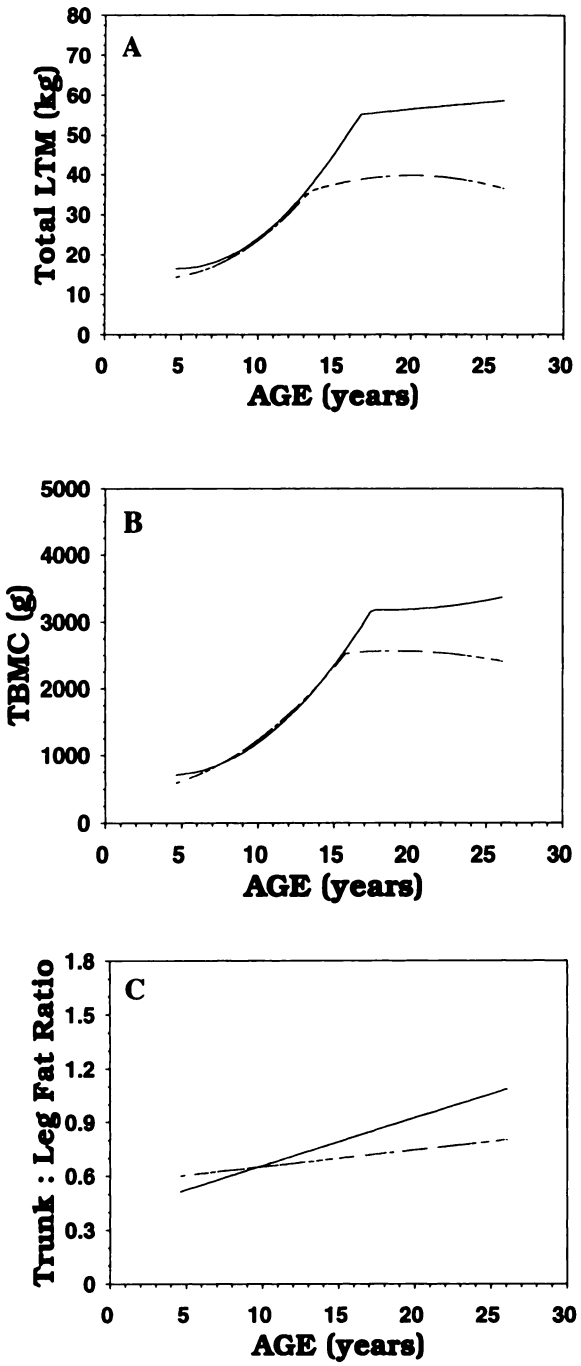

FIGURE 2. The lines of best fit for the cross-sectional data are shown by sex (males, solid line; females, broken line) for lean tissue mass (LTM), total bone mineral content (TBMC), and trunk to leg fat ratio. R^2 for the lines of best fit for females and males for LTM were 0.87 and 0.91, respectively; for bone mineral content 0.87 and 0.89, respectively; and for trunk to leg fat ratio 0.46 and 0.10, respectively.

to 47.7% (median 22.8%, **Figure 4**). The mean $\%BF_{DXA}$ was higher for females (23.7% ± 7.9%) than for males (15.5 ± 6.0%) ($P = 0.001$). The $\%BF_{DXA}$ for males did not show any relation to age except for a transient increase between 10 and 14 y. For females, there was a greater range of $\%BF_{DXA}$ values at all ages, and there was an increase with age ($r = 0.52$, $P < 0.001$, $n = 128$) (Figure 4).

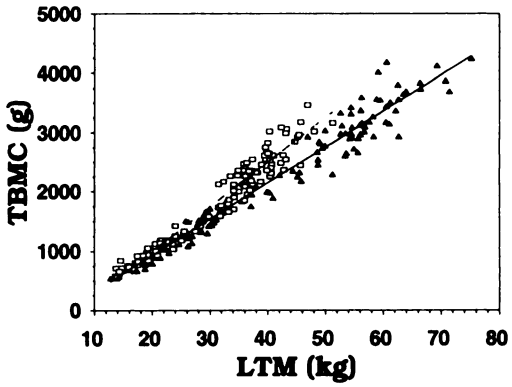

FIGURE 3. Total bone mineral content (TBMC) plotted against lean tissue mass (LTM) for females (□) and males (▲). The regression equations were as follows: BMC = −288.5 + 60.9 × LTM for males ($P = 0.0001$); BMC = −516 + 75.5 × LTM for females ($P = 0.0001$).

Regional body composition

Fat distribution. Figures 2C and 4 show the relation of the TLFR to age for males and females. The TLFR rises in boys after the pubertal years, whereas it remains steady in girls. In postpubertal subjects, the TLFR was higher for males (1.01 ± 0.23) than for females (0.75 ± 0.16) ($P = 0.001$). However, the TLFR for boys younger than 17.0 y was similar to that for girls younger than 15.0 y, 0.66 ± 0.17 and 0.65 ± 0.18, respectively. The relation between fat distribution (TLFR) and increasing body fat (BMI, $\%BF_{DXA}$) was examined for each sex. Significant correlations were found between the TLFR and the BMI SDS ($r = 0.50$) and between the TLFR and $\%BF_{DXA}$ ($r = 0.6$) in females ($P < 0.001$ for both) but not in males.

Lean tissue mass. The relative contribution of both arm and leg LTM to total body LTM increased with age for males and females. However, in boys the contribution of arm LTM continued to rise until the late teens, whereas that of leg LTM plateaued in the early teenage years. In girls, arm and leg contributions both plateaued in the early teenage years (data not shown).

Comparison of DXA with anthropometry

Weight measurement. Although total body weight assessed by DXA correlated very highly with electronic scale weight ($r = 0.999$) it was important to determine the agreement between the two measurements (14). **Figure 5** shows the difference in the two measurements (DXA weight minus scale weight) plotted against the mean of the two weight measurements (DXA weight and scale weight) for males and females. Weight by DXA was significantly less than scale weight (mean difference −0.83 ± 0.59 kg, $P < 0.001$). This was similar for males (−0.71 ± 0.64 kg, $P < 0.001$) and females (−0.95 ± 0.51 kg, $P < 0.001$) and was independent of increasing body fat.

Fat measurement. There was a high correlation between $\%BF_{DXA}$ and $\%BF_{SKINFOLD}$ for males ($r = 0.82$) and females ($r = 0.82$) ($P < 0.001$ for both). The limits of agreement between $\%BF_{SKINFOLD}$ and $\%BF_{DXA}$ are shown in **Figure 6** with the paired differences between the $\%BF_{SKINFOLD}$ and $\%BF_{DXA}$ vs their mean %BF. There was no difference between the means for the males for $\%BF_{SKINFOLD}$ and $\%BF_{DXA}$ (15.0 ± 6.1 and 15.0 ± 6.0, respectively; $n = 117$), but a difference was found for the females (20.9 ± 7.6 and 23.8 ± 8.1, respectively; $n = 115$, $P < 0.001$) for $\%BF_{SKINFOLD}$ and $\%BF_{DXA}$. DXA-derived arm fat

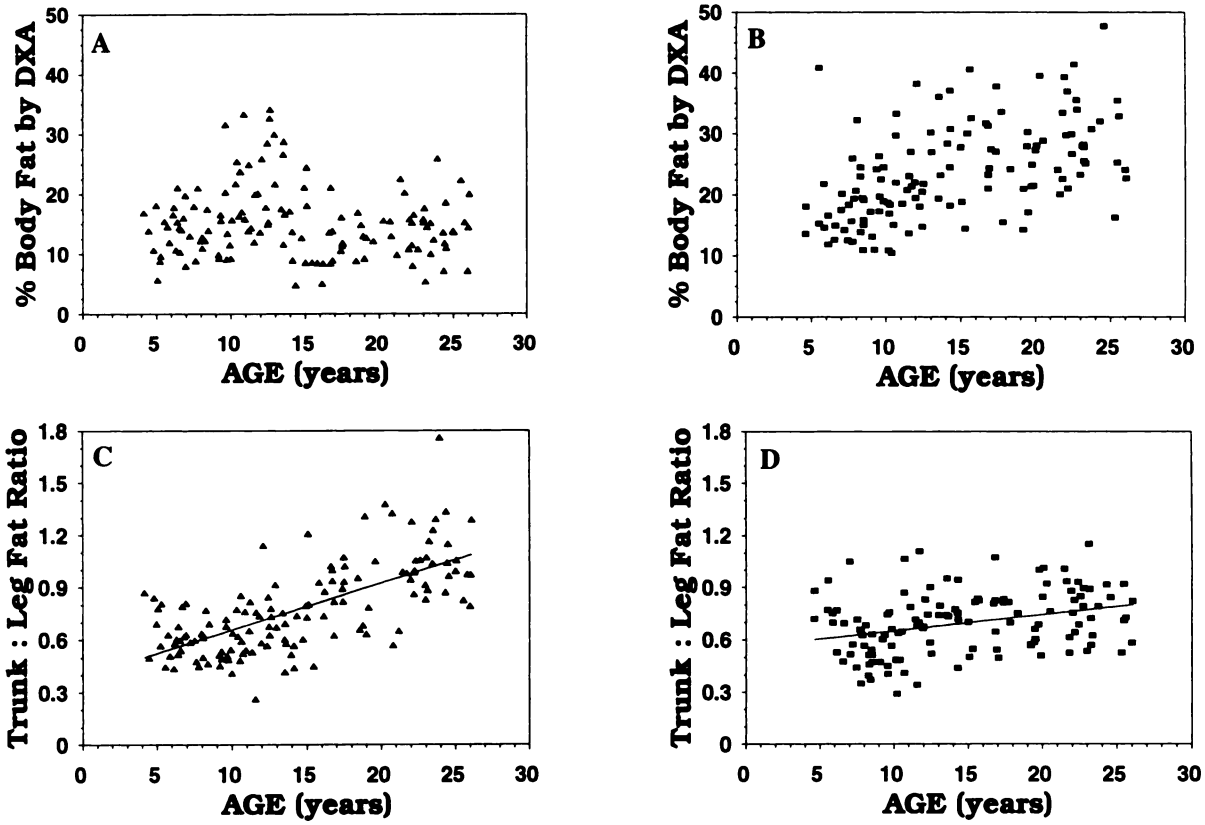

FIGURE 4. Dual-energy x-ray absorptiometry (DXA)–derived percent body fat for males (A) and females (B) and trunk to leg fat ratio for males (C) and females (D), by age.

mass correlated with UAFA derived from anthropometry for both males and females (r = 0.85, P = 0.001, n = 119; and r = 0.85, P = 0.001, n = 111, respectively).

Lean tissue mass measurement. Arm LTM by DXA correlated with UAMA (r = 0.91, P = 0.001, n = 230). The coefficient of correlation was higher for boys (r = 0.93, P = 0.001, n = 119) than for girls (r = 0.83, P = 0.001, n = 111). Total LTM by DXA also correlated well with UAMA (r = 0.91, P = 0.001, n = 230).

Discussion

This study demonstrates the influence of age and sex on body composition in an Australian population ranging from childhood to early adulthood when DXA is used. The results show that boys are generally leaner than girls at all ages and that females demonstrate a trend to increasing body fat with age, findings consistent with previous reports in children when

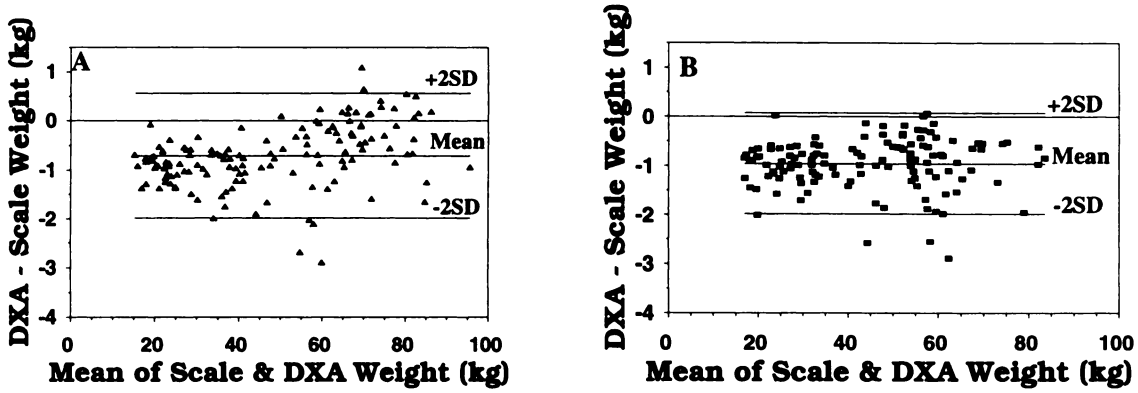

FIGURE 5. The difference between electronic-scale weight and dual-energy x-ray absorptiometry (DXA)–derived weight plotted against the mean of the two weights for males (A) and females (B).

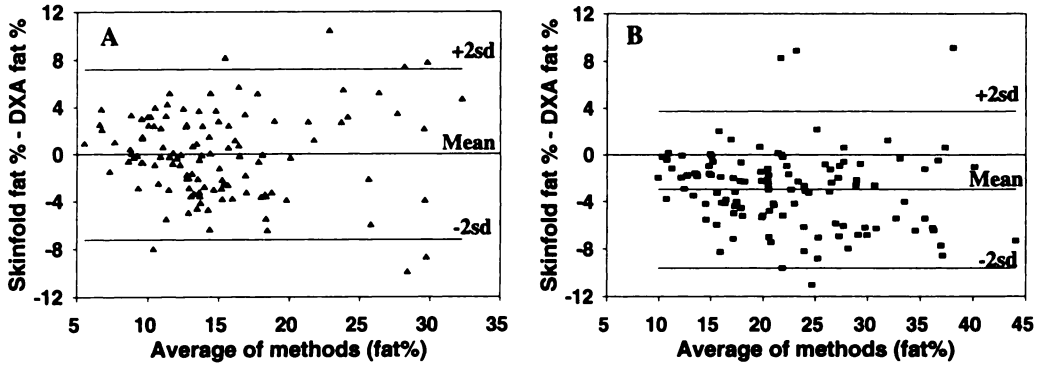

FIGURE 6. The difference between percent body fat derived by skinfold-thickness measurement and by dual-energy x-ray absorptiometry (DXA) plotted against the means of the two fat measurements determined by using the skinfold-thickness method of Slaughter et al (10) for males (A) and females (B).

other techniques were used (14–17). The $\%BF_{DXA}$ for both males and females in the postpubertal age group is remarkably similar to values obtained in adults participating in the Fels longitudinal study in the United States in which DXA apparatus by the same manufacturer was used (18). Our cross-sectional findings suggest that boys have a "fat wave" of increased $\%BF_{DXA}$ peripubertally at ≈10–12 y of age, before $\%BF_{DXA}$ decreases during puberty (16, 17). Male $\%BF_{DXA}$ appears to rise again in the third decade of life. These findings need to be confirmed in a longitudinal study.

The sex and age differences are clearly observed for LTM and BMC. Before age 10 y, values by sex are similar but the increment in males during the pubertal years far exceeds that obtained in females such that there is almost no overlap for LTM and BMC as young adults. We found that LTM plateaus in girls at ≈13.4 y of age whereas it increases in boys until 16.6 y of age, corresponding with the period of growth in which maximum height and weight for each sex are obtained. BMC lags LTM by 1–2 y; therefore, peak values are obtained ≈1 y after linear growth ends, as reported previously (10). Our observations are based on cross-sectional data and although the findings are consistent with those of others in which different techniques were used (19–20), the actual age of inflection points can only be determined by longitudinal studies. In the longitudinal studies of Buckler (20), LTM was assessed by skinfold anthropometry and was found to plateau at ≈15 y of age in females but to increase until age 18 y in males. In males, the proportion of total body LTM that is in the arms continues to increase in late adolescence, but the leg proportion has plateaued earlier, consistent with the well-known phenomenon of males to broaden in the shoulders and upper arms in late adolescence and early adulthood (20).

Our findings are supported by the data of Faulkner et al (22), who described body-composition data in children aged 8–16 y measured by DXA with a different densitometer (Hologic, Waltham, MA). The absolute values could not be directly compared because of the known differences between DXA instruments from different manufacturers (23). Faulkner et al (22) described a similar difference in body fat between males and females for different ages as did our study. Similarly, both studies demonstrated an increase in BMC and LTM with age and a significant correlation between BMC and LTM. This strong relationship in normal subjects suggests that peak BMC is determined by the amount of LTM, which in turn is a function of body size (height and weight) and body phenotype. Further studies are required to examine the influence on the relation between BMC and LTM in disease states and genetic factors, which have recently been described to help explain the population variance in bone mineral density (24).

There is considerable recent interest in regional fat distribution. Abdominal obesity, which results in central body fat distribution, is associated with abnormalities including disturbed glucose-insulin homeostasis and lipid abnormalities not only in adolescents and adults (25–28) but also in prepubertal boys and girls (23, 29–31). DXA assessment has the advantage of quantification of fat by regional distribution. The TLFR, a DXA-derived ratio, displays the relative proportion of "android", or truncal fat, to "gynoid", or hip (leg) fat. This ratio has been shown to be higher in adult males than in females (2, 19), and potentially gives a more accurate indication of body fat distribution than does the waist-to-hip ratio, which is influenced by frame size. Neither technique provides information on the relative amounts of either the subcutaneous or the more metabolically active intraabdominal fat.

Our data show that in males the TLFR rises steadily after puberty until ≥26 y of age, and is higher than in females. This is consistent with studies of adolescent and adult males, which show an increase in abdominal fat with age as assessed by the waist-to-hip ratio (31, 32). The constancy of the TLFR in females across all ages differs from the data for waist-to-hip ratio, which declines in late childhood, not rising until after the age of 30 y (30, 31). Sex differences in the TLFR and $\%BF_{DXA}$ were reflected by the finding that the TLFR was positively influenced by degree of fatness in females but not in males. In absolute terms, after age 20 y the overweight male with a $\%BF_{DXA}$ value of ≈15% will have a TLFR ≈50% greater than that of the same-age female with a $\%BF_{DXA}$ value of ≈30% (Figure 2). The relation of these regional fat measurements by DXA to long-term morbidity needs longitudinal observation and validation (33).

This study shows that DXA correlates well with established anthropometric measures of weight, body fatness, UAFA, and UAMA. This is a finding similar to that in adult studies (1, 2). The agreement analysis shows that for body weight, DXA underestimates scale weight on average by 0.83 kg. This is statistically significant but probably not of clinical importance

because it represents 2.1% and 1.5% of the average body weight for females and males in this study, respectively. However, it represents a larger error in smaller subjects.

The comparison of body fat measured by DXA with skinfold anthropometry showed that DXA provided a result similar to $\%BF_{SKINFOLD}$ for the males and an overestimate of $\%BF_{SKINFOLD}$ for the females. The skinfold equations of Slaughter et al (11) were chosen because they are based on a three-compartment model of body composition—density, water, and bone mineral—to account for the chemical immaturity of children. Other skinfold anthropometry is based on a constant level of hydration in FFM as for adults, and a constant proportion of bone mineral to muscle in FFM, which can lead to an overestimation of fat when applied to children before they reach chemical maturity at ≈15–18 y of age (34).

Validation studies to measure the accuracy of DXA body-composition measurements in children are required. Two recent studies using Hologic densitometers suggest that there may be inaccuracies in measurements of infants (35) and children weighing <35 kg (36). However, both these studies were based on measurements of pigs, which may not be a good model for children because of differences in body fat content and regional distribution (34). In adult studies in which DXA was measured with a Lunar densitometer, there is broad agreement in estimation of body fat when compared with other methods, including skinfold-thickness measurement (21), underwater weighing (18, 37, 38), and total body water measurement (18) but the direction of the difference in body fat between DXA and these methods is not consistent and is dependent on sex and the comparison method.

In conclusion, this study provides DXA-derived normative data on the changes in the LTM, BMC, %BF, and TLFR with age for both sexes. Striking sex differences are found after puberty in all four variables. The good agreement between DXA, scale weight, and skinfold anthropometry suggests that it is a useful method for total and regional body composition in children but further validation of its accuracy is required before it can be accepted as the criterion method for cross-sectional and longitudinal studies.

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