SECTION

6

Body Composition, Energy Balance, and Weight Control

OVERVIEW

Six major reasons justify an accurate appraisal of body composition in a comprehensive program of total physical fitness:

1. It provides a starting point on which to base current and future decisions about weight loss and weight gain.
2. It provides realistic goals about how to best achieve an "ideal" balance between the body's fat and nonfat compartments.
3. It relates to general health status and plays an important role in the health and fitness goals of *all* individuals.
4. It monitors *changes* in the fat and lean components during exercise regimens of different durations and intensities.
5. It allows allied health practitioners (sports nutritionist, dietician, personal trainer, coach, athletic trainer, physical therapist, physician, exercise leader) to interact with the individuals they deal with to provide quality information related to nutrition, weight control, and exercise.
6. It provides the athlete, coach, and scientist with objective information relating body composition assessment to sports performance.

Many diverse methods, both complex and simple, assess human body composition. Of the simpler methods, the popular height–weight tables have become a frequently used standard in the medical community and elsewhere to assess overweight and obesity status.[33,89,154] Unfortunately, this approach is of limited value as "overweight" and excess body fat do not necessarily coincide. Many large-sized athletes, for example, typically exceed the average weight for height by gender but otherwise possess relatively low levels of body fat. Most of these individuals obviously do not require weight loss, which might adversely affect their sports performance. In contrast, a prudent weight loss program would surely benefit the extreme number of overweight men and women not only in the United States but worldwide. This group spends nearly $50 billion each year to purchase diet books, products, and services at more than 1500 weight-control clinics in the hope of permanently reducing excess fat. Medicaid and Medicare finance almost half of the more than $100 billion spent annually on obesity-related medical costs in the United States. Worldwide, more than 300 million people fall within the definition of overweight, and this may be a conservative estimate.

From antiquity to the present, regular physical activity and dietary restraint have played an important role to combat the overweight and obese conditions. In Galen's treatise *De Sanitate Tuenda* [*On Hygiene*], penned five centuries after Hippocrates communicated about overweight and obesity in his many writings (refer to p. xxiii in the Introduction), he describes the treatment for an obese patient using a combination of exercise and food restriction as follows[130]:

> *Now, I have made any sufficiently stout patient moderately thin in a short time by compelling him to do rapid running, then wiping off his perspiration with very soft or very rough muslin, and then massaging him maximally with diaphoretic inunctions, which the younger doctors customarily call restoratives, and after such massage leading him to the bath, after which I did not give him nourishment immediately, but bade him rest for a while or do something to which he was accustomed, then led him to the second bath and then gave him abundant food of little nourishment, so as to fill him up but distribute little of it to the entire body.*

This section discusses body composition, its components and assessment, and the differences in body size and composition between sedentary and physically active men and women. We also consider topics relevant to obesity and discuss the use of diet and exercise for weight management, as Hippocrates, Galen, and others considered over 3000 years ago!

Interview *with* Dr. Claude Bouchard

Education: BPed (Laval University, Quebec City, Canada); MSc (University of Oregon, Eugene, OR); PhD (population genetics, University of Texas, Austin); postgraduate training (Deutsche Sporthochschule, Institute for Research on Circulation and Sport Medicine, Cologne; Growth Research Center, Université de Montreal)

Current Affiliation: Professor and Executive Director, George A. Bray Chair in Nutrition, Louisiana State University System, Pennington Biomedical Research Center, Baton Rouge, LA

Honors and Awards: See Appendix E, available online at http://thepoint.lww.com/mkk7e.

Research Focus: Genetics of adaptation to exercise and nutritional interventions, and genetics of obesity and its comorbidities

Memorable Publication: Bouchard C, et al. Genomic scan for maximal oxygen uptake and its response to training in the HERITAGE Family Study, J Appl Physiol 2000;88:551.

STATEMENT OF CONTRIBUTIONS: ACSM Honor Award

In recognition of his impressive research accomplishments in exercise science, genetics, child growth and maturation, diet and exercise clinical trials, and public health.

Dr. Bouchard has made important contributions to many areas of human performance research, and has been a leader in synthesizing current knowledge to produce consensus statements in exercise science. Among other things, he has conducted innovative research on the effects of experimental manipulation of diet and exercise in monozygotic twins.

He has collected more data on energy balance from carefully controlled studies in this unique population than anyone in the world. This research has led to a better understanding of the variability of responses to dietary manipulation and exercise training and to the genetics of these complex processes.

Dr. Bouchard's career is characterized by high scientific standards, immense productivity, breadth of interests, creative study designs, and a willingness to collaborate with others. He serves as an ideal role model for us all.

What first inspired you to enter the exercise science field? What made you decide to pursue your advanced degree and/or line of research?

➤ As a student in what was known as College Classic (the equivalent of high school, but it takes 9 years and emphasizes the humanities), I became fascinated with human movement and performance. At that time, it was a very diffuse interest—that is, I was curious about the biomechanics, the exertion and the physiology, or the medical aspect, and the aesthetic of human movement. I had several career options but came rapidly to the conclusion that I would move on to the local university, Université Laval, to learn about exercise and sports with the goal of approaching them from a scientific point of view. As you can see, even before I became a student in physical education, I was fascinated by science and human movement.

During my undergraduate studies, I was very frustrated by the poor science to which I was exposed, so I decided to go on to graduate studies. For 2 years during the summer, I traveled with friends on the East Coast of the United States and in the Midwest for the purpose of visiting universities and meeting faculty to select one for a master's degree program. I visited at least 15 such institutions and finally ended up at the University of Oregon, an institution that had been highly recommended to me. There, I was exposed to the teachings of Sigerseth, Clarke, Brumbach, Poley, and others.

After earning my master's degree in Oregon, I felt that I was not quite ready to benefit from a PhD program. Following the advice of a few of my friends, I decided to go to the Sporthochschule in Cologne to work with Professor Wildor Hollmann. He was the Director of the Institute für Kreislaufforschung und Sportmedizin, or the Institute for Research on Circulation and Sport Medicine. I knew that I could not obtain a degree there but wanted to get more hands-on research experience. By then, my interests included not only performance but also the health implications of exercise. I stayed there for 18 months and learned much.

Then I was offered a position at my alma mater, Laval University in Quebec. I decided to accept the position with the expectation to leave after 3 years or so to obtain my PhD. If I had done so immediately, I would have entered an endocrinology PhD program, as I had made contact to be admitted in the lab of Professor Hans Selye at the Université de Montreal. But I became so involved in the development of the programs and the facilities at Laval University that it was 8 years before I left for my doctoral studies. By then, I had decided that genetics and biological individuality would be the focus of my research for the last decades of my career.

I opted to work with Professor Robert Malina, a colleague who had training in both physical education and biological anthropology, at the University of Texas. I spent 3 productive years there, which I completed with 10 months of postgraduate work at the Université de Montreal in the Human Growth and Development Center.

Obviously, mine has not been a linear career path. But I always felt that I was sharpening the focus of my research interest all along. Every phase in my career has been a useful one in the sense that it took me closer to what I am doing today—investigating the genetic and molecular basis of the response to exercise and of obesity and its comorbidities. It would have been impossible to select this line of research 35 years ago, since the field did not exist. The study of individual differences could not be even contemplated at the molecular level then.

Who were the most influential people in your career, and why?

➤ Three scientists have played key roles at different times of my career. The first was Professor Fernand Landry. He was a faculty member at the University of Ottawa, but he was from the same city where I was born and went to the same colleges and community organizations that I later attended. He stimulated my interest in the biological sciences in general and the marvels of the human body's adaptation to exercise and training. He had a lasting impact on my career choices.

The second was Professor Wildor Hollmann. I got to know him very well during my stay in Cologne at his Institute. He stimulated my interest in the general topic of physical activity and health, particularly cardiovascular health. He was a very kind and patient mentor.

The last one was Professor Robert Malina. We became good friends during my doctoral studies at the University of Texas. Bob is a scholar with a strong interest in human diversity. We shared this research focus and many of the small pleasures of life.

What has been the most interesting/enjoyable aspect of your involvement in science? What was the least interesting/enjoyable aspect?

➤ The most enjoyable aspect is that you always think out of the commonly accepted paradigm and look toward the future. You verify one fact only to refocus on the new questions generated by the previous experience. You also constantly meet people who are of the same mind, colleagues who are always trying to be innovative and creative in the presence of the same set of facts as you. The life of a scientist is never dull if you have the chance to interact with the best in your field.

The least enjoyable aspect is the fact that you have to hunt for research funds all the time, particularly if you run a large laboratory operation. At one point, there were 55 people working on my research projects, and I was spending at least a third of my time writing grant applications or renewals to maintain all of these positions.

What is your most meaningful contribution to the field of exercise science, and why is it so important?

➤ If I have contributed anything, it is evidence for the magnitude of the individual differences in fitness and performance in the sedentary state and in the response to regular exercise. My group has also demonstrated over a period of 20 years that these individual differences were not random. They are characterized by familial clustering and are accounted for by a substantial genetic effect. We have identified some of the areas responsible for the heterogeneity in fitness and performance levels, and in trainability.

I have also spent considerable research resources investigating the genetic and molecular basis of obesity and the metabolic disturbances seen in some obese individuals, but not in others. To this end, we have used a combination of twin and family studies as well as intervention protocols to begin the dissection of the complex genotypes that predispose individuals to become overweight and then obese.

I am also proud of my contributions to the efforts undertaken over the past 15 years to arrive at evidence-based consensus concerning the role of physical activity in health and disease.

What advice would you give to students who express an interest in pursuing a career in exercise science research?

➤ You will eventually need to become highly specialized in your own research pursuit, but try to acquire a broad-based understanding of the parent discipline. If you elect to become an exercise molecular biologist, you will find it useful to become an excellent biologist first. Maintaining a reasonable understanding of the changes occurring in biology in general will be a strong asset throughout your career. First, you will derive more satisfaction from your own research because you will be able to see the general implications of your work. Second, you are likely to find that a career in exercise science is more interesting if you understand what is going on in the broader field of science to which you are related.

What interests have you pursued outside of your professional career?

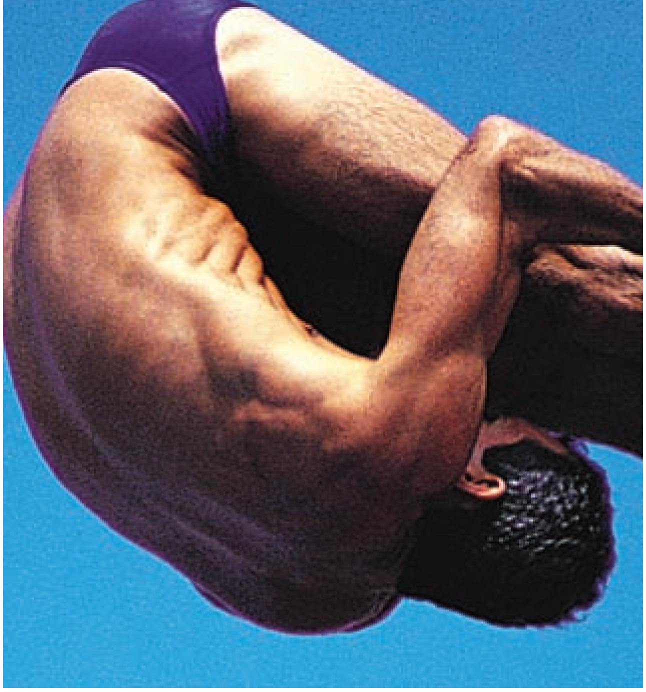
➤ At age 20, I learned to ski and enjoyed it tremendously for many years. I shifted progressively from downhill to cross-country skiing, which I still like to do. At present, my preferred activities are hiking, fly fishing for trout and salmon, working out at the gym, reading, classical music, and wine tasting. I also enjoy traveling, but these days most of my travel is for business purposes.

Where do you see the exercise science field (particularly your area of greatest interest) heading in the next 20 years?

➤ In the next 20 years, the field of exercise science will incorporate the advances in molecular biology and genetics, something that it has failed to do in the past 10 years. The techniques of genomics and proteomics will become common technologies in our field. The benefits should be enormous, as exercise science can offer a wealth of opportunities to verify the functional consequences of DNA sequence variations in people who are not symptomatic for any disease. Such advances in the field of exercise science should make it possible for the exercise science discipline to become a significant player in preventive medicine and public health, as it will be able to develop the probes to identify those who are likely to benefit most from a physically active lifestyle. It will also change the way exercise science contributes to sports performance, as it will have the tools to identify the talented individuals at an early age.

You have the opportunity to give a "last lecture." Describe its primary focus.

➤ It would be on the extent and the causes of biological individuality and its implications for human health in a Darwinian evolutionary perspective.



CHAPTER 28

Body Composition Assessment

CHAPTER OBJECTIVES

- Summarize the early research on inadequacies of height–weight tables
- Distinguish among overweight, overfat, and obesity
- Outline current systems to classify overweight and obese conditions
- Delineate characteristics of the "reference man" and "reference woman," including values for storage fat, essential fat and sex-specific essential fat
- Discuss the prevalence of menstrual irregularities within the general population and specific athletic groups, and factors associated with their occurrence
- Describe Archimedes' principle applied to human body volume measurement
- Discuss limitations in assumptions for computing percentage body fat from whole-body density
- Summarize the rationale, strengths, and weaknesses of air-displacement plethysmography for assessing body composition
- Give the anatomic locations for six frequently measured skinfolds and girths
- Describe how skinfolds and girths provide meaningful information about body fat and its distribution
- Discuss the rationale for bioelectrical impedance analysis and factors that affect body composition estimates with this technique
- Summarize the rationale, strengths, and weaknesses of bioelectrical impedance analysis, near-infrared interactance, ultrasound, computed tomography, magnetic resonance imaging, and dual-energy X-ray absorptiometry to assess body composition
- Give representative average values with variation limits for percentage body fat of typical young and older adult men and women

The life insurance actuary-based **height–weight tables** (weight measured with clothes and height measured with 2-inch heels) provide a popular means to assess the extent of "overweightness" on the basis of gender and body frame size (see "In a Practical Sense," p. 727). These tables, however, provide unreliable information about an individual's relative body composition (muscle, bone, fat). Rather, they provide statistical landmarks based on the average ranges of body mass related to stature associated with the lowest mortality rate for persons' ages 25 to 59 years. They do not consider specific causes of death or quality of health (morbidity) before death.

A person may weigh considerably more than the average weight-for-height standard yet still rate "underfat" for body composition; "extra" weight for this person exists as muscle mass. According to the tables, the desirable body weight (assuming a large frame size) for a professional American football player 188-cm tall and weighing 116 kg ranges between 78 and 88 kg. Similarly, body weight without regard for frame size for young adult men 188-cm tall averages 85 kg. Using either criterion, conventional standards would classify this player as overweight, implying that he should lose at least 28 kg just to achieve the upper limit of the desirable body weight range. He must lose an additional 3 kg to match his "average" American male counterpart. If the player followed these guidelines, he most likely would no longer play football and could jeopardize overall health. Body fat for the football player (even though he weighed 31 kg more than the average) was only 12.7% of body mass, compared with about 15.0% body fat for untrained young men of "normal" weight.

Limitations of Height–Weight Tables

- Uses unvalidated estimates of body frame size
- Developed from data derived primarily from white populations
- Specific focus on mortality data that may not reflect obesity-related comorbidities
- Provides no assessment of body composition

Navy physician Dr. Albert Behnke (1898–1993) first observed body composition variations between elite athletes and untrained individuals in studies of football players in the early 1940s (see "Focus on Research," p. 729). Careful evaluation of each player's body composition revealed that extreme muscular development primarily contributed to excess weight. These observations clearly pointed out that the term **overweight** refers only to a body mass in excess of some standard, usually the average for a given stature. Being above an average, ideal, or desirable body mass based on height-weight tables should not necessarily dictate whether someone begins a reducing regimen. A better alternative determines body composition by one of the laboratory or field techniques reviewed in this chapter. TABLE 28.1 lists terms and definitions common to the area of body composition evaluation.

TABLE 28.1 • Terms Frequently Used in Describing and Measuring Body Composition

Term	Definition
Abdominal fat	Subcutaneous and visceral fat in the abdominal region
Adipose tissue mass (ATM)	Fat (about 83%) plus its supporting structures (about 2% protein and 15% water); consists predominantly of white adipocytes (cells with a single fat droplet, mainly as triacylglycerol)
Anthropometry	Standardized techniques (e.g., calipers, tapes) to quantify (or predict) body size, proportion, and shape (*anthropo,* human; *metry,* measure)
Body density (Db)	Body mass (BM) expressed per unit body volume (body mass ÷ body volume)
Body mass index (BMI)	Ratio of BM to stature squared (body mass ÷ stature^2)
Densitometry	Archimedes' principle of water displacement to estimate whole-body density; other terms include *hydrostatic weighting, hydrodensitometry, underwater weighing*
Essential lipids	Compound lipids (phospholipids) needed for cell membrane formation—about 10% of total body fat
Fat mass (FM)	All extractable lipids from adipose and other body tissues
Fat-free body mass (FFM)	All residual lipid-free chemicals and tissues, including water, muscle, bone, connective tissue, and internal organs
Intraabdominal fat	Visceral fat in the abdominal cavity
Lean body mass (LBM)	FFM plus essential body fat
Minimal body mass	BM plus essential fat (includes sex-specific essential fat); 48.5 kg for the reference woman; computed from bone diameters, stature, and constants
Nonessential lipids	Triacylglycerols found mainly in adipose tissue—about 90% of total body fat
Reference man and reference woman	Behnke's reference standards for men and women that partition body mass into lean body mass, muscle, and bone, with fat subdivided into storage and essential fat; standards for body dimensions developed from military and anthropometric surveys
Relative body fat (%BF)	FM expressed as a percentage of total body mass
Specific gravity	Body mass in air divided by loss of weight in water (body mass ÷ [body mass – body weight in water])
Stature	Height expressed in metric units; e.g., 72 in = 182.88 cm = 1.829 m
Subcutaneous fat	Adipose tissue beneath the skin
Visceral adipose tissue (VAT)	Adipose tissue within and surrounding thoracic (e.g., heart, liver, lungs) and abdominal (e.g., liver, kidneys, intestines) cavities

IN A PRACTICAL SENSE

Determining Body Frame Size from Stature and Two Bone Diameters

Body frame size (BFS) becomes a useful measure for evaluating "normalcy" of body weight with standardized charts that categorize weight by frame size (bony structure). A combination of stature and bony widths (bone diameter measurements) adequately defines BFS, because BFS relates to the fat-free body mass (bone and muscle) and not body fat.

MEASUREMENTS

1. Stature (height [Ht]) measured in cm
2. Biacromial diameter (cm) measured as the distance between the most lateral projections of the acromial processes (see figure)
3. Bitrochanteric diameter (cm) measured as the distance between the most lateral projection of the greater trochanters (see figure)

CALCULATIONS

Regression analyses determine BFS values for women and men from Ht and sum of the biacromial and bitrochanteric bone diameters (ΣBia + Bitroc) with the following equations:

$$\text{Female: } BFS \times Ht + 10.357 + (\Sigma Bia + Bitroc)$$

$$\text{Male: } BFS \times Ht + 8.239 + (\Sigma Bia + Bitroc)$$

STEPS

1. Measure stature and biacromial and bitrochanteric diameters; use the average of two measurements.
2. Sum the average biacromial and bitrochanteric diameter measurements (ΣBia + Bitroc).
3. Compute BFS by substituting in the appropriate gender-specific formulas (example illustrated in Table 1).
4. Determine frame-size category by referring to Table 2.

EXAMPLE

Table 1 shows calculations of BFS for a male and female of different heights and bony diameters. The male's height corresponds to a value below the 10th percentile for height-by-age for men in the U.S. population. This height, combined with large breadth measurements, results in a medium frame-sized ranking (Table 2). In contrast, the female's height of 173.4 cm ranks above the 90th percentile for the U.S. population. However, her small breadth measurements also result in a medium frame-sized ranking (Table 2).

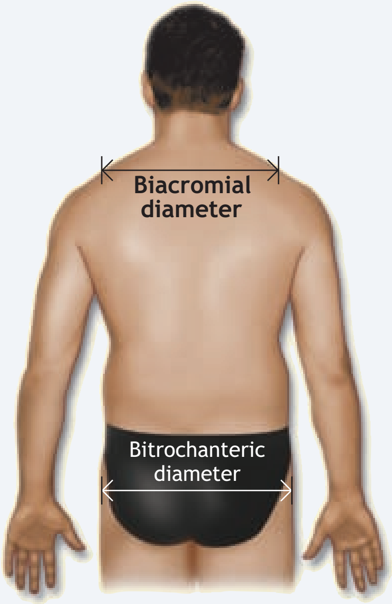


TABLE 2 • BFS Categories

	Frame-Size Category		
Sex	**Small**	**Medium**	**Large**
Male	<1459.3	1459.4−1591.9	<1592.0
Female	>1661.9	1662.0−1850.7	>1850.08

From Katch VL, Freedson PS. Body size and shape: derivation of the "HAT" frame-size model. Am J Clin Nutr 1982;36:669.

TABLE 1 • Example of BFS Calculations for a Male and Female of Different Heights and Bony Measurements

Variable	Subject A (Male)	Subject B (Female)
Ht	167.3 cm	173.4 cm
Biacromial diameter	48.0 cm	29.8 cm
Bitrochanteric diameter	35.0 cm	22.2 cm
ΣBia + Bitroc	83.0 cm	52.0 cm
BFS value	1461.4 cm [BFS = Ht × 8.239 + ΣBia + Bitroc] [BSF = 167.3 × 8.239 + 83.0] [BSF = 1461.4]	1847.9 cm [BFS = Ht × 10.357 + ΣBia + Bitroc] [BSF = 173.4 × 10.357 + 52.0] [BSF = 1847.9]
Frame-size category (from Table 2).	Medium	Medium

From Katch VL, Freedson PS. Body size and shape: derivation of the "HAT" frame-size model. Am J Clin Nutr 1982;36:669.

OVERWEIGHT, OVERFATNESS, AND OBESITY: NO UNANIMITY FOR TERMINOLOGY

Confusion surrounds the precise meaning of the terms *overweight*, *overfat*, and *obesity* as applied to body weight and body composition. Each term often takes on a different meaning depending on the situation and context of use. The medical literature infers the term **overweight** to an overfat condition despite the absence of accompanying body fat measures while **obesity** refers to individuals at the extreme of the overweight (overfat) continuum. The body mass index (see next section) is the measure most often used for this distinction.

Research and contemporary discussion among diverse disciplines reinforces the need to distinguish between overweight, overfat, and obesity to ensure consistency in use and interpretation. In proper context, the overweight condition refers to a body weight that exceeds some average for stature, and perhaps age, usually by some standard deviation unit or percentage. The overweight condition frequently accompanies an increase in body fat, but not always (e.g., male power athletes), and may or may not coincide with the comorbidities glucose intolerance, insulin resistance, dyslipidemia, and hypertension (e.g., physically fit overfat men and women).

When body fat measures are available (hydrostatic weighing, skinfolds, girths, bioelectrical analysis [BIA], dual energy X-ray absorptiometry [DXA], it becomes possible to more accurately place body fat level on a continuum from low to high, independent of body weight. Overfatness then would refer to a condition where body fat exceeds an age- and/or gender-appropriate average by a predetermined amount. In most situations, "overfatness" represents the correct term when assessing individual and group body fat levels.

The term obesity refers to the overfat condition that accompanies a constellation of comorbidities that include one or all of the following components of the "**obese syndrome**": glucose intolerance, insulin resistance, dyslipidemia, type 2 diabetes, hypertension, elevated plasma leptin concentrations, increased visceral adipose tissue, and increased risk of coronary heart disease and cancer. In all likelihood, excess body fat, not excess body weight per se, explains the relationship between above average body weight and disease risk. Such findings emphasize the importance of distinguishing the composition of excess body weight to determine an overweight person's disease risk.

Many men and women may be overweight or overfat yet not exhibit components of the obese syndrome. For these individuals, we urge caution in using the term *obesity* (instead of *overfatness*) in all cases of excessive body weight. We acknowledge that these terms are often used interchangeably (as we at times do in this text) to designate the same condition.

THE BODY MASS INDEX: A POPULAR CLINICAL STANDARD

Clinicians and researchers frequently use the **body mass index** (**BMI**), derived from body mass and stature, to assess "normalcy" for body weight. This measure exhibits a somewhat higher yet still moderate association with body fat and disease risk than estimates based simply on stature and body mass.

BMI Computation

BMI computes as follows:

$$\text{BMI} = \text{Body mass (kg)} \div \text{stature (m}^2\text{)}$$

Example

Male—stature: 175.3 cm, 1.753 m (69 in.); body mass: 97.1 kg (214.1 lb)

$$\begin{aligned}\text{BMI} &= 97.1 \div (1.753)^2 \\ &= 31.6\ \text{kg} \cdot \text{m}^{-2}\text{, or simply } 31.6\end{aligned}$$

The importance of this easily obtained index lies in its curvilinear relationship with the all-cause mortality ratio. As BMI increases throughout the range of moderate and severe overweight, so also does risk increase for cardiovascular complications (including hypertension and stroke), certain cancers, diabetes, Alzheimer's disease, gallstones, sleep apnea, osteoarthritis, and renal disease.[22,113,121,140]

A large prospective study of more than 1 million United States adults during 14 years of follow-up reveals the relationships between BMI and mortality risk. Figure 28.1A shows that smoking status and presence or absence of disease at time of enrollment in the study substantially modified the association between BMI and risk of premature death from all causes. Men and women who never smoked and remained disease free at the study's start *(light blue lines)* experienced the greatest health risk from excess weight. Excessive leanness related to increased death risk among current and former smokers with a history of disease. In healthy people, the nadir of the curve for BMI and mortality occurred between a BMI of 23.5 and 24.9 for men (e.g., 5′10″ at 174 lb) and 22.0 and 23.4 for women (e.g., 5′5″ at 150 lb), with a gradient of increasing risk associated with moderate overweight. Among white men and women with the highest BMI, relative death risk equaled 2.58 (men) and 2.00 (women) compared with counterparts with a BMI of 23.5 to 24.9 (relative risk of 1.00).

Figure 28.1B shows the clear association in men and women between excess weight and a greater death risk from heart disease or cancer. A positive relationship emerged between BMI and cancer risk, with no elevation in risk among the leanest men and women. A J-shaped curve described BMI and cardiovascular disease risk, while a U-shaped curve predicted risk of death for all other causes. The authors attribute the increased death risk among the leanest men and women depicted in the J- and U-shaped curves to the presence of disease at the time of measurement.

FOCUS ON RESEARCH

Overweight But Not Overfat

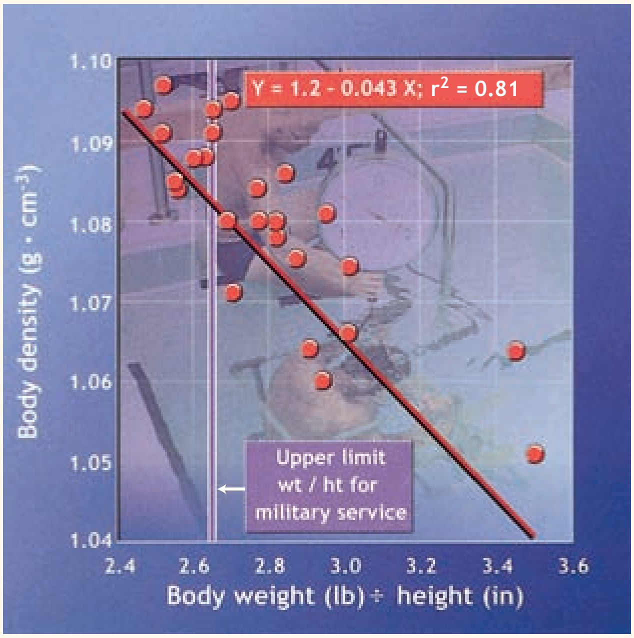
Welham WC, Behnke AR. The specific gravity of healthy men; body weight/volume and other physical characteristics of exceptional athletes and of naval personnel. JAMA 1942;18:498.

➤ The Welham and Behnke research is one of the most frequently cited studies in the body composition and exercise physiology literature. These investigators tested the hypothesis that differences in body fat among men relate chiefly to the body's specific gravity and not body mass per se. The hypothesis predicted that heavy but lean men would have higher body specific gravity values than counterparts of similar body mass, but with high body fat levels. If correct, a relatively large body mass may not always provide an appropriate measure of excessive fatness.

In 1942, the relation between the body density and estimates of body fatness remained undetermined, although scientists knew the specific gravity of the body's fat and nonfat (fat-free) components. Twenty-five professional football players, most of whom had been designated All-Americans, were classified as unfit for military service because of excessive body weight according to standard height–weight tables. Measurements included stature, body mass, and whole-body density determined by hydrostatic weighing. A unique aspect of the body density assessment corrected body volume from estimates of residual lung volume.

The *figure* shows the relationship between body density and height–weight for the athletes. The *vertical line* at a height–weight ratio of 2.65 represents the upper limit for classification as fit for military service. Men of this age who fell to the right of the vertical line did not qualify for life insurance because of their excessive body weight; 17 of the players classified as overweight. However, the high body densities of 11 of these men indicated a low percentage body fat. Body mass of all the players averaged 90.9 kg (200 lb), and body density averaged 1.080 g · cm^{-3}. For the 6 heaviest men, body mass averaged 104.5 kg (230 lb), with body density at 1.059 g · cm^{-3}.

Welham and Behnke's research was the first to show that variations in body density related mainly to individual differences in the body's fat content. The research also pointed up the inadequacies of height–weight tables to infer body fatness or determine a desirable body weight, particularly among highly trained large athletes. The researchers suggested that a body density of 1.060 g · cm^{-3} should serve as the demarcation for excessive fatness for men. With this criterion, 23 of the 25 lean but heavy football players qualified as fit (and not overly fat) for military service.



Relationship between body density and height–weight ratio for 25 All-American football players.

New Standards for Overweight and Obesity

In 1998, the expert panel of the National Heart, Lung and Blood Institute lowered the BMI demarcation point for "overweight" from 27 to 25. Based on the association between excess body weight and disease, individuals with a BMI of 30 or more were categorized as obese. Persons with a BMI of 30 average 30 pounds overweight. For example, a 6′0′′ man weighing 221 pounds and a woman weighing 186 pounds at 5′6′′ each have a BMI of 30, and each is approximately 30 pounds overweight. These revised standards place nearly 130 million, or 62%, of Americans in the overweight and obese categories—up from 72 million under the previous standard. Of this total, 30.5% (59 million people) classify as obese. For the first time, overweight persons (BMI above 25) outnumber persons of desirable weight! More black, Mexican, Cuban, and Puerto Rican males and females

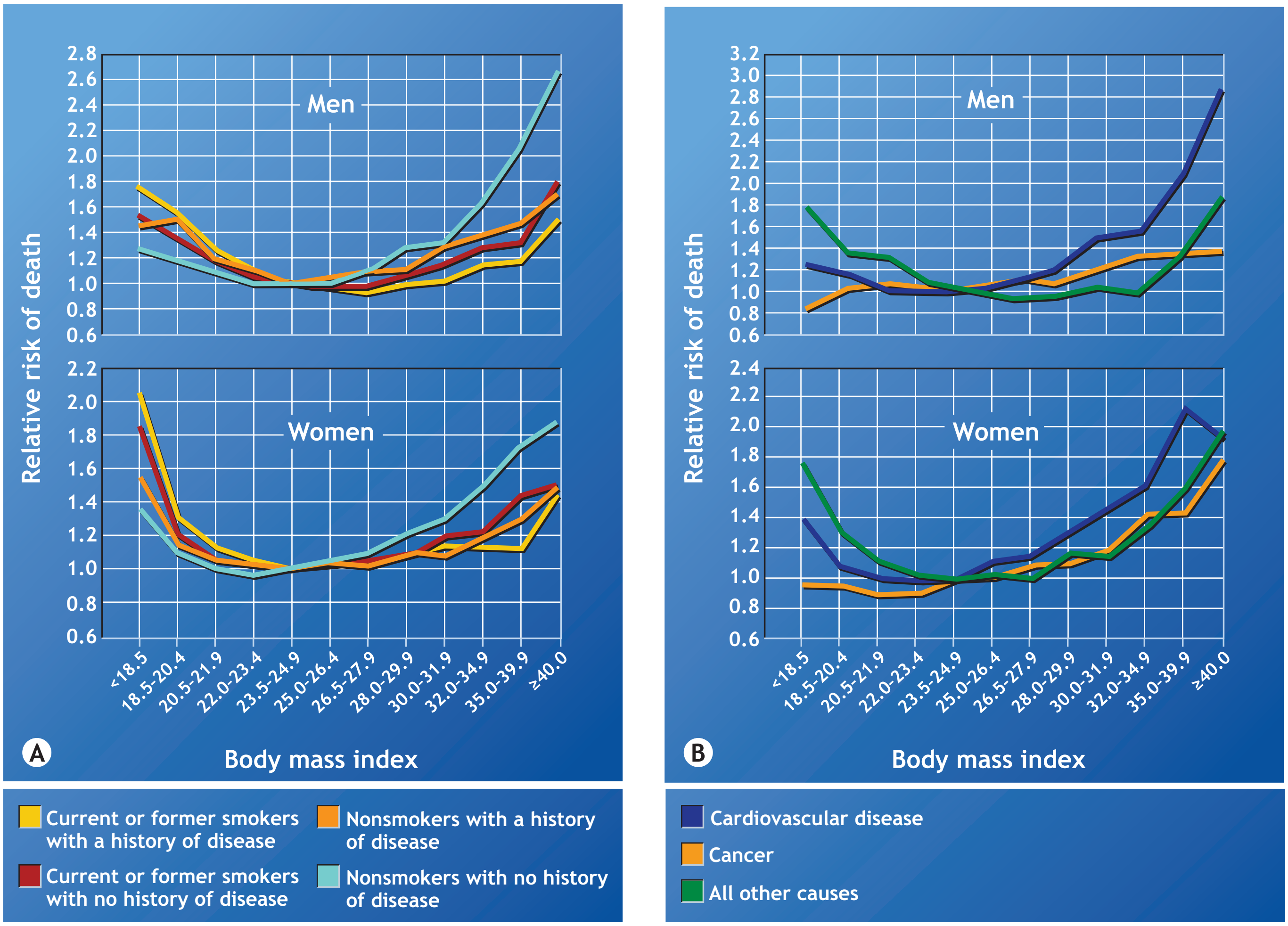


Figure 28.1 • **A.** Multivariate relative risk of death from *all causes* among men and women according to body mass index (BMI), smoking status, and disease status. Data are from four mutually exclusive subgroups. Nonsmokers had never smoked. **B.** Multivariate relative risk of death from cardiovascular disease, cancer, and all other causes according to BMI among men and women who had never smoked and had no history of disease at enrollment. Subjects with BMIs of 23.5 to 24.9 composed the reference category in both figures. (From Calle EE, et al. Body-mass index and mortality in a prospective cohort of U.S. adults. N Engl J Med 1999;341:1097.)

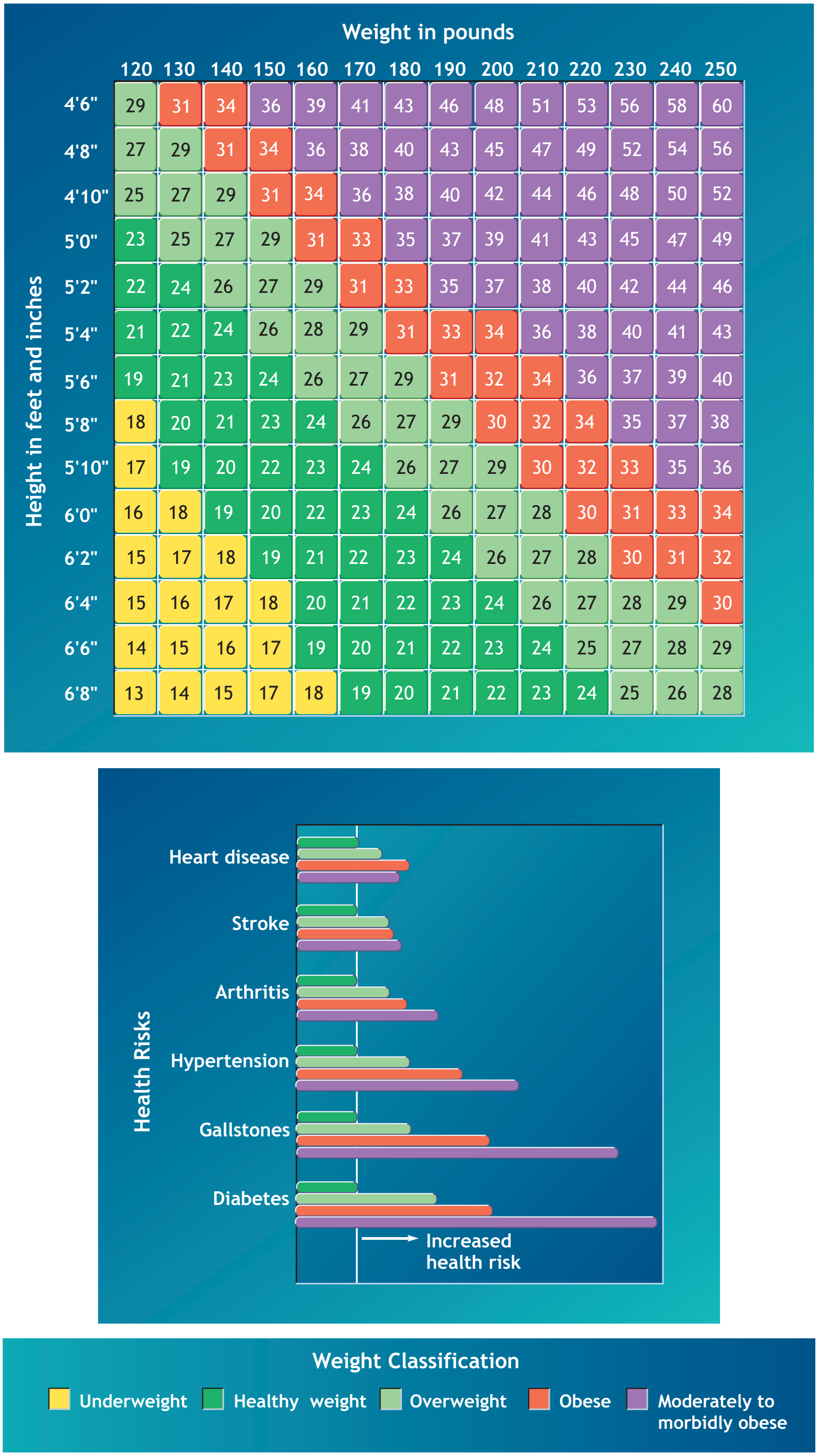
classify as overweight than their white counterparts. Figure 28.2 shows the computed BMI and accompanying weight classifications with associated health risks.

Figure 28.3 presents the revised (2000) growth charts for the United States for boys and girls ages 2 to 20 years. No absolute BMI standard exists to classify children and adolescents as overweight and obese. Expert panels recommend BMI-for-age to identify the increasing number of children and adolescents at the upper end of the distribution who are either overweight (≥95th percentile) or at risk for overweight (≥85th percentile and ≤95th percentile; see Chapter 30). Less specific recommendations exist for the lower end of the distributions, but BMIs in this lower range may indicate underweight or at risk for underweight.[46,171]

BMI Limitations

Current classification for overweight (and obesity) assumes that the relationship between BMI and percentage body fat (and disease risk) remains independent of age, gender, ethnicity, and race, but this is not the case.[34,49] For example, at a given BMI Asians have a higher body fat content than Caucasians and thus show greater risk for fat-related illness. A higher body fat percentage for a given BMI also exists among Hispanic American women compared with European American and African American women.[41] Failure to consider these sources of bias alters the proportion of individuals defined as obese by measured percentage body fat.[70,111] The accuracy of BMI in diagnosing obesity is limited for individuals in the intermediate BMI ranges, particularly in men and in the elderly.[138]

The BMI, like the height-weight tables, fails to consider the body's proportional composition or the all-important component of body fat distribution, referred to as **fat patterning**. In addition, factors other than excess body fat—bone, muscle mass, and even increased plasma volume induced by exercise training—affect the numerator of the BMI equation. A high BMI could lead to an incorrect



Weight in pounds

Height in feet and inches	120	130	140	150	160	170	180	190	200	210	220	230	240	250
4'6"	29	31	34	36	39	41	43	46	48	51	53	56	58	60
4'8"	27	29	31	34	36	38	40	43	45	47	49	52	54	56
4'10"	25	27	29	31	34	36	38	40	42	44	46	48	50	52
5'0"	23	25	27	29	31	33	35	37	39	41	43	45	47	49
5'2"	22	24	26	27	29	31	33	35	37	38	40	42	44	46
5'4"	21	22	24	26	28	29	31	33	34	36	38	40	41	43
5'6"	19	21	23	24	26	27	29	31	32	34	36	37	39	40
5'8"	18	20	21	23	24	26	27	29	30	32	34	35	37	38
5'10"	17	19	20	22	23	24	26	27	29	30	32	33	35	36
6'0"	16	18	19	20	22	23	24	26	27	28	30	31	33	34
6'2"	15	17	18	19	21	22	23	24	26	27	28	30	31	32
6'4"	15	16	17	18	20	21	22	23	24	26	27	28	29	30
6'6"	14	15	16	17	19	20	21	22	23	24	25	27	28	29
6'8"	13	14	15	17	18	19	20	21	22	23	24	25	26	28

Figure 28.2 • Body mass index (BMI), weight classifications, and associated health risks.

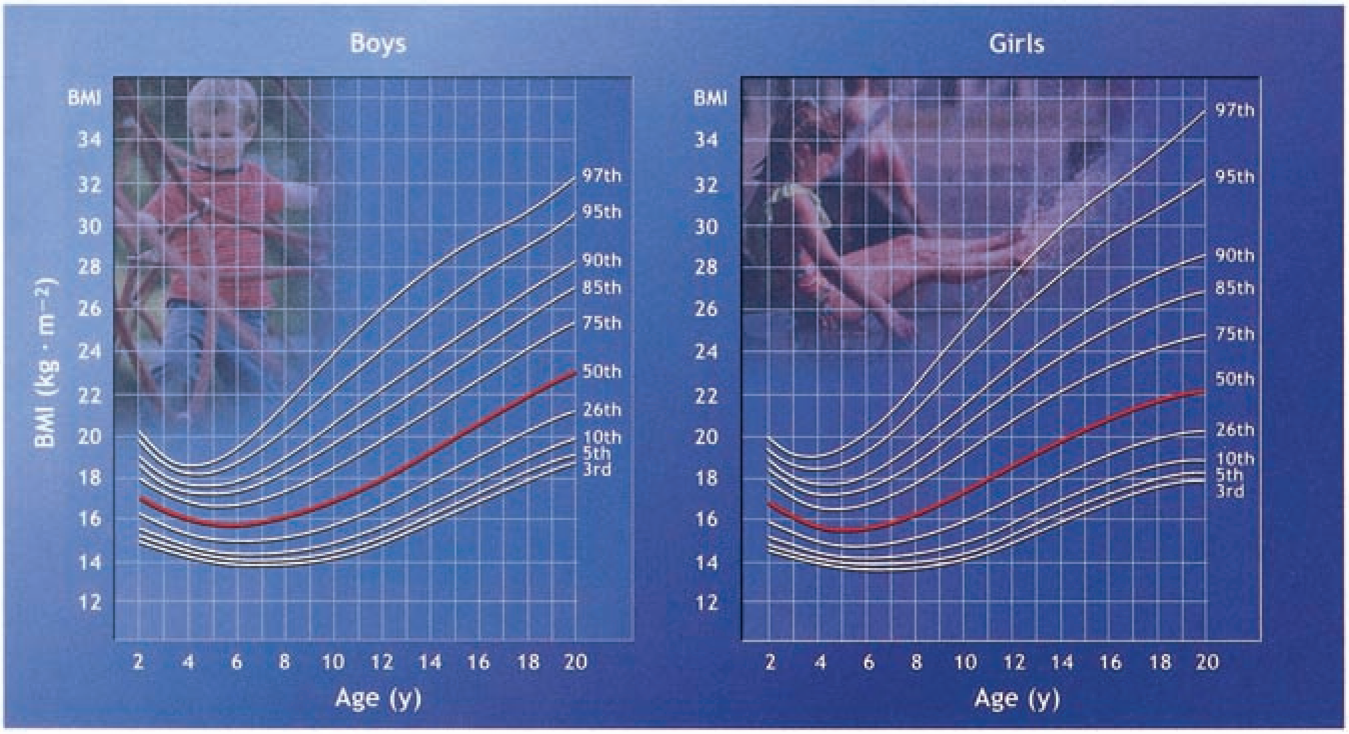


Figure 28.3 • Body mass index-for-age percentiles for boys and girls ages 2 to 20 years. Developed by the National Center for Health Statistics in collaboration with the National Center for Chronic Disease Prevention and Health Promotion (2000). (From Kuczmarski RJ, et al. CDC growth charts: United States. Advance Data 2000;314. From Vital and Health Statistics of the Centers for Disease Control and Prevention/National Center for Health Statistics.)

interpretation of overfatness in lean individuals with excessive muscle mass because of genetic makeup or exercise training.[127]

The possibility of misclassifying someone as overweight by applying BMI standards pertains particularly to large-sized field athletes, bodybuilders, weightlifters, heavier wrestlers, and most professional American football players. Figure 28.4 plots the average BMI for all National Football League (NFL) roster players at each 5-year interval between 1920 and 1996 based on 53,333 players. Average body fat content of players measured during the late 1970s through the 1990s fell below the range typically associated with population data for men. Those with body fat evaluated by densitometry during this era included all roster players of the New York Jets, Washington Redskins, New Orleans Saints, and Dallas Cowboys. Almost all players from 1960 onward classify as overweight based on standard height–weight tables. For the BMI data up to 1989, values for linebackers, skill players, and defensive backs represent the low category for disease risk, while the BMIs for offensive and defensive linemen place them at "moderate" risk. After 1989, risk for linebackers increased from the low to moderate category. The BMIs for offensive and defensive linemen, the largest NFL players, quickly approached a high risk and remained in that category. This does not bode well from a health perspective for these large-size players, at least based on BMI risk predictions for the general population.

In contrast to professional football players, the BMI for the National Basketball Association (NBA) players for the 1993–1994 season averaged only 24.5. This relatively low BMI places them in the very low risk category, yet height–weight standards would classify them as overweight.

Another category of world-class athletes—racing cyclists who participated in the Tour de France—had remarkably low BMIs. In the 1997 race, the BMI for 170 competitors averaged 21.5 (1.79 m stature, 68.75 kg body mass). Three years later in the 2000 race, the BMI for 162 competitors remained essentially unchanged (21.5; 1.79 m stature, 69.1 kg body mass). On average, stature among cycling teams was within 0.2 m (1.78 to 1.80 m) and body mass ranged from 66.8 kg (Swiss) to 72.1 kg (U.S.). The homogeneity in body size variables among these top-level performers makes it unlikely that body composition variables per se determine individual differences in cycling performance.

Miss America and BMI: Undernourished Role Models?

Many consider Miss America beauty pageant contestants to possess the ideal combination of beauty, grace, and

Figure 28.4 • BMIs for all players in the National Football League between 1920 and 1996 (*n* = 53,333). Categories include offensive and defensive linemen, linebackers, skill players (quarterbacks, receivers, backfield), and defensive backs. (Data compiled by K. Monahan and F. Katch, Exercise Science Department, University of Massachusetts, Amherst, 1996.)

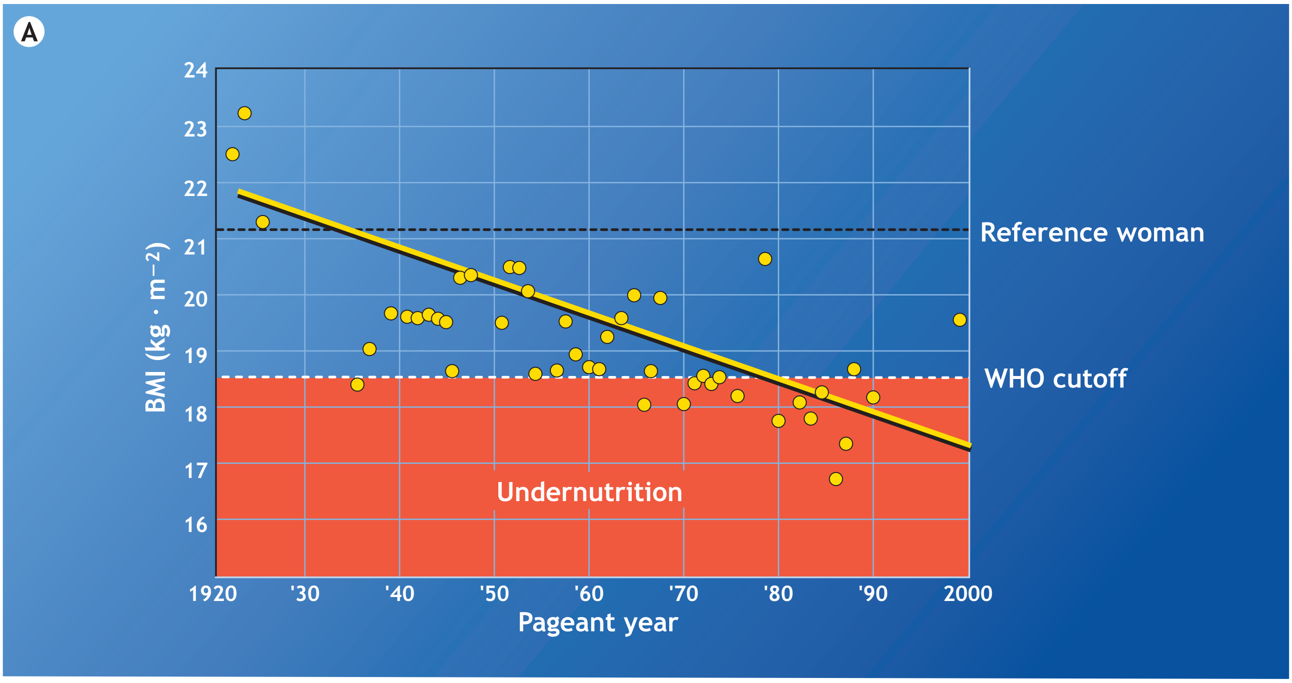
talent. Each competitor survives the rigors of local and state contests, thus satisfying judges that finalists have "ideal qualities" worthy of role-model status. The consummate image of the Miss America physique to some extent shapes society's generalized "ideal" for female size and shape. An important question concerns whether such images, televised worldwide to millions of viewers, reinforce an unhealthful message to young women who attempt to emulate such ideal physiques.

FIGURE 28.5 shows the BMIs and accompanying anthropometric data of Miss America contestants from available data between 1922 and 1999 (excluding 1927–1933, when the pageant was not held, and from 2000 on, when data were no longer available). Also included for comparison about body size is Behnke's standard for the reference woman (Fig. 28.5C; see p. 735). The *bottom horizontal white dashed line* in Figure 28.5A designates the World Health Organization (WHO) cutoff for undernutrition established at a BMI of 18.5.[188] The *top horizontal black dashed line* represents the BMI for the reference woman (see Fig. 28.6; stature: 1.638 m; body mass: 56.7 kg; BMI: 21.1). The downward slope of the regression line from 1922 to 1999 shows a clear tendency for relative undernutrition from the mid-1960s to approximately 1990. Using the WHO cutoff, the BMIs of 30% (*n* = 14) of the 47 Miss America winners fell below 18.5. Raising the BMI cutoff to 19.0 adds another 18 women, or a total of 48% of the winners with undesirable values. Approximately 24% of contest winners had BMIs between 20.0 and 21.0, and no winner after 1924 had a BMI equaling that of the reference woman!

Interestingly, 1965 was the last year we could locate girth measurements from official press releases or newspaper coverage of the contest. We compared the percentage difference between the Miss America girth averages with the corresponding measurements for the reference woman *(bottom yellow row* of Fig. 28.5C). For the average bust, waist, and hip values (35.1, 24.0, 35.4 in, respectively), Miss America's measurement exceeded the reference woman's bust measurement by 2.6 inches (8%) but fell 7% below for the waist value (−1.8 in.) and 5% (−1.7 in.) for the hips. Unfortunately, no contemporary data exist from 1966 through 2010, so we cannot compare the current Miss America's physique with historical data.

COMPOSITION OF THE HUMAN BODY

In 1921, Czech anthropologist J. Matiega described a four-component model consisting of the weight of the skeleton (S), skin plus subcutaneous tissue (Sk + St), skeletal muscle (M), and a remainder (R).[105] The sum of the four components equaled the body mass.



B

	1922-1948				1951-1968				1970-1999		
	Age	Ht	Wt		Age	Ht	Wt		Age	Ht	Wt
1922	18	65	135	1951	20	65.5	119	1970	21	65.5	110
1923	19	65	140	1952	25	70	143	1971	21	68	121
1924	18	66	132	1953	19	66.5	128	1972	22	67	118
1926	18	52.5	118	1954	20	68	132	1973	23	68	120
1936	22	66	114	1955	19	68.5	124	1974	23	69	125
1937	17	66.5	120	1957	19	67	120	1976	18	70.5	128
1939	19	67	126	1958	20	68.5	130	1979	22	64	121
1941	19	65.5	120	1959	21	65	114	1980	22	67	114
1942	21	65	118	1960	21	67	120	1983	25	67	115
1943	21	68	130	1961	18	66	116	1984	20	66	110
1944	21	67	125	1962	19	65.5	118	1985	20	68	120
1945	18	70	136	1964	21	66.5	124	1986	21	69	114
1946	21	68	123	1965	22	124	124	1987	21	68.5	116
1947	21	67	130	1966	19	115	115	1988	24	70	131
1948	18	69	138	1967	19	116	116	1990	24	67.5	118
				1968	19	135	135	1999	24	69	133

C

Girths (in)

	Bust	Waist	Hips	Calf	Thigh	Ankle	Biceps	Wrist
1926	33	24.5	33.5	12.5	19.5	7	—	—
1935	33	23	35.5	—	—	—	—	—
1926	34	23.5	34.5	13	19	8.5	9.5	5.5
1941	34	24	36	14	23	8	11	6
1942	34	24	34.5	—	—	—	—	—
1943	36	23	35	—	—	—	—	—
1944	36.5	25	37.5	13	19.5	8	—	—
1945	35.5	25	35	14.5	20	8.5	—	—
1946	35.5	25.5	36	13.5	22	8.5	—	—
1947	35	35	—	—	—	—	—	—
1948	37	37	—	—	—	—	—	—
1951	35	35	—	—	—	—	—	—
1952	36	24	36	—	—	—	—	—
1953	35	23	35	—	—	—	—	—
1954	37	24	36	—	—	—	—	—
1955	34.5	22	35	—	—	—	—	—
1957	35	23	35	—	—	—	—	—
1958	35	25	36	—	—	—	—	—
1959	34	22	35	—	—	—	—	—
1960	36	24	36	—	—	—	—	—
1961	35	22	35	—	—	—	—	—
1962	35	24	35	—	—	—	—	—
1964	35	23	35	—	—	—	—	—
1965	36	24	36	—	—	—	—	—
Ref W*	36.1	30.3	36.8	14.1	21.6	8.9	12.5	6.8

Ref W* = Behnke's reference woman; stature = 163.8 cm,
body mass = 56.7 kg

Figure 28.5 • **A.** Body mass index (BMI) of 47 Miss America pageant contestants from 1922 to 1999. The *top horizontal black dashed line* represents the BMI for Behnke's reference woman (21.1 kg · m^{-2}). The *bottom horizontal white dashed line* designates the World Health Organization's (WHO) BMI demarcation for undernutrition (18.5 kg · m^{-2}). **B.** Available data for age, height (in.), and weight (lb) for the contest winners. **C.** Selected girths for 24 Miss America winners from 1926 to 1965. Despite our best efforts, we were unable to locate height or weight data for Miss America winners from 2000 on.

Over the past 85 years, studies have focused on body composition and how best to measure the various components. One methodology partitions the body into two distinct compartments: (1) fat-free body mass and (2) fat mass. The density of homogenized samples of fat-free body tissues in small mammals equals 1.100 g · cm^{-3} at 37°C.[137] Fat-free tissue maintains water content of 73.2%,[120] with potassium at 60 to 70 mmol · kg^{-1} in men and 50 to 60 mmol · kg^{-1} in women.[16] Fat stored in adipose tissue has a density of 0.900 g · cm^{-3} at 37°C.[112] Subsequent body composition studies expanded the two-component model to account for biologic variability in three (water, protein, fat) or four (water, protein, bone mineral, fat) distinct components.[184,186] Women and men differ in relative quantities of specific body composition components. Consequently, gender-specific reference standards provide a framework to evaluate on a relative basis what constitutes "normal" body composition. Behnke's model for the reference man and reference woman proves useful for such purposes.[12]

Reference Man and Reference Woman

FIGURE 28.6 shows the body composition compartments for the **reference man** and **reference woman**. This schema partitions body mass into lean body mass, muscle, and bone, with total body fat subdivided into storage and essential fat components. This model integrates the average physical dimensions from thousands of individuals measured in large-scale civilian and military anthropometric surveys with data from laboratory studies of tissue composition and structure.

The reference man is taller and heavier, his skeleton weighs more, and he possesses a larger muscle mass and lower body fat content than the reference woman. These differences exist even when expressing fat, muscle, and bone as a percentage of body mass. Just how much of the gender difference in body fat relates to biologic and behavioral factors, perhaps from lifestyle differences, remains unclear. Undoubtedly, hormonal differences play an important role. The concept of reference standards does not mean that men and women should strive to achieve this body composition or that the reference man and woman reflect some healthful standard. Instead, the reference model proves useful for statistical

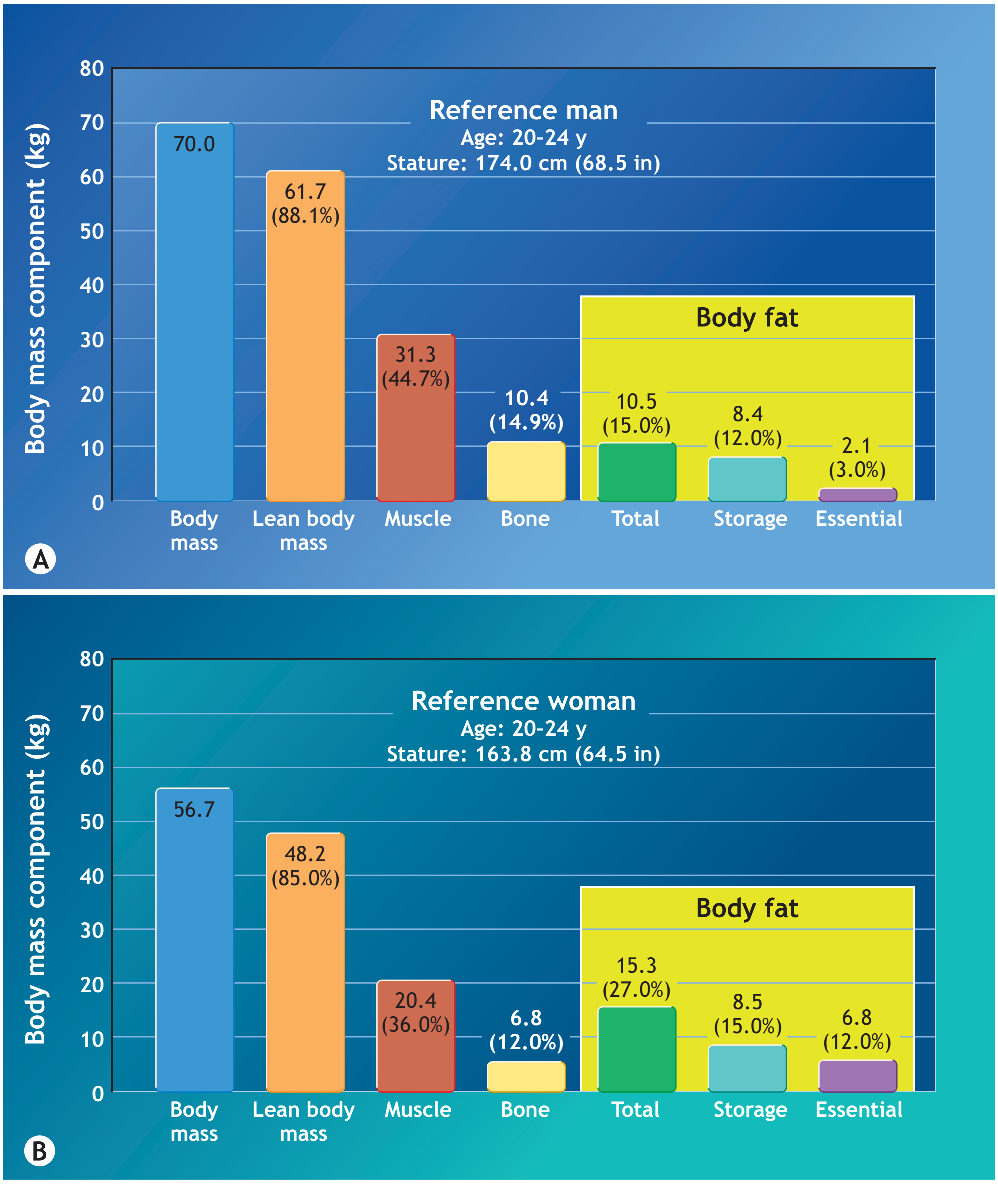


Figure 28.6 • Behnke's theoretical model for the body composition of the reference man (**A**) and reference woman (**B**). Values in parenthesis indicate percentage of total body mass.

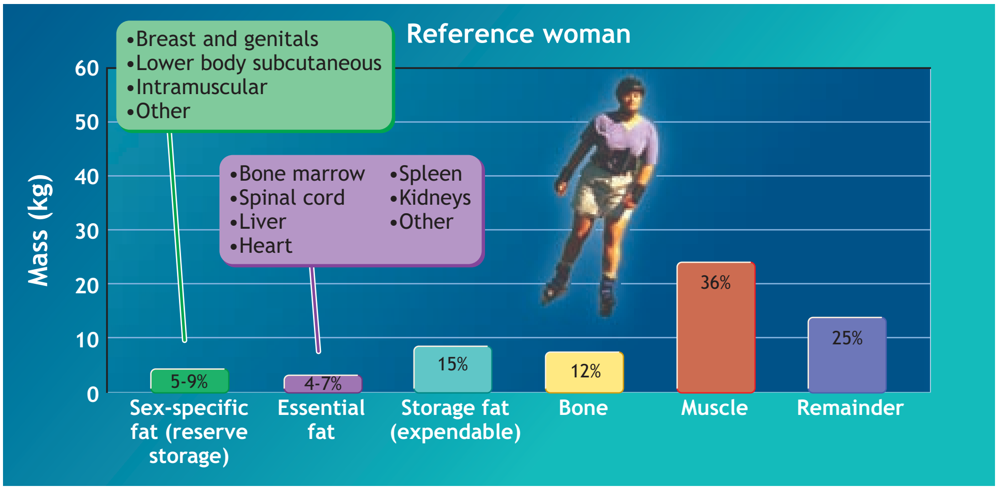


Figure 28.7 • Theoretical model for body fat distribution for the reference woman with body mass of 56.7 kg, stature of 163.8 cm, and 27% body fat. (From Katch VL, et al. Contribution of breast volume and weight to body fat distribution in females. Am J Phys Anthropol 1980;53:93.)

comparisons and interpretations of data from other studies of elite athletes, individuals involved in exercise training, different racial and ethnic groups, and the underweight and the obese.

Essential and Storage Fat

In the reference model, total body fat exists in two storage sites or depots—essential fat and storage fat. **Essential fat** consists of the fat in heart, lungs, liver, spleen, kidneys, intestines, muscles, and lipid-rich tissues of the central nervous system and bone marrow. *Normal physiologic functioning requires this fat*. In the heart, for example, dissectible fat from cadavers represents approximately 18.4 g, or 5.3%, of an average heart weighing 349 g in males and 22.7 g, or 8.6%, of a heart weighing 256 g in females.[187] Importantly, essential fat in the female includes additional **sex-specific essential fat**. Whether this fat provides reserve storage for metabolic fuel is unclear.

The **storage fat** depot includes fat primarily in adipose tissue. The adipose tissue energy reserve contains approximately 83% pure fat, 2% protein, and 15% water within its supporting structures. Storage fat includes the visceral fatty tissues that protect the organs within the thoracic and abdominal cavities from trauma, and the larger adipose tissue volume deposited beneath the skin's surface. A similar proportional distribution of storage fat exists in men and women (12% of body mass in men, 15% in women), but the total percentage of essential fat in women that includes the sex-specific fat averages four times the value in men. *The additional essential fat most likely serves biologically important functions for child bearing and other hormone-related functions*. Considering the reference body's total quantity of storage fat (approximately 8.5 kg), this depot theoretically represents 63,500 kCal of available energy, or the energy equivalent of playing pickup basketball nonstop for 107 hours, golfing without a cart or walking at a normal pace on a track for 176–180 continuous hours, or treading water in a swimming pool without a break for 10 days straight!

FIGURE 28.7 partitions the distribution of body fat for the reference woman. As part of the 5 to 9% sex-specific fat reserves, breast fat probably contributes no more than 4% of body mass for women whose total fat content ranges between 14 and 35%.[80] We interpret this to mean that other substantial sex-specific fat depots exist (e.g., pelvic, buttock, and thigh regions) that contribute to the female's body fat stores.

Fat-Free Body Mass and Lean Body Mass. The terms **fat-free body mass** (**FFM**) and **lean body mass** refer to specific entities. Lean body mass contains the small percentage of non–sex-specific essential fat equivalent to approximately 3% of body mass. In contrast, FFM represents the body mass devoid of *all* extractable fat (FFM = body mass − fat mass). Behnke points out that FFM refers to an *in vitro* entity appropriate to carcass analysis. He considered lean body mass as an *in vivo* entity relatively constant in water, organic matter, and mineral content throughout the active adult's life span. *In normally hydrated, healthy adults, the FFM and lean body mass differ only in the essential fat component.*

Figure 28.6 showed that lean body mass in men and **minimal body mass** in women consist chiefly of essential fat (plus sex-specific essential fat for women), muscle, water, and bone. The whole-body density of the reference man with 12% storage fat and 3% essential fat is 1.070 $g \cdot cm^{-3}$; the density of his FFM is 1.094 $g \cdot cm^{-3}$. If the reference man's total body fat percentage equals 15.0% (storage fat plus essential fat), the density of a hypothetical fat-free body attains the upper limit of 1.100 $g \cdot cm^{-3}$.

In the reference woman, the average whole-body density of 1.040 $g \cdot cm^{-3}$ represents a body fat percentage of 27%; of this, approximately 12% consists of essential body fat. A density of 1.072 g $\cdot$ cm^{-3} represents the minimal body mass of 48.5 kg. In actual practice, density values that exceed 1.068 for women (14.8% body fat) and 1.088 g $\cdot$ cm^{-3} for men (5% body fat) rarely occur except in young, lean athletes.

Minimal Leanness Standards

A biologic lower limit exists beyond which a person's body mass cannot decrease without impairing health status or altering normal physiologic functions.

Men

To estimate the lower body fat limit in men (i.e., lean body mass), subtract storage fat from body mass. For the reference man, the lean body mass (61.7 kg) includes approximately 3% (2.1 kg) essential body fat. Encroachment into this reserve may impair optimal health and capacity for vigorous exercise.

Low body fat values exist for male world-class endurance athletes and some conscientious objectors to military service who voluntarily reduced body fat stores during a prolonged experiment with semistarvation. The low fat levels of marathon runners, which ranges from 1 to 8% of body mass, probably reflect adaptation to severe training for distance running.[92] A low body fat level reduces the energy cost of weight-bearing exercise; it also provides a more effective gradient to dissipate metabolic heat generated during prolonged, intense exercise.

Considerable variation exists in the FFM of different athletes, with values ranging from a low of 48.1 kg in some jockeys to over 100 kg in football linemen and field-event athletes. Seven elite sumo wrestlers *(seki-tori)* possessed an average FFM of 109 kg.[85]

Women

In comparison to the lower limit of body mass for the reference man (with 3% essential fat), the lower limit for the reference woman includes approximately 12% essential fat. This theoretical lower limit developed by Dr. Behnke, termed *minimal body mass,* is 48.5 kg for the reference woman. Generally, the leanest women in the population do not possess less than 10 to 12% body fat, a narrow range at the lower limit for most women in good health. *Behnke's theoretical concept of minimal body mass in women that incorporates 12% essential fat, corresponds to the lean body mass in men that includes 3% essential fat.*

Leanness, Regular Exercise, and Menstrual Irregularity

Physically active women, mainly participants in the "low weight" or "appearance" sports (e.g., distance running, bodybuilding, figure skating, diving, ballet, and gymnastics), increase their likelihood for one of three maladies: (1) delayed onset of menstruation, (2) irregular menstrual cycle (**oligomenorrhea**), or (3) complete cessation of menses (**amenorrhea**). Menstrual and ovarian dysfunction results largely from changes in the pituitary gland's normal pulsatile secretion of luteinizing hormone regulated by gonadotropin-releasing hormone from the hypothalamus.

Amenorrhea occurs in 2 to 5% of women of reproductive age in the general population, but it can reach 40% in some athletic groups. As a group, ballet dancers remain lean, with a greater incidence of menstrual dysfunction and eating disorders and a higher mean age at menarche than age-matched, nondance counterparts.[47] One-third to one-half of female endurance athletes exhibit some menstrual irregularity. In premenopausal women, irregularity or absence of menstrual function accelerates bone loss and increases risk of musculoskeletal injury during exercise and causes a longer interruption of training (see Chapter 2).[11,122]

A prolonged level of physical stress may disrupt the hypothalamic–pituitary–adrenal axis and modify the output of gonadotropin-releasing hormone, which results in irregular menstruation (**exercise stress hypothesis**). A concurrent hypothesis maintains that energy (fat) reserves inadequate to sustain pregnancy induce cessation of ovulation (**energy availability hypothesis**).

INTEGRATIVE QUESTION

What arguments counter the following position? No true sex difference exists in body fat level, but only a difference caused by gender-related patterns of regular physical activity and caloric intake.

Lean-to-Fat Ratio

An optimal **lean-to-fat ratio** is important to normal menstrual function, perhaps through peripheral fat's role that converts androgens to estrogens or through adipose tissue's production of leptin, a hormone intimately linked to body fat levels and appetite control (see Chapter 30) and initiation of puberty.[155] Thus, linkage exists between hormonal regulation of sexual maturity onset (and perhaps continued optimal sexual function) and level of stored energy from accumulated body fat.

Some researchers assert that 17% body fat represents a lower-end critical level for the onset of menstruation, with 22% fat needed to sustain a normal menstrual cycle.[47,48] They reason that lower body fat levels trigger hormonal and metabolic disturbances that affect menses. *Objective data indicate that many physically active females who are below the supposedly critical 17% body fat level have normal menstrual cycles with high levels of physiologic and exercise capacity.* Conversely, some amenorrheic athletes maintain body fat levels considered average for the population. One of our laboratories compared 30 athletes and 30 nonathletes, all with less than 20% body fat, for menstrual cycle regularity.[78] Four athletes and 3 nonathletes, ranging from 11 to 15% body fat, maintained regular cycles, whereas 7 athletes and 2 nonathletes had irregular cycles or were amenorrheic. For the total sample, 14 athletes and 21 nonathletes maintained regular menstrual cycles. These data indicate that normal menstrual function *does not require* a critical body fat level of 17 to 22%.

Potential causes of menstrual dysfunction include the complex interplay of physical, nutritional, genetic, hormonal, regional fat distribution, psychologic, and environmental factors.[84] An intense exercise bout triggers the release of an array of hormones, some of which disrupt normal reproductive function.[56,181] Intense and/or prolonged exercise that releases cortisol and other stress-related hormones also can alter ovarian function via the hypothalamic–pituitary–adrenal axis.[31,101]

Consuming well-balanced, nutritious meals prevents or reverses athletic amenorrhea without requiring the athlete to reduce exercise training volume or intensity.[100] In this regard, when injuries to young amenorrheic ballet dancers prevent them from exercising regularly, normal menstruation resumes even though body weight remains low.[72,191] *Proponents of this* ***"energy deficit" explanation*** *maintain that exercise per se exerts no deleterious effect on the reproductive system other than the potential impact of its additional energy cost on creating a negative energy balance.*[5,98,99,102,180]

The effects and risks of sustained amenorrhea on the reproductive system remain unknown. A gynecologist/endocrinologist should evaluate failure to menstruate or cessation of the normal cycle because it may reflect pituitary or thyroid gland malfunction or premature menopause.[10,97] As we point out in Chapter 2, prolonged menstrual dysfunction affects bone mass profoundly and negatively.

Delayed Onset of Menstruation and Cancer Risk

The delayed onset of menarche in chronically active young females may offer positive health benefits. Female athletes who start training in high school or earlier show a lower lifetime occurrence of cancers of the breast and reproductive organs, and non–reproductive-system cancers than less-active counterparts.[48] Even among older women, regular exercise protects against reproductive cancers. Swedish researchers studied the country's entire female population ages 50 to 74 years in 1994–1995.[119] Higher levels of occupational and leisure-time physical activity in normal-weight nonsmokers during ages 18 to 30 years related to lower postmenopausal endometrial cancer risk. Women who exercise an average of 4 hours a week after menarche reduce breast cancer risk by 50% compared with age-matched inactive women.[14] One proposed mechanism for reduced cancer risk links lower total estrogen production (or a less potent estrogen form) over the athlete's lifetime with fewer ovulatory cycles because of the delayed onset of menstruation.[93,176] Lower body fat levels in physically active individuals also may contribute to lowered cancer risk because peripheral fatty tissues convert androgens to estrogen.

COMMON TECHNIQUES TO ASSESS BODY COMPOSITION

Two procedures evaluate body composition:

1. Direct measurement by chemical analysis of the animal carcass or human cadaver
2. Indirect estimation by hydrostatic weighing, simple anthropometric measurements, and other clinical and laboratory procedures

Direct Assessment

Two approaches directly assess body composition. One technique dissolves the body in a chemical solution to determine its mixture of fat and fat-free components. The other physically dissects fat, fat-free adipose tissue, muscle, and bone. Considerable research has chemically assessed body composition in various animal species, but few studies have directly determined human fat content.[25,26,27] These labor-intensive and tedious analyses require specialized laboratory equipment and involve ethical questions and legal hurdles in obtaining cadavers for research purposes.

Direct body composition assessment suggests that while considerable individual differences exist in total body fatness, the compositions of skeletal mass and the fat-free and fat tissues remain relatively stable. Researchers have developed mathematical equations to indirectly predict the body's fat percentage on the basis of the assumed constancy of these tissues.

Indirect Assessment

Diverse indirect procedures assess body composition. One involves Archimedes' principle applied to hydrostatic weighing (also referred to as *hydrodensitometry*, or *underwater weighing*). This method computes percentage body fat from body density (ratio of body mass to body volume). Other procedures predict body fat from skinfold thickness and girth measurements, X-ray, total body electrical conductivity or bioimpedance (including segmental impedance), near-infrared interactance, ultrasound, computed tomography, air plethysmography, and magnetic resonance imaging.

Hydrostatic Weighing: Archimedes' Principle

The Greek mathematician and inventor **Archimedes** (287–212 BC) discovered a fundamental principle currently applied to evaluate human body composition. An itinerant scholar of that time described the circumstances surrounding the event:

> King Hieron of Syracuse suspected that his pure gold crown had been altered by substitution of silver for gold. The King directed Archimedes to devise a method for testing the crown for its gold content without dismantling it. Archimedes pondered over this problem for many weeks without succeeding, until one day, he stepped into a bath filled to the top with water and observed the overflow. He thought about this for a moment,

> and then, wild with joy, jumped from the bath and ran naked through the streets of Syracuse shouting, "Eureka, Eureka! I have discovered a way to solve the mystery of the King's crown."

Archimedes reasoned that a substance such as gold must have a volume proportional to its mass; measuring the volume of an irregularly shaped object would require submersion in water with collection of the overflow. To apply his reasoning, Archimedes took lumps of gold and silver of the same mass as the crown and submerged each in a water-filled container. He discovered the crown displaced more water than the lump of gold and less than the lump of silver. This could only mean that the crown consisted of *both* silver and gold as the king suspected.

Essentially, Archimedes compared the **specific gravity** of the crown with the specific gravities for gold and silver. He also reasoned that an object submerged or floating in water becomes buoyed up by a counterforce that equals the weight of the volume of water it displaces. This buoyant force supports an immersed object against gravity's downward pull. Thus, an object *loses* weight in water. *Because the object's loss of weight in water equals the weight of the volume of water it displaces, its specific gravity refers to the mass of an object in air divided by its loss of weight in water*. The loss equals the weight in air minus the weight in water.

$$\text{Specific gravity} = \text{Weight in air} \div \text{Loss of weight in water}$$

In practical terms, suppose a crown weighed 2.27 kg in air and 0.13 kg less, or 2.14 kg, when weighed underwater (Fig. 28.8). Dividing the crown's mass (2.27 kg) by its weight loss in water (0.13 kg) yields a specific gravity of 17.5. Because this ratio differs considerably from gold's specific gravity of 19.3, we too can conclude: "Eureka, the crown is a fraud!" The physical principle Archimedes discovered allows us to use water submersion to determine the body's volume. Dividing body mass by its volume yields body density (**density = mass ÷ volume**), and from this, an estimate of percentage body fat.

One can think of specific gravity as an object's "heaviness" related to its volume. Objects of the same volume may vary considerably in density defined as mass per unit volume. One gram of water occupies exactly 1 cm^3 at a temperature of 4°C (39.2°F); the density equals 1 $\text{g} \cdot \text{cm}^{-3}$. Water achieves its greatest density at 4°C; thus, increasing water temperature increases the volume of 1 g of water and decreases its density. One must correct the volume of an object weighed in water for water density at the weighing temperature (see Appendix A, available online at http://thepoint.lww.com/mkk7e). The temperature effect distinguishes density from specific gravity.

INTEGRATIVE QUESTION

Why does a solid piece of steel or concrete sink rapidly when placed in water while a ship made of either substance readily floats?

Body Volume Measurement

The principle discovered by Archimedes applies body volume measurement in one of two ways: (1) water displacement or (2) hydrostatic weighing. Body volume requires accurate measurement because small volume variations substantially affect the density calculation and computed percentage body fat and FFM.

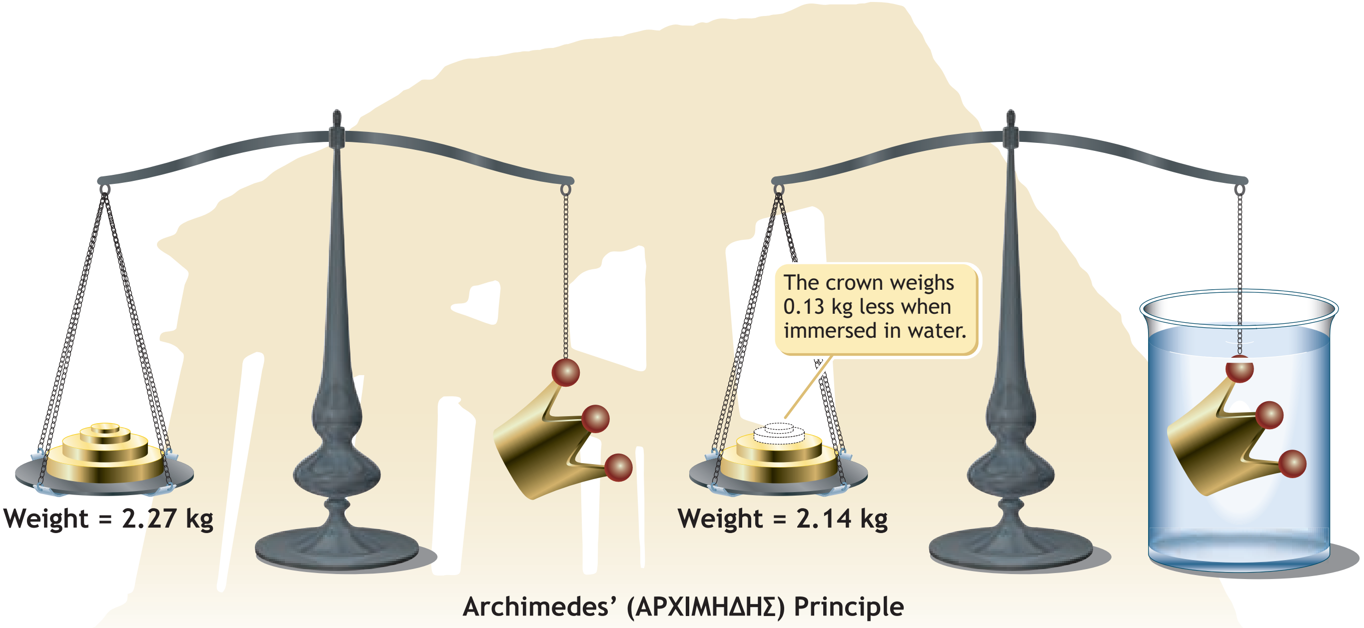


Figure 28.8 • Archimedes' principle of buoyant force to determine the volume and, subsequently, specific gravity of the king's crown.

Water Displacement

One can measure the volume of an object submerged in water by the corresponding rise in the level of water within a container. With this technique, a finely calibrated tube, secured to the side of the container, that measures the rise of water permits accurate volume measurements. With this method, one must account for the volume of air remaining in the lungs during submersion. The usual protocol assesses this lung volume before the subject enters the tank and subtracts it from the total body volume determined by water displacement. **Water displacement** has proved effective in assessing arm and leg volumes and their corresponding changes with exercise training, weight gain or loss, or physical inactivity.

Hydrostatic Weighing

Hydrostatic weighing provides the most common application of Archimedes' principle to determine body volume. It computes body volume as the difference between body mass measured in air (M_a) and body weight measured during water submersion (W_w; the correct term because body mass remains unchanged under water). *Body volume equals loss of weight in water with the appropriate temperature correction for water's density.*

FIGURE 28.9 illustrates measurement of body volume by hydrostatic weighing under four different conditions. The first step in each condition accurately assesses the subject's body mass in air, usually within ±50 g. The subject, who wears a thin nylon swimsuit, sits in a lightweight, plastic tubular chair suspended from the scale and submerged beneath the water's surface. A swimming pool serves the same purpose as the tank, with the scale and chair assembly suspended from a support at the side of the pool or diving board. The tank maintains a comfortable water temperature near 95°F, similar to skin temperature. Water temperature provides the correction factor to determine water density at the weighing temperature. A diver's belt secured around the waist (or placed across the lap) stabilizes the subject from floating toward the surface

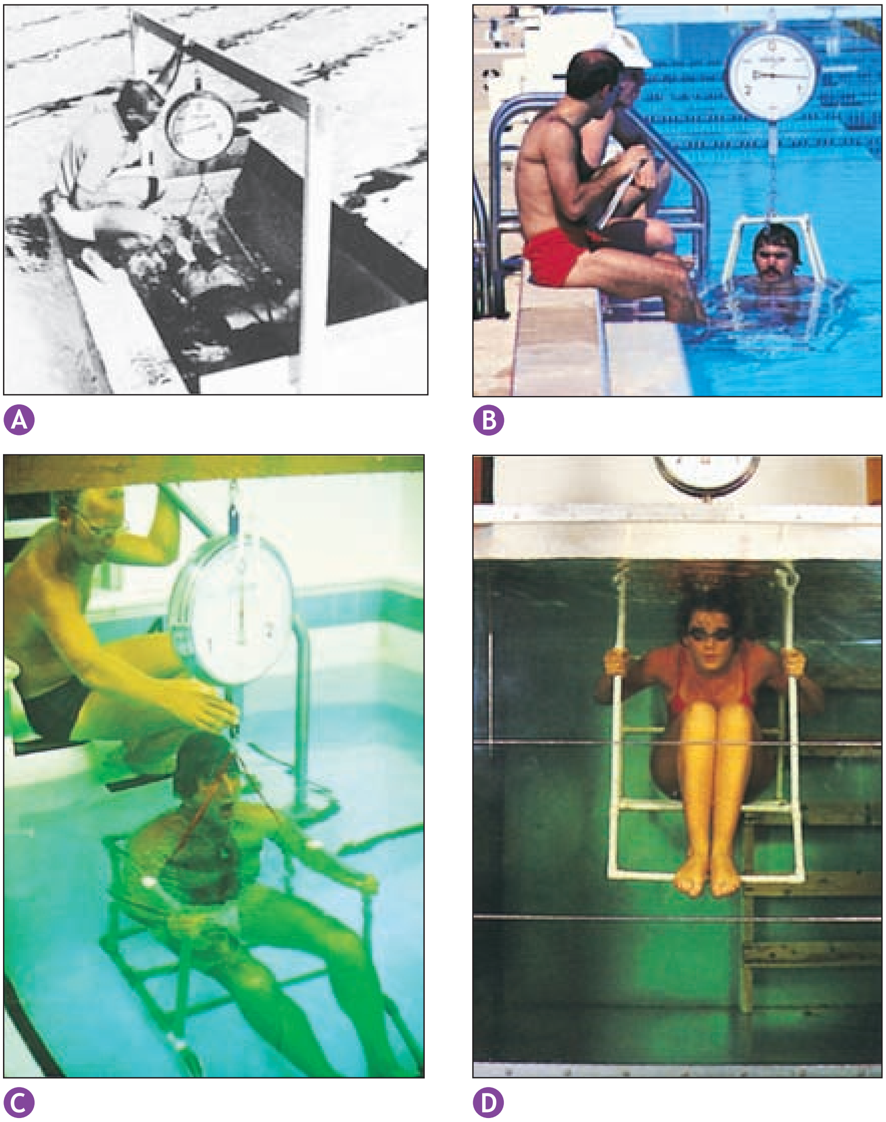


Figure 28.9 • Measuring body volume by underwater weighing. Prone and supine underwater weighing methods provide the same values with residual lung volume measured before, during, or after the underwater weighing. Measurements taken (**A**) prone in a swimming pool, (**B**) seated in a swimming pool, (**C**) seated in a therapy pool, and (**D**) seated in a stainless steel tank with Plexiglas front in the laboratory. For any of the methods, subjects can use a snorkel with nose clip if they express apprehension about submersion. The final calculation of underwater weight must account for these added objects.

during submersion. The underwater weight of this belt and chair (tare weight) is subtracted from the subject's total weight under water.

Seated with the head above water, the subject makes a forced maximal exhalation while slowly lowering the head under the water. The breath is held for 5 to 8 seconds to allow the scale pointer to stabilize before recording the reading at the midpoint of the oscillations. The subject repeats the procedure 8 to 12 times to obtain a dependable underwater weight score. Even when achieving a full exhalation, a small volume of air, the residual lung volume, remains in the lungs. Body volume calculation requires subtracting the buoyant effect of the residual lung volume measured immediately before, during, or following the underwater weighing. Failure to account for residual lung volume *underestimates* whole-body density because the lungs' air volume contributes to buoyancy. This omission creates a "fatter" person when converting body density to percentage body fat.

Variations with Menstruation. Normal fluctuations in body mass (chiefly body water) related to the menstrual cycle generally do not affect body density and body fat assessed by hydrostatic weighing. However, some females experience noticeable increases in body water (>1.0 kg) during menstruation. Water retention of this magnitude affects body density and introduces a small error in computing percentage body fat.[21]

Calculating Body Composition from Body Mass, Body Volume, and Residual Lung Volume. Data for two professional football players, an offensive guard and a quarterback, illustrate the sequence of steps in computing body density, percentage fat, fat mass, and FFM (TABLE 28.2). Mass ÷ volume is the conventional formula for computing density, with density expressed in grams per cubic centimeter ($g \cdot cm^{-3}$), mass in kilograms, and volume in liters. The difference between M_a and W_w equals body volume after applying the appropriate water temperature correction (D_w). Air remaining in the lungs and other body "spaces" (abdominal viscera, sinuses) contributes some buoyancy at the time of underwater weighing. In the extreme, consuming 800 mL of a carbonated beverage increases gastric gas volume by approximately 600 mL. This underestimates body density by hydrostatic weighing by 0.7% and overestimates percentage body fat by 11% compared with measures made before drinking the beverage.[135] In most subjects, abdominal gas and sinus air volume remain small (<100 mL) and can be ignored. *This contrasts with the relatively large and variable residual lung volume, which requires measurement and subsequent subtraction from total body volume.*

Whereas the residual lung volume decreases slightly in a person immersed in water compared with residual volume in air (from water's compressive force against the thoracic cavity), the difference exerts only a small effect on computed percentage body fat.[64] Consequently, most laboratories measure residual lung volume in air just prior to underwater weighing.

TABLE 28.2 • Measurements of Two Professional Football Players from Underwater Weighing

Variable	Symbol	Defensive Lineman	Running Back
Body mass (kg)	M_a	121.73	97.37
Net underwater weight (kg)	W_w	7.30	6.52
Water temperature correction	D_w	0.99336	0.99336
Residual lung volume (L)	RLV	1.213	1.374
Total body volume (L)	TBV	113.89	90.08
Body density ($g \cdot cm^{-3}$)	D_b	1.0688	1.0809
Body Composition			
Relative percentage body fat (%)	%Fat	13.1	8.0
Absolute body fat (kg)	FM	15.9	7.2
Fat-free body mass (kg)	FFM	105.8	90.2

[a] Siri equation, %fat = (495/density) ÷ 450.

The following formula computes body density (D_b) from underwater weighing variables:

$$
\begin{aligned}
D_b &= \text{mass} \div \text{volume} \\
&= M_a \div [(M_a \times W_w) \div D_w] - RLV
\end{aligned}
$$

For ease in computation, the following formula can be used to compute body density:

$$D_b = M_a \times D_w/(M_a - W_w - RLV \times D_w)$$

The lower part of Table 28.2 presents body composition results for the two football players based on body density.

Validity of Hydrostatic Weighing to Estimate Body Fat. Experimental evidence supports the validity of hydrostatic weighing to estimate the body's fat content. Behnke's early studies of Navy divers placed 64 subjects into two groups based on their body density. The mean difference between the groups in body mass (12.4 kg) and body volume (13.3 L) allowed Behnke to easily discern body composition differences between the groups. The ratio of the average differences (Δ mass ÷ Δ volume) equaled 0.933 $g \cdot cm^{-3}$, a value within the density range of 0.92 to 0.96 $g \cdot cm^{-3}$ for human adipose tissue. The difference in body mass between the high- and low-density groups represented the density of adipose tissue. Body density for a group of heavy but lean professional football players (lean body mass 20 kg higher than the Navy divers) averaged 1.080 $g \cdot cm^{-3}$. Behnke stated, "Here indeed was a presumptive demonstration that fat could be 'separated' from bone and muscle *in vivo* or 'the silver from the gold' by application of a principle renowned in antiquity."[12]

The lower and upper limits of body density among humans range from 0.93 g · cm^{-3} in the massively obese to nearly 1.10 g · cm^{-3} in the leanest males. This coincides nicely with the 1.10 density of fat-free tissue and 0.90 for homogenized samples of fat tissue from small mammals at 37°C.

Computing Body Density. For illustrative purposes, suppose a 50-kg person weighs 2 kg submerged in water. According to Archimedes' principle, loss of weight in water of 48 kg equals the weight of the displaced water. One can easily compute the volume of water displaced by correcting for the density of water at the weighing temperature. In this example, 48 kg of water equals 48 L, or 48,000 cm^3 (1 g of water = 1 cm^3 by volume at 39.2°F [4°C]). Measuring the person at a water temperature of 39.2°F requires no density correction for water temperature. In practice, researchers use warmer water and apply the appropriate density value for water at the weighing temperature.

The density of this person, computed as mass divided by volume, equals 50,000 g (50 kg) ÷ 48,000 cm^3, or 1.0417 g · cm^{-3}. The total volume of any body segment can be determined using densitometry, for example, the volume of the hands.[66] The next step estimates percentage body fat and mass of the fat and fat-free tissues.

Computing Percentage Body Fat. An equation that incorporates whole-body density estimates the body's fat percentage. The simplified equation derived by UC Berkeley scientist William Siri (1919–1998) substitutes 0.90 g · cm^{-3} for the density of fat and 1.10 g · cm^{-3} for the density of the fat-free tissues.[145] The final derivation, referred to as the **Siri equation**, computes percentage body fat as:

$$\text{Percentage body fat} = (495 \div \text{body density}) - 450$$

This equation assumes the two-component model of body composition; the density of fat extracted from adipose tissue equals 0.90 g · cm^{-3} and 1.10 g · cm^{-3} for fat-free tissue at 37°C. The pioneer researchers in this area maintained that each of these densities remains relatively constant among individuals despite large individual variations in total fat and FFM. They also assumed that the densities of the lean tissue components of bone and muscle remained the same among individuals.

In the previous example (body mass: 50 kg; body volume: 48 L), the whole-body density of 1.0417 g · cm^{-3} converted to percentage fat by the Siri equation equaled 25.2%.

$$\begin{aligned}\text{Percentage body fat} &= (495 \div 1.0417) - 450 \\ &= 25.2\%\end{aligned}$$

Several formulas other than Siri's equation also estimate percentage body fat from body density.[20,82] The basic difference among the formulas in calculating body fat generally averages less than 1% body fat units for body fat levels between 4 and 30%.

Limitations of Density Assumptions. The generalized density values for the fat-free (1.10 g · cm^{-3}) and fat (0.90 g · cm^{-3}) tissue compartments represent averages for young and middle-aged adults. These "constants" vary among individuals and groups, particularly the density and chemical composition of the FFM. Such variation places some limitation in partitioning body mass into fat and fat-free components and predicting percentage body fat from whole-body density.[50] More specifically, average density of the FFM is higher for blacks and Hispanics than for whites (1.113 g · cm^{-3} blacks, 1.105 g · cm^{-3} Hispanics, and 1.100 g · cm^{-3} whites).[128,141,150] Racial differences also exist among adolescents.[157,189] Consequently, existing equations formulated from assumptions for whites to calculate body composition from body density in blacks or Hispanics *overestimates* FFM and *underestimates* percentage body fat. The following modification of the Siri equation computes percentage body fat from body density for blacks:

$$\text{Percentage body fat} = (437.4 \div \text{body density}) - 392.8$$

Applying constant density values for the different tissues in growing children or aging adults also introduces errors in predicting body composition. For example, the water and mineral contents of the FFM continually change during the growth period including the demineralization of osteoporosis with aging. Reduced bone density makes the density of the fat-free tissue of young children and the elderly lower than the assumed 1.10 g · cm^{-3} constant. This invalidates assumptions of constant densities of fat and fat-free masses in the two-compartment model and *overestimates* relative body fat calculated from densitometry. For this reason, many researchers do not convert body density to percentage body fat in children and aging adults. Others apply a multicompartment model to adjust for such factors to compute percentage body fat from body density in prepubertal children.[146,178] Table 28.3 gives equations adjusted to maturation level to predict percentage body fat from whole-body density of boys and girls ages 7 to 17.

Adjust for Large Musculoskeletal Development. Chronic resistance training affects the density of the FFM, altering body fat estimation from whole-body density determinations. White male weightlifters with considerable muscular development and nontrained controls were assessed for body density, total body water, and bone mineral content.[117] Comparisons included estimations of percentage body fat with both the two-compartment model and a four-compartment model using the body's fat, water, mineral, and protein content and corresponding densities. Percentage body fat estimated from body density (two-compartment Siri equation) produced higher values than percentage body fat from the four-compartment model for the weight trainers but not for untrained controls. A *lower* FFM density in weight trainers than in controls (1.089 vs. 1.099 g · cm^{-3}) explained this discrepancy; it resulted from larger water and smaller mineral and protein fractions of the FFM in the resistance-trained

TABLE 28.3 • Percentage Body Fat Estimated from Body Density (BD) Using Age- and Gender-Specific Conversion Constants to Account for Changes in the Density of the Fat-Free Body Mass as a Child Matures

Age (y)	Boys	Girls
7–9	% Fat = (5.38/BD − 4.97) × 100	% Fat = (5.43/BD − 5.03) × 100
9–11	% Fat = (5.30/BD − 4.89) × 100	% Fat = (5.35/BD − 4.95) × 100
11–13	% Fat = (5.23/BD − 4.81) × 100	% Fat = (5.25/BD − 4.84) × 100
13–15	% Fat = (5.08/BD − 4.64) × 100	% Fat = (5.12/BD − 4.69) × 100
15–17	% Fat = (5.03/BD − 4.59) × 100	% Fat = (5.07/BD − 4.64) × 100

From Lohman T. Applicability of body composition techniques and constants for children and youth. Exerc Sports Sci Rev 1986;14:325.

men. For them, incorrect assumptions underlying the Siri equation *overestimated* percentage body fat.

For the weightlifters, muscularity increased disproportionately to changes in bone mass. A lower FFM density occurred because the density of their fat-free muscle ($1.066\ g \cdot cm^{-3}$ at 37°C) was below the $1.1\ g \cdot cm^{-3}$ value assumed in the Siri equation. Disproportionate increases in muscle mass relative to increases in bone mass accounted for the reduced density of the FFM below $1.1\ g \cdot cm^{-3}$, overpredicting percentage body fat from the two-compartment model. If resistance training does indeed progressively lower FFM density, then applying the Siri equation fails to accurately reflect true body composition changes from this training mode.

Based on revised densities of the FFM ($1.089\ g \cdot cm^{-3}$) and fat mass ($0.9007\ g \cdot cm^{-3}$), a modified equation more accurately appraises resistance-trained white males:[117]

$$\text{Percentage body fat} = (521 \div \text{body density}) - 478$$

Computing Fat Mass. Using data from the example on page 742, fat mass computes by multiplying body mass by percentage body fat as follows:

$$\begin{aligned}\text{Fat mass} &= \text{body mass} \times (\%\ \text{fat}/100)\\ &= 50\ \text{kg} \times 0.252\\ &= 12.5\ \text{kg}\end{aligned}$$

Further computations subdivide this person's fat mass into essential and storage fat. A female with 25.2% body fat has approximately 12% essential fat, or 6.0 kg (0.12 × 50 kg); the remaining 13.2% (6.6 kg) exists as storage fat (0.132 × 50 kg). For a male with 3% essential fat and 22.2% storage fat (based on 25.2% body fat), the corresponding values equal 1.5 kg for essential fat and 11.1 kg for storage fat. Clearly, for a man and woman with identical percentage body fat, the man rates "fatter" because storage fat represents a larger percentage of total body fat. Each gram of body fat (83% pure fat) contains approximately 7.5 kCal (7500 kCal per kg). One can compute the approximate potential energy stored in each fat depot. For storage fat in this example, the values are 49,500 kCal for the woman and 83,260 kCal for the man; for essential fat, including a female's sex-specific fat, the values are 45,000 kCal for the woman and 11,250 kCal for the man.

Computing Fat-Free Body Mass. Compute FFM by subtracting fat mass from body mass.

$$\begin{aligned}\text{Fat-free body mass} &= \text{body mass} \times \text{fat mass}\\ &= 50\ \text{kg} \times 12.5\ \text{kg}\\ &= 37.5\ \text{kg}\end{aligned}$$

BOD POD Measurement of Body Volume

A procedure has been perfected to assess body volume and its changes for groups that range from infants to the elderly, to collegiate wrestlers and exceptionally large athletes like American professional football and basketball players.[45,162,190] The method has adapted helium-displacement plethysmography first reported in the late 1800s. The subject sits inside a small chamber marketed commercially as **BOD POD** (FIG. 28.10A). Measurement requires only 3 to 5 minutes, with high reproducibility of test scores ($r > 0.90$) within and across days. After being weighed to the nearest ±5 g on an electronic scale (*bottom left* of BOD POD illustration), the subject sits comfortably in the 750-L volume, dual-chamber fiberglass shell. The molded front seat separates the unit into front and rear chambers. The electronics, housed in the rear chamber, contain the pressure transducers, breathing circuit, and air circulation system.

The BOD POD determines body volume by measuring the initial volume of the empty chamber and then the volume with the person inside. To ensure measurement reliability and accuracy, the person wears a tight-fitting swimsuit.[169] Body volume represents the initial volume minus the reduced chamber volume with the subject inside. The subject breathes several breaths into an air circuit to assess pulmonary gas volume, which when subtracted from measured body volume yields body volume. Body density computes as body mass (measured in air) divided by body volume (measured in BOD POD, including a correction for a small negative volume caused by isothermal effects related to skin

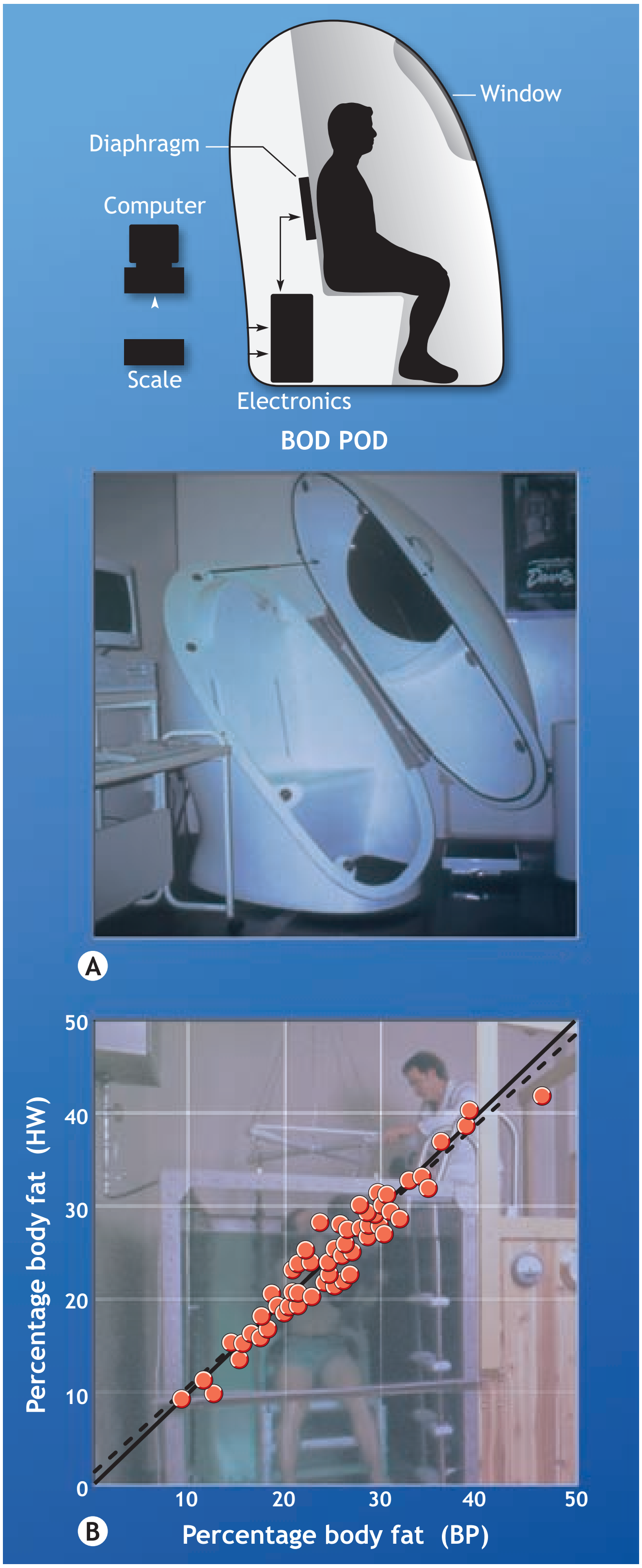


Figure 28.10 • **A.** BOD POD for measuring human body volume. (Photo courtesy of Dr. Megan McCrory, Purdue University, West Lafayette, IN.) **B.** Regression of percentage body fat by hydrostatic weighing (HW) versus percentage body fat by BOD POD (BP). (Data from McCrory MA, et al. Evaluation of a new air displacement plethysmograph for measuring human body composition. Med Sci Sports Exerc 1995;27:1686.)

surface area). The Siri equation converts body density to percentage body fat.

Some Discrepancies in the Literature

Figure 28.10B shows the regression of percentage body fat assessed by hydrostatic weighing versus percentage body fat assessed by BOD POD in an ethnically diverse group of adult women and men. A difference of only 0.3% (0.2% fat units) occurred between body fat determined by the two methods, with a validity coefficient of $r = 0.96$. In contrast to these rather impressive findings, BOD POD assessments of collegiate football players, although producing reliable scores, underpredicted percentage body fat compared with hydrostatic weighing and DXA.[29] Underprediction of body fat also occurred in a heterogeneous sample of black men who varied considerably in age, stature, body mass, percentage body fat, and self-reported physical activity level and socioeconomic status.[174] The method underpredicted percentage body fat compared with densitometry (−1.9% fat units) and DXA(−1.6% fat units). Similar underpredictions compared with DXA-derived body fat (−2.9% fat units) occurred in 54 boys and girls 10 to 18 years of age.[95] BOD POD also underestimated body fat of young adults compared with body fat predictions from a four-component model.[44,115] The method overestimated percentage body fat among lean individuals in a heterogeneous group of adults.[168] A BOD POD validation study in children ages 9 to 14 concluded that compared with DXA, total body water, and densitometry, BOD POD precisely and accurately estimated fat mass without introducing bias estimates.[42] The method has also been shown to accurately detect body composition changes from a small-to-moderate weight loss in overweight women and men.[179] Numerous studies have assessed the efficacy of BOD POD compared with other body composition methods in children; young, middle-age, and elderly adults; obese persons; and athletes.[4,6,9,13,28,39,43,133,161,170]

Skinfold and Girth Measurements

In field situations, two relatively simple procedures that measure either subcutaneous fat (**skinfolds**) or circumferences (**girths**) predict body fatness with reasonable accuracy.

Subcutaneous Fat Measurement with Skinfolds

The rationale for using skinfolds to estimate body fat comes from the interrelationships among three factors: (1) adipose tissue directly beneath the skin (subcutaneous fat), (2) internal fat, and (3) whole-body density.

The Caliper. By 1930, a pincer-type caliper accurately measured subcutaneous fat at selected anatomic sites. The three calipers shown in Figure 28.11 operate on a principle similar to a micrometer that measures distance between two points. Measuring skinfold thickness requires firmly grasping a fold of skin and subcutaneous fat with the thumb and

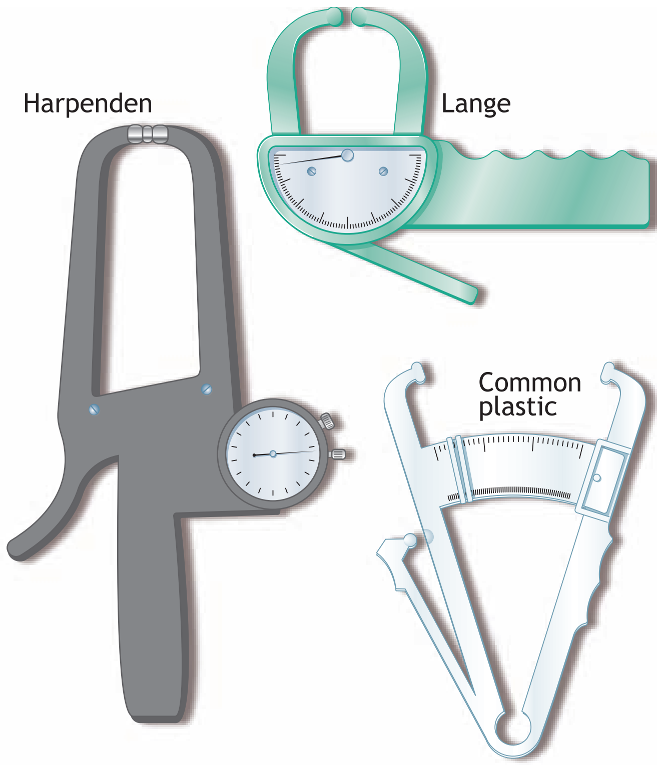


Figure 28.11 • Common calipers for skinfold measurements. The Harpenden and Lange calipers provide constant tension at all jaw openings.

forefingers, pulling it away from the underlying muscle tissue following the natural contour of the skinfold. When calibrated, the pincer jaws exert a relatively constant tension of 10 g · mm^{-2} at the point of contact with the double layer of skin plus subcutaneous adipose tissue. The caliper dial indicates skinfold thickness in mm recorded within 2 seconds after applying the full force of the caliper. This time limitation avoids skinfold compression when taking the measurement. For research purposes, the investigator has considerable experience in taking measurements and demonstrates consistency in duplicating values for the same subjects on the same day, consecutive days, or weeks apart. A rule of thumb to achieve consistency requires duplicate or triplicate practice measurements on approximately 50 individuals who vary in body fat. Careful attention to detail usually ensures high measurement reproducibility.

Measurement Sites. Common anatomic sites for skinfold measurements include triceps, subscapular, suprailiac, abdominal, and upper thigh sites. The investigator should take a minimum of two or three measurements in rotational order at each site on the right side of the body with the subject standing. The average value represents the skinfold score. FIGURE 28.12 shows the anatomic location of five of the more frequently measured sites:

- *Triceps:* Vertical fold at the posterior midline of the right upper arm, halfway between the tip of the shoulder and tip of the elbow; elbow remains in an extended, relaxed position
- *Subscapular:* Oblique fold, just below the bottom tip of the right scapula
- *Iliac* (iliac crest): Slightly oblique fold, just above the right hipbone (crest of ileum); the fold follows the natural diagonal line
- *Abdominal:* Vertical fold 1 inch to the right of the umbilicus
- *Thigh:* Vertical fold at the midline of the right thigh, two thirds the distance from the middle of the patella (kneecap) to the hip

Other sites include:

- *Chest:* Diagonal fold with long axis directed toward the right nipple; on the anterior axillary fold as high as possible
- *Biceps:* Vertical fold at the posterior midline of the right upper arm

Usefulness of Skinfold Scores

Skinfold measurements provide meaningful information about body fat and its distribution. We recommend two ways to use skinfolds. The first sums the skinfold scores to indicate *relative* fatness among individuals. The sum-of-skinfolds and individual values reflect either absolute or percentage skinfold changes before and after an intervention program.

One can draw the following conclusions from the skinfold data in TABLE 28.4 obtained from a 22-year-old female college student before and after a 16-week aerobic exercise program:

- Largest changes in skinfold thickness occurred at the iliac and abdomen sites
- Triceps showed the largest percentage decrease and the subscapular the smallest percentage decrease
- Total reduction in subcutaneous skinfolds at the five sites was 16.6 mm or 12.6% below the "before" condition

A second use of skinfolds incorporates population-specific mathematical equations to *predict* body density or percentage body fat. The equations prove accurate for subjects similar in age, gender, training status, fatness, and race to the group from which they were derived.[18,38,124,132,165] *When meeting these criteria, predicted body fat for an individual usually ranges between 3 and 5% body fat units computed from body density with hydrostatic weighing.*

Our laboratories developed the following equations to predict percentage body fat from triceps and subscapular skinfolds in young women and men:[75–77]

Young women, ages 17 to 26 years

$$\%\text{ Body fat} = 0.55A + 0.31B + 6.13$$

Young men, ages 17 to 26 years

$$\%\text{ Body fat} = 0.43A + 0.58B + 1.47$$

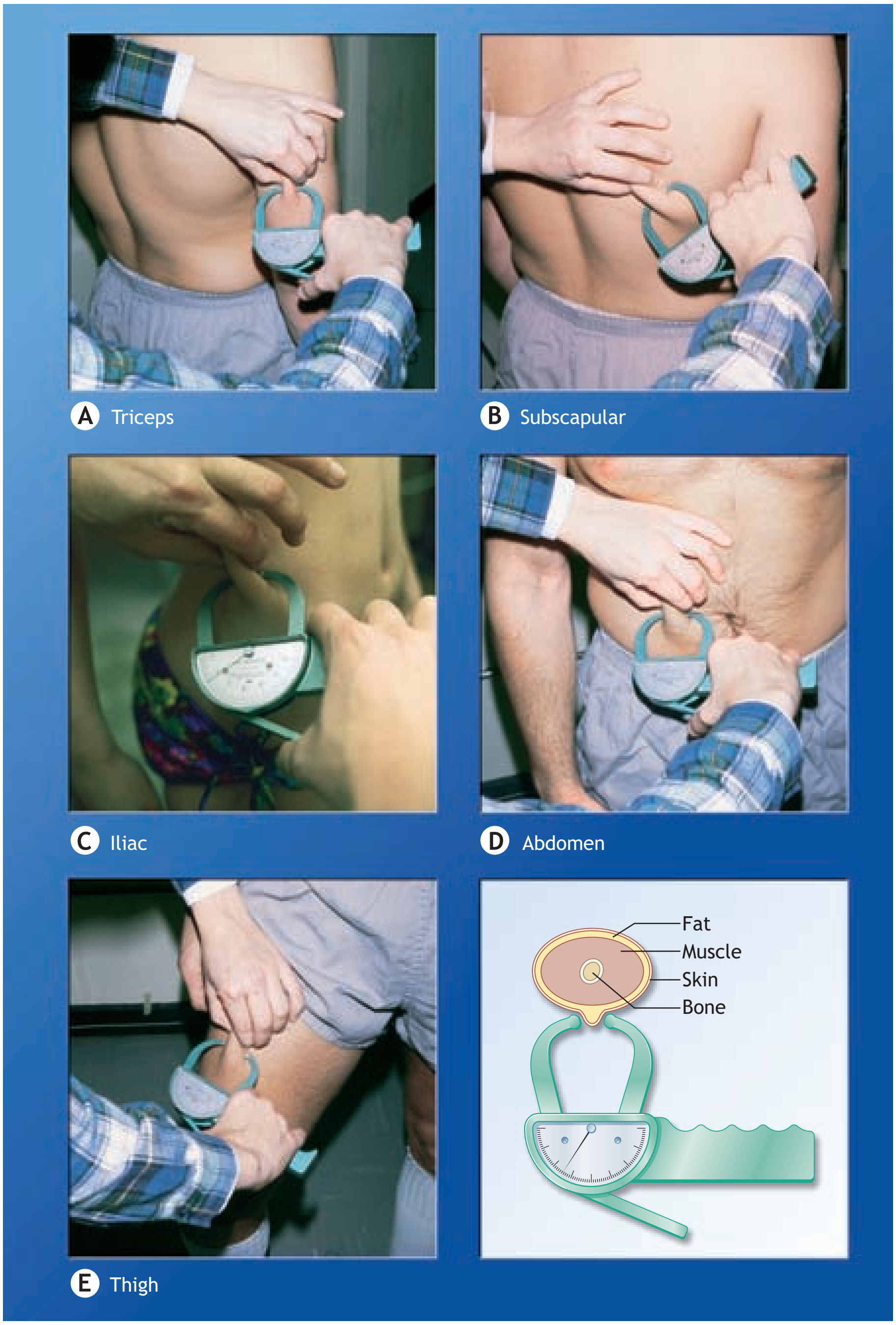


Figure 28.12 • Anatomic location of five common skinfold sites: **A.** Triceps. **B.** Subscapular. **C.** Iliac. **D.** Abdomen. **E.** Thigh. Measurements taken on the right side of the body in the vertical plane except diagonally at subscapular and iliac sites.

TABLE 28.4 • **Changes in Selected Skinfolds of a Young Woman During a 16-Week Exercise Program**

Skinfolds (mm)	Before	After	Absolute Change	Percentage Change
Triceps	22.5	19.4	−3.1	−13.8
Subscapular	19.0	17.0	−2.0	−10.5
Suprailiac	34.5	30.2	−4.3	−12.8
Abdomen	33.7	29.4	−4.3	−12.8
Thigh	21.6	18.7	−2.9	−13.4
Sum	131.3	114.7	−16.6	−12.6

In both equations, A is triceps skinfold (mm) and B is subscapular skinfold (mm).

We computed the “before” and “after” percentage body fat of the woman who participated in the 16-week physical conditioning program (Table 28.4). Percentage body fat equals 24.4% by substituting the pretraining values for triceps (22.5 mm) and subscapular (19.0 mm) skinfolds into the equation.

$$
\begin{aligned}
\%\ \text{Body fat} &= 0.55A + 0.31B + 6.13 \\
&= 0.55\,(22.5) + 0.31(19.0) + 6.13 \\
&= 12.38 + 5.89 + 6.13 \\
&= 24.4\%
\end{aligned}
$$

Substituting posttraining values for triceps (19.4 mm) and subscapular (17.0 mm) skinfolds produced a body fat value of 22.1%.

$$\begin{aligned}\%\text{ Body fat} &= 0.55(19.4) + 0.31(17.0) + 6.13\\ &= 10.67 + 5.27 + 6.13\\ &= 22.1\%\end{aligned}$$

Percentage body fat determined before and after a physical conditioning or weight-loss program provides a convenient way to evaluate alterations in body composition, independent of body weight changes.

Skinfold Prediction for Athletes

Predict body fat in athletes from an equation validated against a 4-component model (total body water, bone mineral by DXA, and body density by underwater weighing).

$$\%\text{ Body fat} = 8.997 + 0.24658\ (3\text{ SKF}) - 6.343\ (\text{gender}) - 1.998\ (\text{race})$$

Where 3 SKF = sum of skinfolds in mm at abdomen, thigh, and triceps; gender = 0 for female, 1 for male; race = 0 for white, 1 for black.

From Evans EM, et al. Skinfold prediction equation for athletes developed using a four-component model. Med Sci Sports Exerc 2005;37: 2006.

Skinfolds and Age

In young adults, approximately one-half of total fat consists of subcutaneous fat, with the remainder visceral and organ fat. With advancing age, proportionately more fat deposits internally than subcutaneously. Thus, the same skinfold score reflects a *greater* total percentage of body fat as one ages. *For this reason, use age-adjusted **generalized equations** to predict body fat from skinfolds or girths in older men and women.*[68,69,136,159]

User Beware

The person taking skinfold measurements must develop expertise with the proper techniques. Also, with extremely obese people, the skinfold thickness often exceeds the width of the caliper's jaws. The particular caliper also contributes to errors of measurement.[53] Under these conditions, girth becomes the measure of choice (see next section).

INTEGRATIVE QUESTION

A friend complains that three different fitness centers determined her percentage body fat from skinfolds as follows: 25%, 29%, and 21%. How can you reconcile the differences in these values?

Measurement of Girths

Apply a linen or plastic measuring tape (not a metal tape) lightly to the skin surface so the tape remains taut but not tight. This avoids skin compression, which produces below-normal scores. Make duplicate measurements at each site and average the scores. Figure 28.13 shows six common anatomic landmarks for anthropometric measurement:

1. **Right upper arm (biceps):** arm straight and extended in front of the body; measurement taken at midpoint between the shoulder and the elbow
2. **Right forearm:** maximum girth with arm extended in front of the body
3. **Abdomen:** 1 inch above the umbilicus
4. **Buttocks:** maximum protrusion with heels together
5. **Right thigh:** upper thigh, just below the buttocks
6. **Right calf:** widest girth midway between ankle and knee

Prediction equations based on girths exist for each gender and different age groups.[75,114,160] The equations for these subgroups show considerable population specificity. They do not apply to individuals who (1) appear overly thin or excessively fat, (2) train regularly in strenuous endurance sports or activities with a substantial resistance-training (and subsequent muscular-enlargement) component, and (3) differ in race from the specific group used to derive the original equations.

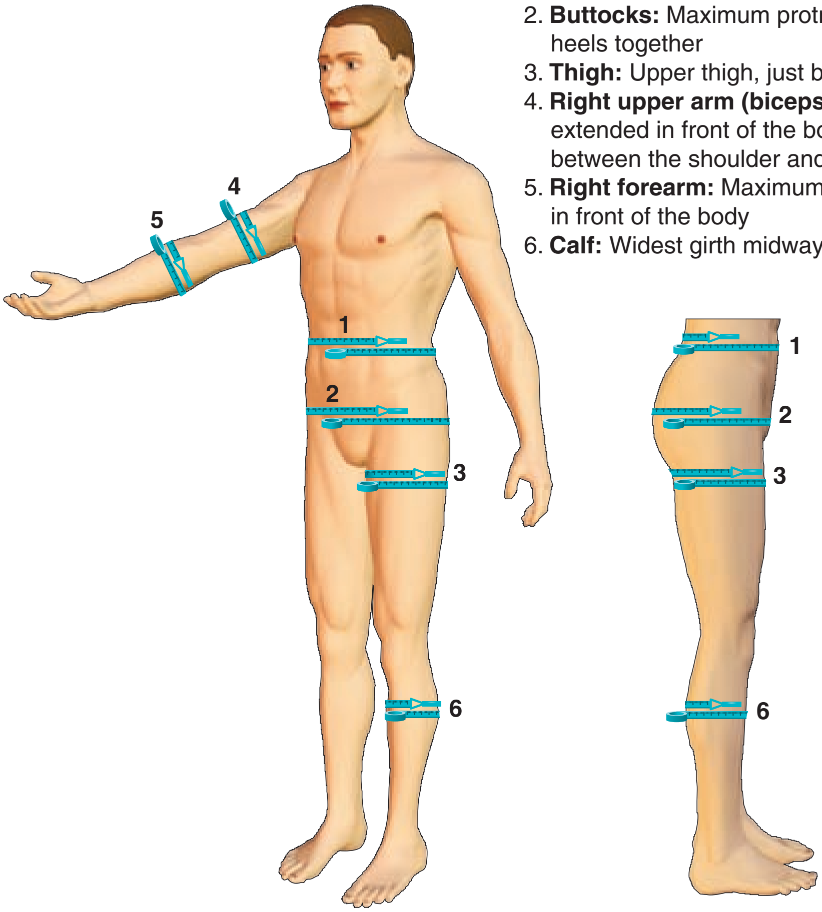
Usefulness of Girth Scores

Girths prove most useful in ranking individuals within a group according to relative fatness. As with skinfolds, girth-based equations predict body density and/or percentage body fat with a certain degree of error. The equations and constants presented in "Body Composition" on this book's companion website at http://thepoint.lww.com/mkk7e for young and older men and women predict body fat to within ±2.5 to 4.0% body fat units of the actual value. The prediction error depends on whether the individual portrays physical characteristics similar to the original validation group. Such relatively small errors make girth predictions particularly useful in nonlaboratory settings. Specific equations based on girths also estimate body composition of obese adult men and women.[17,159,177]

Along with predicting percentage body fat, girths can analyze patterns of body fat distribution, including changes in fat patterning during weight loss.[57,173] Not surprisingly, those equations that use the more labile sites of fat deposition (e.g., waist and hips instead of upper arm or thigh in females and abdomen in males) provide the greatest accuracy to predict *changes* in body composition.[46]

Body Fat Predictions from Girths

From the appropriate tables on http://thepoint.lww.com/mkk7e, substitute the corresponding constants *A*, *B*, and *C* in the formula shown at the bottom of each table. This



1. **Abdomen:** 1 inch above the umbilicus
2. **Buttocks:** Maximum protrusion of buttocks with the heels together
3. **Thigh:** Upper thigh, just below the buttocks
4. **Right upper arm (biceps):** Palm up, arm straight and extended in front of the body; taken at the midpoint between the shoulder and the elbow
5. **Right forearm:** Maximum girth with the arm extended in front of the body
6. **Calf:** Widest girth midway between the ankle and knee

Figure 28.13 • Landmarks for measuring various girths at six common anatomic sites.

requires one addition and two subtraction steps. The following five-step example shows how to compute percentage fat, fat mass, and FFM for a 21-year-old man who weighs 79.1 kg:

Step 1. Measure upper arm, abdomen, and right forearm girths with a cloth tape to the nearest 0.25 in. (0.6 cm): upper arm = 11.5 in. (29.21 cm); abdomen = 31.0 in. (78.74 cm); right forearm = 10.75 in. (27.30 cm)

Step 2. Determine the three constants *A, B,* and *C* corresponding to the three girths from the table: *A,* corresponding to 11.5 in = 42.56; *B*, corresponding to 31.0 in = 40.68; and *C,* corresponding to 10.75 in = 58.37.

Step 3. Compute percentage body fat by substituting the constants from step 2 in the formula for young men as follows:

$$\begin{aligned}\text{Percentage fat} &= A + B - C - 10.2\\ &= 42.56 + 40.68 - 58.37 - 10.2\\ &= 83.24 - 58.37 - 10.2\\ &= 24.87 - 10.2\\ &= 14.7\%\end{aligned}$$

Step 4. Determine fat mass

$$\begin{aligned}\text{Fat mass} &= \text{Body mass} \times (\%\ \text{fat} \div 100)\\ &= 79.1\ \text{kg} \times (14.7 \div 100)\\ &= 79.1\ \text{kg} \times 0.147\\ &= 11.6\ \text{kg}\end{aligned}$$

Step 5. Determine FFM

$$\begin{aligned}\text{FFM} &= \text{Body mass} - \text{fat mass}\\ &= 79.1\ \text{kg} - 11.6\ \text{kg}\\ &= 67.5\ \text{kg}\end{aligned}$$

Bioelectrical Impedance Analysis

In the single mode of low-frequency **bioelectrical impedance analysis** (**BIA**), a small alternating current flowing between two electrodes passes more rapidly through hydrated fat-free body tissues and extracellular water than through fat or bone tissues because of the greater electrolyte content (lower electrical resistance) of the fat-free component. In essence, the body's water content conducts the flow of electrical charges, so when current flows through the fluid, sensitive instrumentation can detect the water's impedance. Impedance to electric current flow, calculated by measuring current and voltage, is based on Ohm's law (R = V/I, where R = resistance, V = volume, and I = current). These relationships can quantify the volume of water within the body, and from this, percentage body fat and FFM.

Figure 28.14A and B show an example for single-frequency BIA. A person lies on a flat, nonconducting surface with injector (source) electrodes attached on the dorsal surfaces of the foot and wrist and detector (sink) electrodes attached between the radius and ulna (styloid process) and at the ankle between the medial and lateral malleoli. A painless,

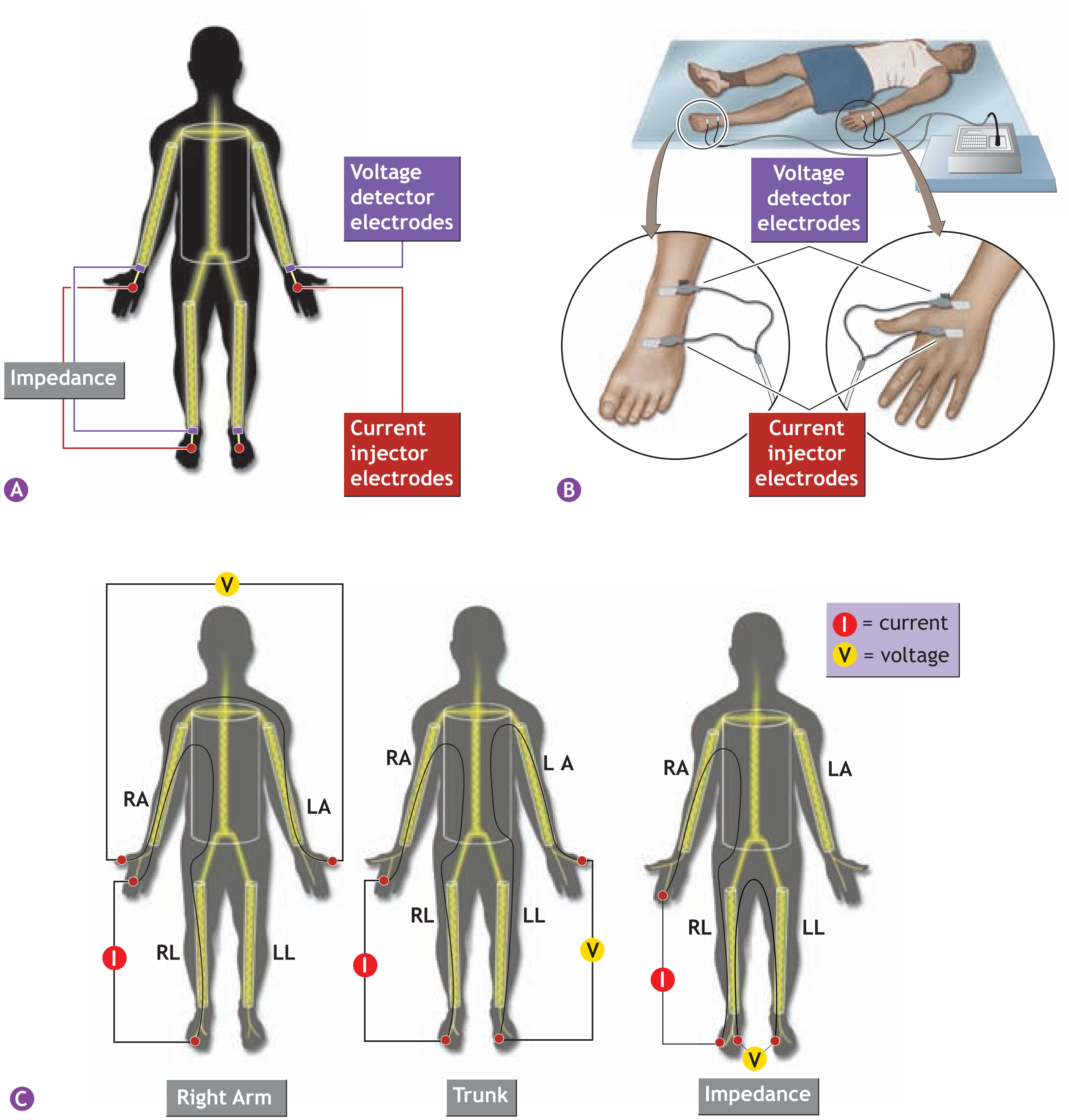


Figure 28.14 • Method to assess body composition by bioelectrical impedance analysis. **A.** Four-surface electrode technique (whole-body impedance) applies current via one pair of distal (injector) electrodes, while the proximal (detector) electrode pair measures electrical potential across the conducting segment. **B.** Standard placement of electrodes and body position during whole-body impedance measurement. **C.** Segmental measurement illustrating assessment of current *(I)* and voltage *(V)* for the right arm, trunk, and right leg.

localized electrical current (approximately 800 μA at a frequency of 50 kHz) is introduced, and the impedance (resistance) to current flow between the source and detector electrodes determined. Conversion of the impedance value to body density—adding body mass and stature; gender, age, and sometimes race; level of fatness; and several girths to the equation—computes percentage body fat from the Siri equation or other density conversion equations. Body composition prediction with such a system depends on the additional input data as part of the BIA equation. Thus, any unreliability of data input produces different prediction results. This becomes more pronounced for individuals at the extremes of body composition. For example, a difference of only 5 mm in a girth measurement or difference of 1.5 cm in "true" stature from measurement to measurement can produce up to a 2% change in an output variable—unrelated to any real change in a computed body composition variable such as fat mass or FFM. Figure 28.14C illustrates the segmental measurement approach including electrode configuration and how current (I) and voltage (V) are assessed for the right arm, trunk, and right leg.

Influence of Hydration Level and Ambient Temperature

Hydration level affects the accuracy of BIA and may give incorrect information about an individual's body fat content.[86,126] Hypohydration and hyperhydration alter the body's normal electrolyte concentrations; this in turn affects current flow independent of real body composition changes. For example, voluntary fluid restriction decreases the impedance measure. This lowers the percentage body fat estimate; hyperhydration produces the opposite effect (higher body fat estimate). Skin temperature, influenced by ambient conditions, also affects whole-body resistance and BIA prediction of body fat. Predicted body fat is lower in a warm environment (moist skin produces less impedance to electrical flow) than in a cold one.

Even with normal hydration and environmental temperature, body fat predictions with BIA prove less valid than with hydrostatic weighing. BIA tends to overpredict body fat in lean and athletic subjects and underpredict body fat in obese subjects.[103,142] BIA often predicts body fat less accurately than do girths and skinfolds.[19,37,79,151] Whether BIA detects small changes in body composition during weight loss remains unclear.[88,123,134] Conventional BIA technology cannot determine regional fat distribution.

At best, BIA represents a noninvasive, safe, relatively easy, and reliable means to assess total body water. The technique requires that experienced personnel make measurements under standardized conditions. Particularly important are electrode placement and the subject's body position, hydration status, plasma osmolality and sodium concentration, skin temperature, recent physical activity, and previous food and beverage intake.[15,87,88] For example, ingestion of consecutive meals progressively decreases bioelectrical impedance (possibly the combined effect of increased electrolytes and a redistribution of extracellular fluid), which decreases computed percentage body fat.[147] Body fatness and racial characteristics also influence BIA's predictive accuracy.[3,129,152,189] The tendency to overestimate percentage body fat increases among black athletes[61,142] and lean subjects.[153] Fatness-specific BIA equations exist that predict body fat for obese and nonobese American Indian, Hispanic, and white men and women.[151] With proper measurement standardization, the menstrual cycle does not affect body composition assessment by BIA.[108]

Applicability of BIA in Sports and Exercise Training

Coaches and athletes require a safe, easily administered, and valid tool to assess body composition and detect changes with caloric restriction or exercise training. A major limitation in achieving these goals concerns BIA's lack of sensitivity to detect small body-compositional changes, particularly without appropriate control over factors that affect measurement accuracy and reliability. For example, sweat-loss dehydration from prior exercise or reduced glycogen reserves (and associated loss of glycogen-bound water) from an intense training session reduces body resistance (impedance) to electrical current flow. This overestimates FFM and underestimates percentage body fat.

Chapter 29 ("In a Practical Sense") includes BIA equations (in addition to equations using skinfolds and girths) to estimate body density and percentage body fat for athletes in general and athletes in specific sports. Without sport-specific equations, population-based generalized equations that account for age and gender usually provide an acceptable alternative to estimate body fat.[68,144,156]

Near-Infrared Interactance

Near-infrared interactance (**NIR**) applies technology developed by the U.S. Department of Agriculture to assess body composition of livestock and the lipid content of various grains. The commercial versions to assess human body composition use principles of light absorption and reflection. A fiber optic probe or light wand emits a low-energy beam of near-infrared light into the single measuring site at the anterior midline surface of the dominant biceps. A detector within the same probe measures the intensity of the reemitted light, expressed as optical density. Shifts in wavelength of the reflected beam as it interacts with organic material in the arm inserted into the manufacturer's prediction equation (including adjustments for subject's body mass and stature, estimated frame size, gender, and physical activity level) computes percentage body fat and FFM. The safe, portable, lightweight equipment requires minimal training to use and necessitates little physical contact with the subject during measurement. These test administration aspects make NIR popular for body composition assessment in health clubs, hospitals, and weight-loss centers. The important question about the usefulness of NIR concerns its validity.

Questionable Validity

Early research indicated a relationship between spectrophotometric measures of light interactance at various body sites and body composition assessed by total body water.[32] Subsequent studies with humans have not confirmed NIR's validity versus hydrostatic weighing or skinfold measurements. NIR does *not* accurately predict body fat across a broad range of body fat levels; it often provides less accuracy than skinfolds.[19,60,167] It overestimates body fat in lean men and women and underestimates it in fatter subjects.[109] Figure 28.15 shows the inadequacy of NIR compared with skinfold measurements to predict body fat compared to hydrostatic weighing. In more than 47% of the subjects, an error greater than 4% body fat units occurred with NIR, with the largest errors at the extremes of body fatness. NIR produced large errors when estimating body fat for children[24] and youth wrestlers,[63] and underestimated body fat in collegiate football players.[62] NIR did not accurately assess body composition changes from resistance training.[19] *At this time, research does not support NIR as a robust, valid method to assess human body composition.*

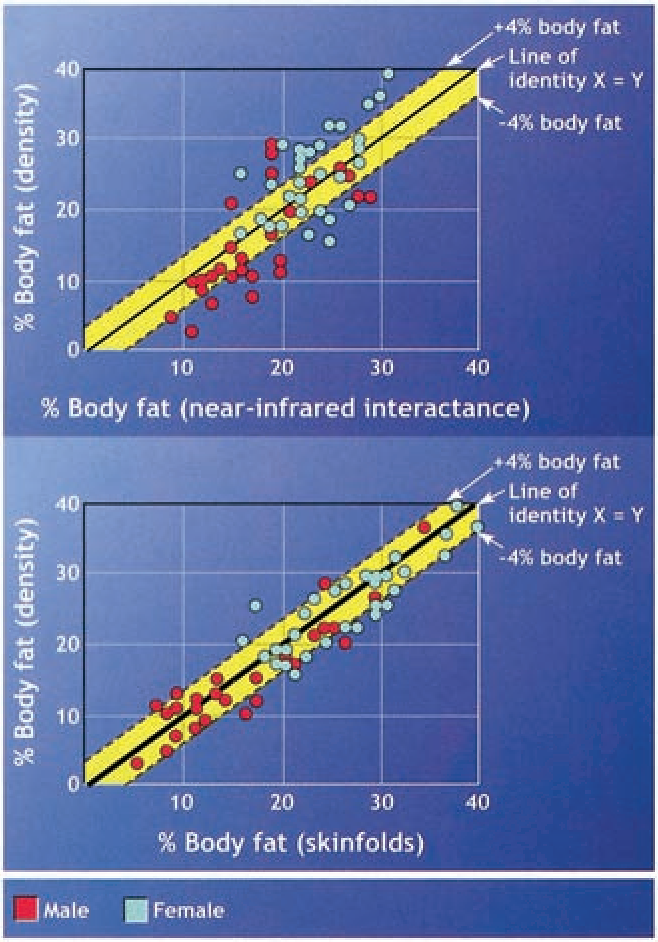


Figure 28.15 • Comparison of near-infrared interactance (Futrex-5000) *(top)* and skinfolds *(bottom)* for assessing percentage body fat. *Shaded area* around line incorporates ±4% body fat units. (From McLean K, Skinner JS. Validity of Futrex-5000 for body composition determination. Med Sci Sports Exerc 1992;24:253.)

Ultrasound Assessment of Fat

Ultrasound technology can assess the thickness of different tissues (fat and muscle) and image the deeper tissues such as a muscle's cross-sectional area. The method converts electrical energy through a probe into high-frequency (pulsed) sound waves that penetrate the skin surface into the underlying tissues. The sound waves pass through adipose tissue to penetrate the muscle layer. They then reflect from the fat–muscle interface (after reflection from a bony surface) to produce an echo, which returns to a receiver within the probe. The simplest type of ultrasound (A-mode) does not produce an image of the underlying tissues. Rather, the time required for sound wave transmission through the tissues and back to the transducer converts to a distance score that indicates fat or muscle thickness. With the more expensive and technically demanding B-mode ultrasound, a 2-dimensional image provides considerable detail and tissue differentiation.

Ultrasound exhibits high reliability for repeat measurements of subcutaneous fat thickness at multiple sites in the lying and standing positions on the same day and different days.[67,74] The technique can determine total and segmental subcutaneous adipose tissue volume.[2] It has also shown validity for assessing FFM of high school wrestlers, which may prove useful as a field-based body composition assessment method.[163] Ultrasound proves particularly useful with obese persons who show considerable variation and compression of subcutaneous body fat with skinfold measures. When used to map muscle and fat thickness at different body regions and quantify changes in topographic fat patterns, ultrasound serves as a valuable adjunct to body composition assessment. In hospitalized patients, ultrasonic fat and muscle thickness determinations aid in nutritional assessment during weight loss and weight gain. Ultrasonic imaging also serves a clinical role in assessing tissue growth and development, including fetal development and structure and function of the heart and other organs. With imaging devices, reflected sound waves from the soft tissues convert to a real-time image for convenient visualization or for computer digitization (area, volume, and diameter) directly from the image. Color and multiple-frequency imaging allows clinicians to trace blood flow through organs and tissues or, with the use of miniaturized probes, identify internal tissues, vessels, and organs. In consumer-oriented research, ultrasonic imaging of thigh fat depth provided evidence that treatments using two topical cream applications to the thighs and buttocks to reduce "cellulite" (dimpled fat) failed to reduce local fat thickness compared with control conditions.[30]

Computed Tomography, Magnetic Resonance Imaging, and Dual-Energy X-Ray Absorptiometry

Computed Tomography

Computed tomography (**CT**) generates detailed cross-sectional, 2-dimensional radiographic images of body segments when an X-ray beam (ionizing radiation) passes through tissues of different densities. The CT scan produces pictorial and quantitative information about total tissue area, total fat and muscle area, and thickness and volume of tissues within an organ.[52,116,172]

Figure 28.16A–C shows CT scans of the upper legs and a cross section at the midthigh of a professional walker who walked 11,200 miles through the 50 United States in 50 weeks. Total cross section and muscle cross section increased and subcutaneous fat decreased correspondingly in the midthigh region in the "after" scans (not shown). Studies have demonstrated the efficacy of CT scans to establish the relationship between simple anthropometric measures (skinfolds and girths) at the abdomen and total abdominal fat volume measured from single or multiple pictorial "slices" through this region.[143] The single cut through the L4 to L5 region minimizes radiation dose and provides the best view of visceral and subcutaneous fat. Figure 28.17 illustrates the high association between waist circumference and deep **visceral adipose tissue** (**VAT**) area; men with larger waist girth also possessed greater VAT. The relationship exceeded the association between subcutaneous fat thickness (skinfolds) and VAT. An increased amount of deep abdominal adipose tissue relates to increased risk for type 2 diabetes, blood lipid profile disorders, and hypertension, including the metabolic syndrome and cardiovascular disease. Chapter 30 discusses health risks from the deep type of abdominal obesity.

Magnetic Resonance Imaging

Magnetic resonance imaging (**MRI**), originally discovered by physician and research scientist R. V. Damadian (1936–) in 1971, patented in 1974, and first constructed in 1977, provides an invaluable, noninvasive assessment of the body's tissue compartments.[1,73,91] Figure 28.18 shows a color-enhanced MRI transaxial image of the midthigh of a 30-year-old male middle-distance runner. Computer software subtracts fat and bony tissues *(lighter-colored areas)* to compute thigh muscle cross-sectional area *(red area)*. With MRI, electromagnetic radiation (not ionizing radiation as in CT scans) in a strong magnetic field excites the hydrogen nuclei of the body's water and lipid molecules. The nuclei then project a detectable signal that rearranges under computer control to visually represent the various body tissues. MRI can quantify total and subcutaneous adipose tissue in individuals of varying body fatness. Combined with muscle mass analysis, MRI assesses changes in a muscle's lean and fat components following resistance training, changes in muscle volume in and out of training, or during different stages of growth and aging.[71,158] MRI analysis has assessed postflight changes in muscle volume after a 17-day space mission and 16- to 28-week duration shuttle/MIR missions.[90] MRI has wide acceptance for diagnosis in almost all fields of medicine and related disciplines, including muscular dystrophy.[51] The latest MRI technologies allow imaging of pacemakers with fiber optic leads rather than wire leads, MRI compatible defibrillators, and FONAR stand-up MRI that scans patients in numerous weight-bearing positions—standing, sitting, in flexion and

Figure 28.16 • CT scans. **A.** Plot of pixel elements (CT scan) illustrating the extent of adipose and muscle tissue in a cross section of the thigh. The two other views show (**B**) a cross section of the midthigh and (**C**) an anterior view of the upper legs prior to a 1-year walk across the United States by a champion walker. (CT scans courtesy of Dr. Steven Heymsfeld, Obesity Research Center, St. Luke's-Roosevelt Hospital, Columbia University, College of Physicians and Surgeons, New York, NY.)

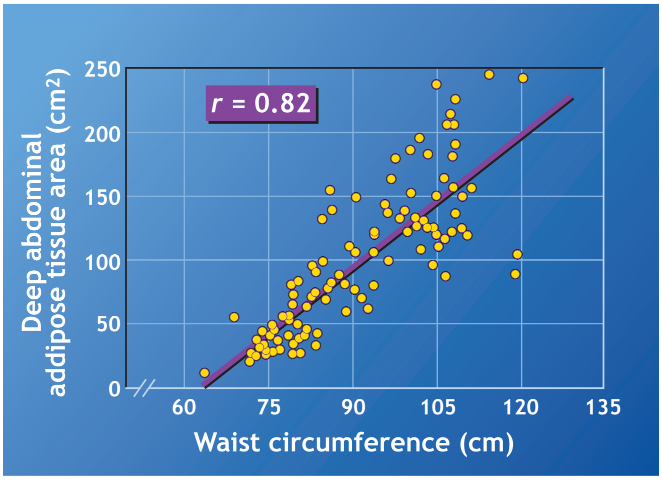


Figure 28.17 • Relationship between deep visceral adipose tissue (VAT) determined by CT scanning and waist girth in 110 men, ages 18 to 42 years, who varied considerably in percentage body fat by densitometry ($\bar{X}$ = 22.9%; range, 2.2-39.9%). The best predictors of VAT included *(a)* abdominal skinfold thickness in mm, *(b)* waist girth in cm, and *(c)* waist-hip ratio. VAT $(cm^2) = -363.12 + (-1.113a) + 3.478b + 186.7c$. For example, if abdominal skinfold is 23.0 mm, waist girth is 92.0 cm, and waist–hip ratio is 0.929, then by substitution in the equation, VAT = 104.7 cm^2. (Modified from Dépres J-P, et al. Estimation of deep abdominal adipose-tissue accumulation from simple anthropometric measurements in men. Am J Clin Nutr 1991;54:471.)

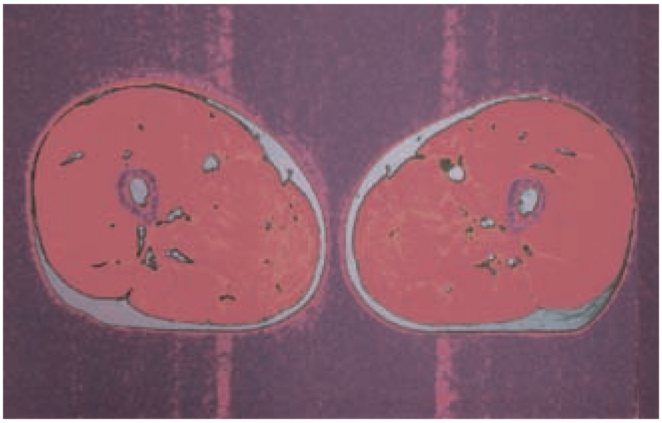


Figure 28.18 • MRI scans of the midthigh of a 30-year-old male middle-distance runner. (MRI scans courtesy of J. Staab, Department of the Army, USARIEM, Natick, MA.)

extension, and the conventional lie-down position (www.invent.org/hall_of_fame/36.html; www.fonar.com/).

Figure 28.19 *(top)* shows a plot of percentage body fat determined by MRI scanning of 30 transaxial images along the length of the body and underwater weighing of 20 Swedish women, ages 23 to 40 years. Total fat from scans of the calves, thighs, lower- and upper-trunk, and lower- and upper-arms provided the basis for computing MRI percentage body fat. Good agreement emerged between the two body fat estimates (r = 0.84). Similar validity emerged between MRI-determined total body fat and hydrostatic weighing and total body water estimates of body fat.[110]

The *bottom of* Figure 28.19 shows the distribution of total adipose tissue, subcutaneous adipose tissue, and nonsubcutaneous adipose tissue measures from different body regions. The *bar graphs* show the smallest to the largest adipose tissue depots. Of all body regions, adipose tissue in the lower trunk (both subcutaneous and nonsubcutaneous) contained the greatest percentage of total body fat (38.5%); the lower arm region included 2.7%, the smallest amount. The *pie chart* at the *lower right* of the figure shows the relative amounts of adipose tissue in each body compartment in relation to the MRI-determined total volume of body fat. Subcutaneous fat accounted for 75.2% of the total 21.8 L of body fat. Nonsubcutaneous fat accounts for the remaining 24.8%, making it reasonable to conclude that "excess" fat deposits to the greatest extent in the subcutaneous tissues.

Comparison of Lean and Obese. Seventeen MRI-derived tissue slices from groups of lean and obese females provided comparative data for total fat and VAT volume at four anatomic sites between the top of the patella and sternal notch. Body fat determined by densitometry for the light women (BMI: 20.6) averaged 25.4%; the heavy women's BMI averaged 42.4 with about 42% body fat. The three graphs in Figure 28.20 display differences between the relatively light and heavy groups in total body tissue (sum of fat and nonfat tissues), total adipose tissue, and subcutaneous adipose tissue at the 17 sites. The results show a fairly consistent pattern in MRI-derived adipose tissue volumes. The overfat subjects possessed 165% more subcutaneous adipose tissue and 155% more total adipose tissue. Abdominal and upper-thigh regions showed the largest fat accretion. Interestingly, the light women had a greater amount of nonfat tissue (not shown) at the upper-thorax and lower-thigh regions. The *inset graph* shows the strong relationship between MRI-determined percentage of body adipose tissue (4 instead of 17 sites) and percentage body fat determined by densitometry. MRI yields a wealth of useful information for accurately assessing total and regional body composition.

Exercise Training. MRI and dual-energy X-ray absorptiometry (DXA, discussed in the next section) assessed changes in regional (trunk and extremities) and whole-body fat mass, lean body mass, and bone mineral content at 3 and 6 months of periodized resistance training in 31 women.[125] MRI measured changes in thigh muscle morphology in a subset of 11 women exercisers. The women decreased fat mass by 10% and body mass and soft tissue lean mass by 2.2%, but bone mineral content did not change compared with non-training groups of men and women. Soft tissue lean mass was distributed less in women's arms than in men's both before and after training. The most striking training-induced differences occurred in the tissue composition of the women's arms (31% loss in fat mass without change in lean mass) compared with the legs (5.5% gain in lean mass without change in fat mass).

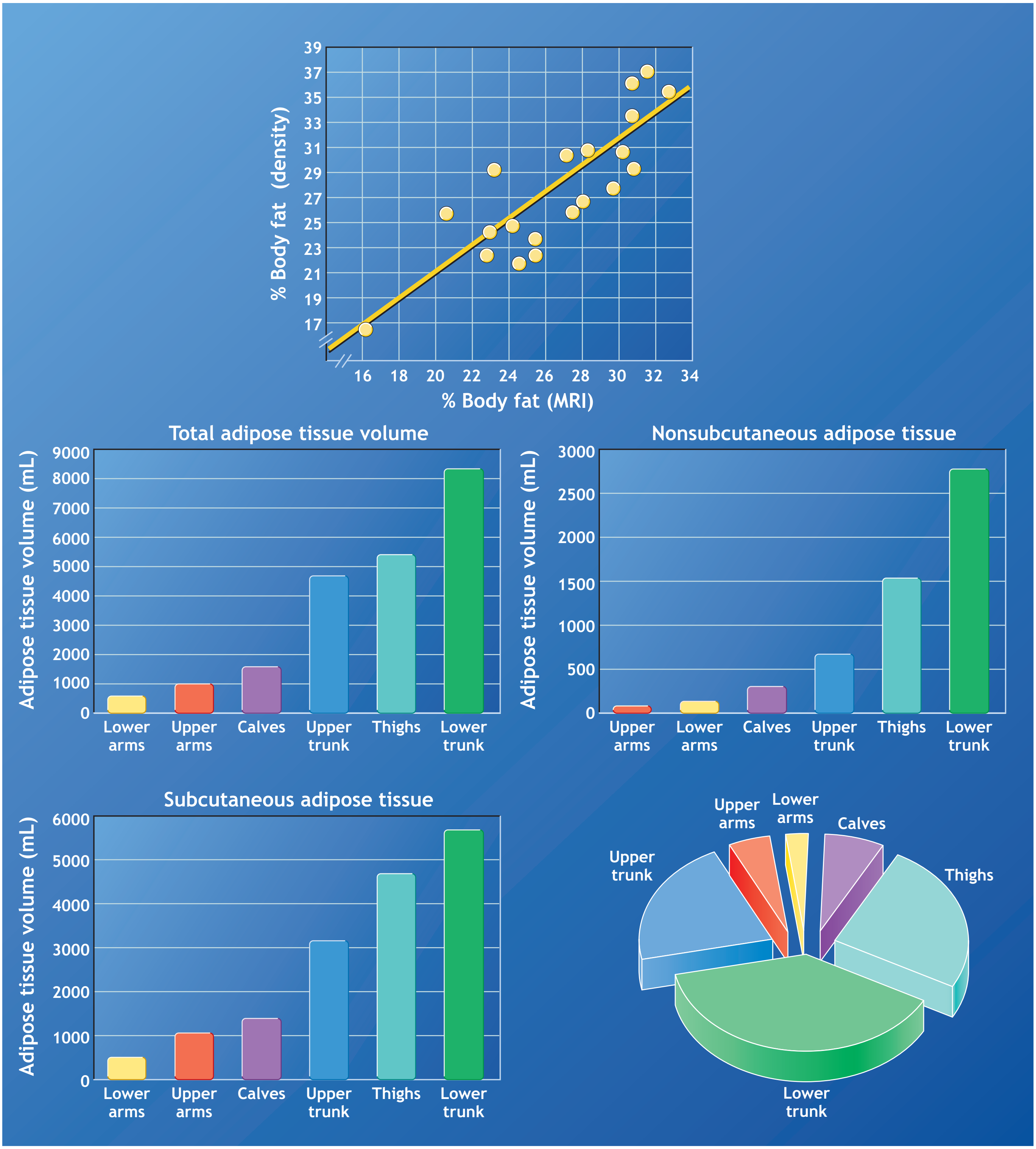


Figure 28.19 • *Top.* Percentage body fat determined by hydrostatic weighing (density) and MRI scanning (graph created from individual data points presented in the original article). *Bottom bar graphs.* Distribution of adipose tissue (total, subcutaneous, and nonsubcutaneous) within the various body compartments; arrangement progresses from smallest to largest. The *right pie chart* displays the relative distribution of adipose tissue in different body regions. (Modified from Sohlstrom A, et al. Adipose tissue distribution as assessed by magnetic resonance imaging and total body fat by magnetic resonance imaging, underwater weighing, and body-water dilution in healthy women. Am J Clin Nutr 1993;58:830.)

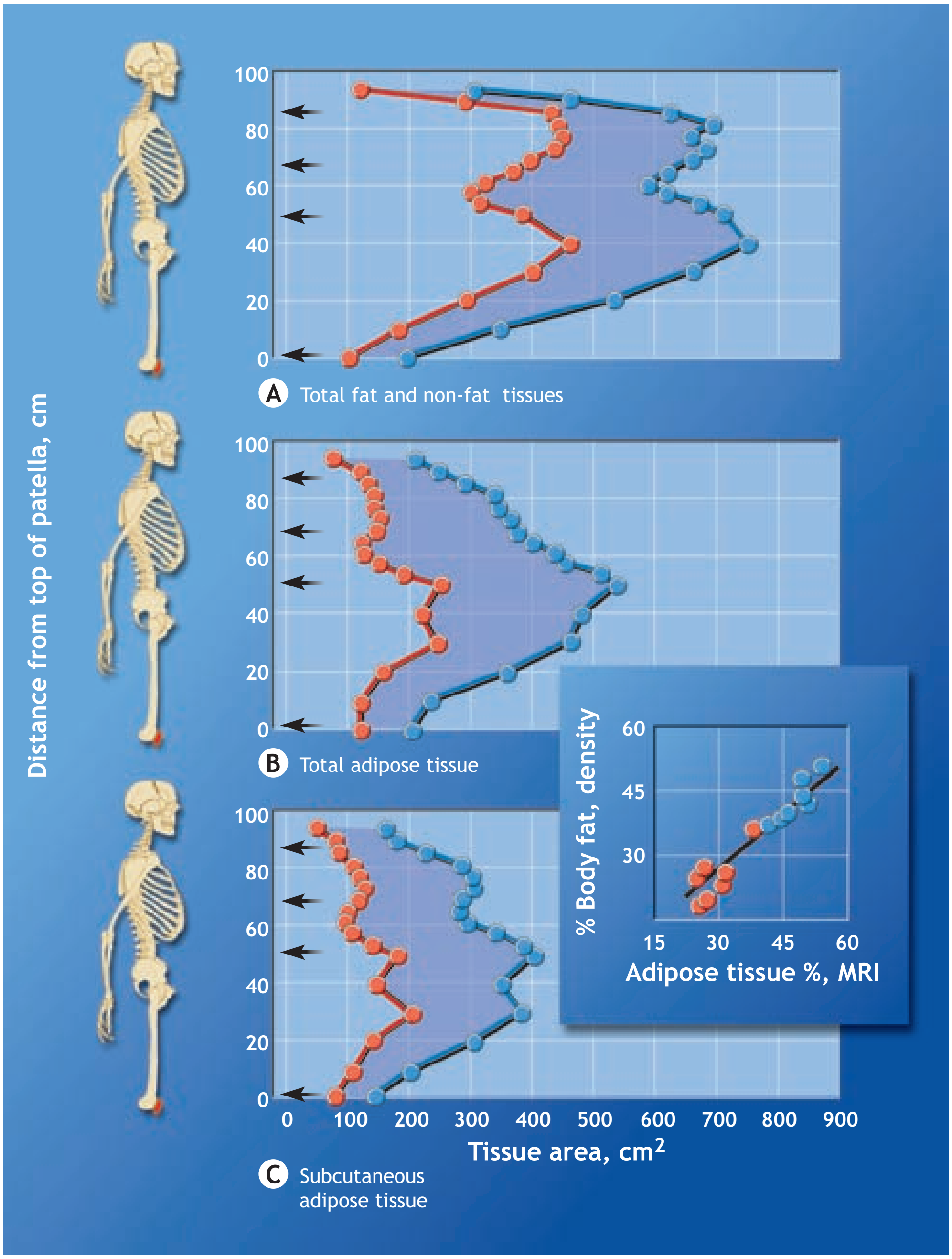


Figure 28.20 • MRI-determined distribution of body tissues in seven lean *(red)* and seven obese *(blue)* females. **A.** Total body tissues (sum of fat and nonfat tissues). **B.** Total adipose tissue. **C.** Subcutaneous adipose tissue. *Arrows to the right of the y-axis* indicate the four anatomic markers in relation to position on the skeleton. The *inset graph* displays the relationship between percentage body adipose tissue (using 4 instead of 17 MRI sites) and percentage body fat determined by hydrostatic weighing in obese and lean subjects. (Modified from Fowler PA, et al. Total and subcutaneous adipose tissue in women: the measurement of distribution and accurate prediction of quantity by using magnetic resonance imaging. Am J Clin Nutr 1991;54:18.)

Fat decreased in the trunk by 12% without change in soft tissue lean mass. The changes for fat mass by MRI and DXA showed close relationships (range between $r = 0.72$ and $r = 0.92$). Both techniques also similarly assessed increases in lean leg tissue mass. This experiment reinforced the importance of apprising changes in regional tissue morphology (including total body changes) with an experimental treatment—in this case, the effects of periodized resistance training.

Dual-Energy X-Ray Absorptiometry

Dual-energy X-ray absorptiometry (DXA) reliably and accurately quantifies fat and nonbone regional lean body mass, including the mineral content of the body's deeper bony structures.[81,83,96,131,139] It has become the accepted clinical tool to assess spinal osteoporosis and related bone disorders.[40] When used for body composition assessment, DXA does not require assumptions concerning the biologic constancy of the fat and fat-free components inherent with hydrostatic weighing.

With DXA, two distinct low-energy X-ray beams (short exposure with low radiation dosage) penetrate bone and soft tissue areas to a depth of approximately 30 cm. The subject lies supine on a table so that the source and detector probes slowly pass across the body over a 12-minute period. Computer software reconstructs the attenuated X-ray beams to produce an image of the underlying tissues and quantify bone mineral content, total fat mass, and FFM. Analysis can include selected trunk and limb regions for detailed study of tissue composition and relation to disease risk, including the effects of exercise training and detraining.[94,104,185]

DXA shows excellent agreement with other independent estimates of bone mineral content. Strong relationships also exist between DXA-determined total body fat and body fat by either densitometry,[58,106] segmental body composition (upper- and lower-extremity mass), total body potassium, or total body nitrogen[107] and abdominal adiposity.[50] Recent studies have focused on body fat estimation by DXA with other methods in young children,[36] prepubertal children, [23,65,149] younger and older men[8] and women,[7,118] the elderly,[54,148] and changes during intense resistance training.[166] FIGURE 28.21 shows the strong association between percentage body fat estimates by DXA and hydrostatic weighing over a broad age range in men and women. The strength of the prediction decreases for older and fatter subjects but remains within the typical range for comparisons among discrete methodologies. Using a more robust model of body composition assessment, the error is less than 2% body fat units between DXA and densitometry in the heterogeneous age group of adults shown in the figure.[59]

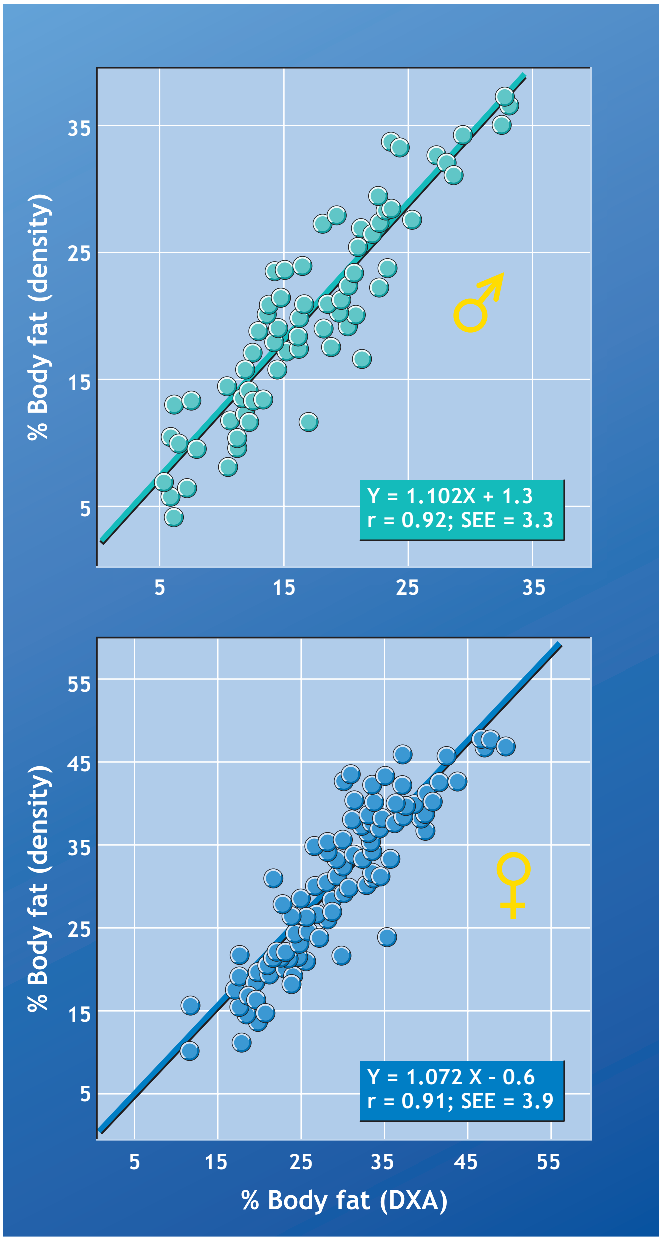


Figure 28.21 • Comparison of total body fat determined by hydrostatic weighing and DXA in men *(top)* and women *(bottom)*. (Modified from Snead DB, et al. Age-related differences in body composition by hydrodensitometry and dual-energy absorptiometry. J Appl Physiol 1993;74:770.)

INTEGRATIVE QUESTION

Outline your response to a student who asks: "Why am I considered overfat by some criteria for obesity while my body fat assessment with other methods falls within normal limits?"

AVERAGE PERCENTAGE BODY FAT

TABLE 28.5 lists average values for percentage body fat in samples of men and women throughout the United States. The column headed "68% Variation Limits" indicates the range of percentage body fat that includes approximately 68 of every 100 persons measured. As an example, the average percentage body fat of 15.0% for young men from the New York sample includes the 68% variation limits from 8.9 to 21.1% body fat. This means that for every 68 of 100 young men measured, percentage fat ranges between 8.9 and 21.1%. Of the remaining 32 young men, 16 possess more than 21.1% body fat, while 16 other men have a body fat percentage below 8.9. *In general, percentage body fat for young adult men averages between 12 and 15%; the average value for women falls between 25 and 28%.*

Representative Samples are Lacking

Considerable data describe average body composition for many groups of men and women of different ages and fitness levels and athletic specialties (see Chapter 29). No systematic evaluation exists for the body composition of a representative sample of the general population to warrant establishing norms or precise recommended values for body composition. At this time, it seems appropriate to present average values from various studies of different age groups.

TABLE 28.5 • Average Values of Body Fat for Younger and Older Women and Men from Selected Studies

Study	Age Range	Stature (cm)	Mass (kg)	% Fat	68% Variation Limits
Younger women					
North Carolina, 1962	17–25	165.0	55.5	22.9	17.5–28.5
New York, 1962	16–30	167.5	59.0	28.7	24.6–32.9
California, 1968	19–23	165.9	58.4	21.9	17.0–26.9
California, 1970	17–29	164.9	58.6	25.5	21.0–30.1
Air Force, 1972	17–22	164.1	55.8	28.7	22.3–35.3
New York, 1973	17–26	160.4	59.0	26.2	23.4–33.3
North Carolina, 1975	—	166.1	57.5	24.6	—
Army Recruits, 1986	17–25	162.0	58.6	28.4	23.9–32.9
Massachusetts, 1998	17–31	165.2	57.8	21.8	16.7–27.9
Older women					
Minnesota, 1953	31–45	163.3	60.7	28.9	25.1–32.8
	43–68	160.0	60.9	34.2	28.0–40.5
New York, 1963	30–40	164.9	59.6	28.6	22.1–35.3
	40–50	163.1	56.4	34.4	29.5–39.5
North Carolina, 1975	33–50	—	—	29.7	23.1–36.5
Massachusetts, 1993	31–50	165.2	58.9	25.2	19.2–31.2
Younger men					
Minnesota, 1951	17–26	177.8	69.1	11.8	5.9–11.8
Colorado, 1956	17–25	172.4	68.3	13.5	8.3–18.8
Indiana, 1966	18–23	180.1	75.5	12.6	8.7–16.5
California, 1968	16–31	175.7	74.1	15.2	6.3–24.2
New York, 1973	17–26	176.4	71.4	15.0	8.9–21.1
Texas, 1977	18–24	179.9	74.6	13.4	7.4–19.4
Army Recruits, 1986	17–25	174.7	70.5	15.6	10.0–21.2
Massachusetts, 1998	17–31	178.1	76.4	12.9	7.8–19.0
Older men					
Indiana, 1966	24–38	179.0	76.6	17.8	11.3–24.3
	40–48	177.0	80.5	22.3	16.3–28.3
North Carolina, 1976	27–50	—	—	23.7	17.9–30.1
Texas, 1977	27–59	180.0	85.3	27.1	23.7–30.5
Massachusetts, 1993	31–50	177.1	77.5	19.9	13.2–26.5

The general trend of these data indicates a distinct tendency for percentage body fat to steadily increase with advancing age. The mechanisms that lead to increased body fat with age are poorly understood. It also remains unanswered to what extent additional fat in older age poses an increased health risk. The trend does not necessarily imply a desirable or normal aging process because participation in vigorous physical activity throughout life frequently blunts body fat accretion with age.[164,182,183] Regular physical activity maintains or increases bone mass while preserving muscle mass. A sedentary lifestyle, in contrast, increases storage fat and reduces muscle mass. This occurs even if daily caloric intake remains unchanged.

DETERMINING GOAL BODY WEIGHT

Average values for percentage body fat approximate 15% for young men and 25% for young women. In contact sports and activities that require muscular power (e.g., football, sprint swimming, and running), successful performance typically requires a large fat-free body mass with average or below-average body fat. Successful athletes in weight-bearing endurance activities generally possess a relatively light body mass with low body fat. *Proper assessment of body composition, not body weight, determines a person's ideal body weight. For athletes,* ***goal body weight*** *must coincide with optimizing sport-specific measures of physiologic functional capacity and exercise performance.* The following equation computes a goal body weight based on a desired percentage body fat level:

$$\text{Goal body weight} = \text{fat-free body mass} \div (1.00 - \text{desired \%fat})$$

Suppose a 91-kg (200-lb) man, currently with 20% body fat, wants to know how much fat weight to lose to attain a body fat composition of 15%. The computations progress as follows:

$$\begin{aligned}\text{Fat mass} &= 91\text{ kg} \times 0.20\\ &= 18.2\text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Fat-free body mass} &= 91\text{ kg} - 18.2\text{ kg}\\ &= 72.8\text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Goal body weight} &= 72.8\text{ kg} \div (1.00 - 0.10)\\ &= 72.8\text{ kg} \div 0.90\\ &= 80.9\text{ kg (178 lb)}\end{aligned}$$

$$\begin{aligned}\text{Goal fat loss} &= \text{Current body weight} - \text{Goal body weight}\\ &= 91\text{ kg} - 80.9\text{ kg}\\ &= 10.1\text{ kg (22.2 lb)}\end{aligned}$$

If this athlete lost 10.1 kg of body fat, his new body weight of 80.9 kg would contain fat equal to 10% of body mass. These calculations assume no change in FFM during weight loss. Moderate caloric restriction plus increased daily energy expenditure through exercise induce fat loss and conserve the FFM. Chapter 30 discusses prudent yet effective approaches to fat loss.

Summary

1. Standard height–weight tables reveal little about body composition. Studies of athletes clearly show that overweight does not necessarily coincide with excessive body fat.
2. BMI relates more closely to body fat and health risk than simply body mass and stature. BMI still fails to consider the body's proportional composition.
3. Total body fat consists of essential fat and storage fat. Essential fat contains fat present in bone marrow, nerve tissue, and organs; it is an important component for normal biologic function. Storage fat represents the energy reserve that accumulates as adipose tissue beneath the skin and visceral depots.
4. Storage fat averages 12% of body mass for men and 15% for women. Essential fat averages 3% of body mass for men and 12% for women. The greater essential fat in females relates to childbearing and hormonal functions.
5. A person probably cannot reduce body fat below the essential fat level and still maintain optimal health.
6. Menstrual dysfunction occurs in athletes who train hard and maintain low body fat levels. This effect relates to the interaction between the physiologic and psychologic stress of regular training, hormonal balance, energy and nutrient intake, and body fat.
7. Delayed onset of menarche in chronically active young females may confer health benefits because such individuals show a lower lifetime occurrence of reproductive organ and other cancers.
8. Popular indirect methods of body composition assessment include hydrostatic weighing and prediction methods that incorporate skinfold and girth measurements.
9. Hydrostatic weighing determines body density with subsequent estimation of percentage body fat. The computation assumes a constant density for the body's fat and fat-free tissue compartments.
10. The air displacement method of BOD POD provides a reasonable alternative to hydrostatic weighing for body volume determination and subsequent body composition assessment.
11. The error inherent in predicting body fat from whole-body density lies in assumptions concerning the densities of the fat and fat-free components. These densities, especially fat-free body mass, differ from assumed constants because of race, age, and athletic experience.
12. Body composition assessments that use skinfolds and girths show population specificity; they are most accurate with subjects similar to those who participated in the equations' original derivation.
13. Hydrated fat-free body tissues and extracellular water facilitate electrical flow compared with fat tissue because of the greater electrolyte content of the fat-free component. Impedance to electric current flow in BIA analysis relates to the body's fat quantity.
14. Near-infrared interactance should be used with caution to assess body composition in the exercise sciences; this methodology currently lacks verification of adequate validity.
15. Ultrasound, CT, MRI, and DXA indirectly assess body composition. Each has a unique application and special limitations for expanding knowledge of the compositional components of the live human body.
16. Average males possess a body fat content of approximately 15% and women, 25%. These values from healthy individuals often provide a frame of reference to evaluate body fat of individual athletes and specific athletic groups.
17. Goal body weight computes as fat-free body mass: 1.00 − desired %fat.

References are available online at http://thepoint.lww.com/mkk7e.

On the Internet

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