Body Composition Development of Adolescent White Females

The Penn State Young Women’s Health Study

Tom Lloyd, PhD; Vernon M. Chinchilli, PhD; Douglas F. Eggli, MD; Nan Rollings, MEd, RN; Howard E. Kulin, MD

Objective: To obtain simultaneous and longitudinal measures of height, weight, total body bone mineral content, total body bone mineral density, percentage of body fat, lean body mass, and body mass index in healthy white females between the ages of 11 and 18 years.

Design: A longitudinal, observational study.

Setting: University medical center in a small city.

Study Participants: At initiation in 1990, 112 premenarchal, healthy girls were enrolled. Results presented in this report are based on measurements made on the 82 participants who remained in the study in 1996 and for whom we had comprehensive measurements.

Interventions: None.

Main Outcome Measures: Dual-energy x-ray absorptiometry was used to obtain measurements of total body bone mineral content, total body bone mineral density, percentage of body fat, and lean body mass every 6 months for the first 4 years of the study and yearly thereafter.

Results: The mean age for peak velocity and peak accumulation for each measurement was as follows: height, 11½ and 17½ years, respectively; weight, 11½ and 17½ years; body mass index, 11½ and 17½ years; percentage of body fat, 11½ and 13½ years; lean body mass, 12 and 17½ years; total body bone mineral content, 13½ and 17½ years; and total body bone mineral density, 13½ and 17½ years.

Conclusions: Among a healthy population of white females, the age of peak velocities for height, weight, body fat, and lean body mass occur at 11½ to 12 years. Thus, peak soft-tissue velocities precede hard-tissue velocities by about 2 years, with peak accumulation of all tissue components being reached, on average, by age 17½ years.

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Editor’s Note: Perhaps studies like this will help to determine which women are most in need of hormone and calcium supplementation in postmenopausal years. In the meantime, most of us will keep poppin’ the pills.

Catherine D. DeAngelis, MD

There is growing evidence that body composition patterns acquired early in life can provide insight into the tempo of adolescent hormone changes and the likelihood of disease risk in adulthood. Nearly 30 years ago, Tanner and coworkers developed the concept of interval velocity measurements. Using longitudinal measurements, these workers and others produced a series of clinically accurate and useful growth assessment techniques. To fully appreciate individual differences in timing and tempo of adolescent growth, a point of reference other than chronological age is necessary. Such markers have included skeletal age, age at appearance of secondary sex characteristics, and age at peak height and weight velocity.

The advent of body composition assessment by dual-energy x-ray absorptiometry (DXA) provides the opportunity to observe soft tissue (fat and lean tissue) and hard tissue (bone) development during growth, in addition to observing the changes in height and weight. The basic theory and methods for DXA measurements rely on the generation of 2 x-ray–generated photon beams that have different energies. As the beams pass through the body, they are differentially attenuated depending on body composition. The manufacturer’s tissue bar is used for calibration of lean and fat equivalent tissue. When total body DXA scans are made in the presence of the manufacturer’s tissue bar, accurate measurements can be made of total body bone mineral content (TBBMC), total body bone mineral density (TBBMD), lean body mass, and percentage of body fat.
Subjects and Methods

The Penn State Young Women’s Health Study was begun in 1990 when the subjects were 11.9 ± 0.3 years old. The study population is representative of white females attending public school in Pennsylvania and was limited by design to descendants of northern Europeans. We have previously reported details of the recruitment and retention strategies; baseline anthropometric, endocrine, and bone measurements; and effects of a calcium supplementation trial on adolescent bone gain. All procedures were reviewed and approved by the Pennsylvania State University College of Medicine Institutional Review Board, Hershey. All subjects or their parents provided informed consent. Accurate velocity measurements require a stable study population, and the results presented in this report are based on the cumulative measurements of the 82 females who remained in the study from April 1990 through 1996 and for whom we obtained continuous records. Data from the 24 subjects who dropped out are not included in any analyses.

No significant differences were detected between those who dropped out and those who remained in the study in terms of age, height, weight, body mass index (BMI [obtained by dividing the weight, in kilograms, by the height in meters, squared]), or bone measurements. Subject ages presented in this report are rounded to the nearest half-year for her chronological age at her visit.

Anthropometric and Pubertal Assessment

All subjects were seen individually by the research coordinator (N.R.), who measured height, weight, and Tanner stages as previously described. The BMI was calculated as measured weight in kilograms divided by height in meters squared.

Body Composition Measurements

Whole-body composition measurements were made initially with one dual-energy x-ray absorptiometer (Hologic QDR, 1000 W, Hologic Inc, Waltham, Mass), which was replaced with a newer model (QDR 2000) when it became available. A series of normal volunteers were scanned with both machines to determine reproducibility of measurements. As has been reported by others, our observed coefficient of variation for this quality control study was less than the 0.7% day-to-day reproducibility for the scans of the manufacturer’s spine phantom. All body composition scans were made by means of the pencil beam mode in the presence of the manufacturer’s 3-step acrylic/acrylic-aluminum wedge standard that simulates lean and soft tissue. During the first 4 years of the study, participants were scanned at 6-month intervals, ie, visit 1 (baseline) through visit 9 (age 16 years). They were scanned yearly thereafter. A whole-body scan exposes the subject to about 3 mR of radiation, which is equivalent to 3 days of ambient radiation exposure in central Pennsylvania. Body composition analysis was performed with the manufacturer’s analytic software.

Statistical Analysis

Descriptive statistics for generating the tables and graphs were calculated with a range of procedures from SAS statistical software. Velocities were calculated as individual changes during 6-month intervals. Graphical representations of velocities and accumulations involve the means and ±2 SEs at each half-year of age.

Results

Females gain 40% of their adult skeletal mass between the ages of 12 and 18 years. Setting the genetic contributions aside, it is generally believed that risk of osteoporotic fracture depends on (1) peak bone mass achieved by the end of the second decade of life and (2) the rate of bone loss thereafter. Thus, learning exactly how and when this 40% of skeletal mass (900-1000 g of bone mineral) is acquired is important. Relatively large cross-sectional studies on bone accretion by females demonstrated that the most rapid period of bone gain among white females is between 12 and 14½ years of age, with approximately 85% of adult bone mass acquired by age 14½ years.

The purpose of the present study was to perform a longitudinal analysis of soft and hard tissue measurements made on a cohort of 82 white females between the ages of 11 and 18½ years. The major objective of this investigation was to determine and compare the ages for peak velocity and peak accumulation for hard and soft tissue components.

Data reported herein are derived from a total of 968 whole-body DXA scans on the study participants during ages 11 to 18 years. A summary of the means and SDs for height, weight, BMI, percentage of body fat, and TBBMC is presented in the Table. Body composition measurements, including BMI (Figure 1), total fat mass (Figure 2), percentage of body fat (Figure 3), lean body mass (Figure 4), TBBMC (Figure 5), and TBBMD (Figure 6), are presented graphically. For each graph, velocity data are shown with the solid lines and accumulation data with the dashed lines. The middle lines represent the mean values, and the lines above and below the means are 2 SDs away from the mean. The numeric data that generated these graphs are available by request from us and include means, SDs, and minimum and maximum values.

Changes in BMI (Figure 1) document a decreasing velocity during ages 11½ to 18 years, accompanied by a steady increase from about 18.5 to 22.0 kg/m² during ages 11½ to 18 years. Changes in total fat mass (Figure 2) show highest velocities before age 12 years and after age 16 years. The total fat accumulation during ages 12 to 18 years is on average about 6 kg. Change in percentage of body fat (Figure 3) is also bimodal, with greatest rates occurring before age 12 years and after age 16 years. Overall percentage of body fat decreases between 13½ and 16 years of age.

Figure 4 shows that lean body mass increases steadily from 11 to 18 years of age; in contrast, the velocity of lean body mass decreases steadily during this period, approaching zero by age 18 years. Likewise, TBBMC (Figure 5) increases steadily from 11 to 18 years of age, increasing from about 1200 g of skeletal mineral to 2200 g, an increase of 45%. Peak velocity for bone mineral accumulation occurs over a relatively broad time
frame between ages 12 and 14 years. Apparent TBBMD (Figure 6) increases from 0.84 g/cm² to the adult value of 1.10 g/cm² by age 18 years. The velocity curve for TBBMD is bimodal, showing spikes between the ages of 13 and 14 years and between 15 and 16 years.

Assessment of growth by clinicians and researchers is assisted by reference to normative growth standards that reflect differences resulting from race, culture, and era. Data about body composition of lean, normal, and overweight adolescent girls are needed to address issues with athletes and patients with eating disorders. Longitudinal growth and body composition studies of adults are providing clinically useful tools relating specific body composition changes with disease processes.21-24 This study provides, to our knowledge, the first simultaneous measurements of changes in hard and soft tissue during pubertal growth in white females. The goal of the present study has been to understand the normal sequence and progression of changes in hard tissue, namely bone, and in the common divisions of soft tissue, namely lean body mass and body fat, in healthy females.

By age 18 years, the working terminal point for this study, we observed that our cohort had, on average, attained their maximum height, weight (and therefore BMI), lean body mass, total fat mass, and TBBMC. Maximum percentage of body fat was attained considerably earlier, at 13½ years. The maximum velocity for all soft tissue accumulation occurred between 11 and 12 years, while skeletal bone retention.

Although a large series of normative reference growth curves based on longitudinal velocity studies pioneered by Tanner and coworkers3 have been compiled and widely used, it is now apparent that, at least in the United States,
Our "normative data" are changing as we become an increasingly heavy society.\textsuperscript{25-27} The mean values for peak height and weight velocities (age 11\frac{1}{2} years) and mean height and weight at 18 years of age, 165 cm and 58.4 kg, respectively, observed in our cohort are in good agreement with larger current databases from US and United Kingdom studies.\textsuperscript{28,29}

Before the use of DXA scanning, body composition research used hydrostatic weighing, skinfold thickness measurements, and bioimpedance analysis along with age-, sex-, and race-specific equations.\textsuperscript{27} Underwater weighing and skinfold measurements have been the most frequently used methods for laboratory and field studies. The 3-compartment model (bone, fat, and fat-free or lean body mass) has been used extensively to compare body composition measurements made by the different techniques. There is active debate as to the accuracy, precision, reducibility, and agreement of body composition measurements from underwater weighing, skinfold measurements, bioimpedance, and DXA scanning.\textsuperscript{3,10,31}

Body composition data derived from DXA from large cross-sectional studies of females have provided normative data and new insights about relationships among pubertal status, race, body composition, and total body bone measurements. Goulding et al\textsuperscript{32} observed that lean tissue mass doubled between Tanner stages 1 and 5, and fat mass increased 3-fold during the same developmental period. Further, whereas increases in lean body mass in the trunk and legs remained relatively constant with pubertal progression, fat distribution became more central and less peripheral. The multiethnic study by Ellis et al\textsuperscript{33} provides normative body composition values for European-American (white), African-American (black), and Mexican-American (Hispanic) female populations, aged 3 to 18 years, living in the United States, and their results indicate that body composition values for young females should be ethnicity-specific.\textsuperscript{33} Peak values for TBBMC (approximately 2300 g at age 17\frac{1}{2} years) and TBBMD (approximately 1.10 g/cm\textsuperscript{2} at age 17\frac{1}{2} years) observed in the present longitudinal study are in close agreement with peak measurements made in cross-sectional studies.\textsuperscript{10,13,34}

Most correlational investigations that have examined relationships among hard and soft tissue changes have studied postmenopausal women, with the goal of learning whether body composition changes are related to, or predictive of, osteoporotic fractures.\textsuperscript{35-40} These studies demonstrated that body composition relationships are site dependent, and whole-body relationships do not correlate well with osteoporosis-sensitive sites, namely the lumbar spine and femoral neck.
Correlations between dietary calcium intake and bone gain during adolescence have been obtained by the ongoing University of Saskatchewan Pediatric Bone Mineral Study. Using 507 scans from 115 young white females and a cross-sectional analysis of the pooled data, Martin and coworkers observed that peak height velocity occurred at 11.4 years when the rate was 6.3 cm/y, and peak bone mineral content velocity lagged by 1.6 years, occurring at age 13.0 years when the rate was 240 g/y. The results of the present study are similar, with peak height velocity at 11.5 years when the rate was 6.5 cm/y and peak bone mineral content velocity at 13.5 to 14 years when the observed rates were 250 and 249 g/y.

Martin et al and others have pointed out that throughout the period of most rapid bone accretion, ages 12 to 14.5 years, females are gaining 240 to 250 g of bone mineral per year, or 670 mg/d. During ages 12 to 14.5 years, approximately 265 mg of calcium is incorporated into skeletal bone each day. Assuming a calcium absorption and retention efficiency of 26%, the daily dietary intake of calcium to achieve incorporation of 265 mg of calcium into bone would be 1020 mg, a daily amount not regularly consumed by US and Canadian females aged 12 to 14.5 years. Detailed growth and calcium intake data for 6 individuals in the Saskatchewan Study were used to illustrate that, although retention efficiency for males appears steady at 25% to 27%, it may vary from 19% to 37% among the 3 females with high (1589 mg/d), moderate (1039 mg/d), or low (576 mg/d) calcium intake. In summary, we have used DXA to (1) provide normative data on development of the 3 major body composition components in females aged 11 to 18 years; (2) document that peak rates of bone accretion occur at age 13.5 to 14 years, which is 1.5 to 2 years after the peak rates for height, weight, lean body mass, and fat mass; and (3) show that the highest rates of fat mass accumulation occur before age 12 years and after age 16.5 years. Dual-energy x-ray absorptiometry is noninvasive, involves negligible radiation exposure, and is rapid, reproducible, and becoming less expensive. It remains to be seen whether individual body composition studies will become a clinical tool as well as a research necessity.