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AHA Scientific Statement

Assessing Adiposity

A Scientific Statement From the American Heart Association

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The prevalence of obesity in the United States and the world has risen to epidemic/pandemic proportions. This increase has occurred despite great efforts by healthcare providers and consumers alike to improve the health-related behaviors of the population and a tremendous push from the scientific community to better understand the pathophysiology of obesity. This epidemic is all the more concerning given the clear association between excess adiposity and adverse health consequences such as cardiovascular disease (CVD) and type 2 diabetes mellitus (T2DM). The risks associated with overweight/obesity are primarily related to the deposition of adipose tissue, which leads to excess adiposity or body fatness. Furthermore, weight loss, specifically loss of body fat, is associated with improvement in obesity-related comorbidities. Before weight loss interventions can be recommended, however, patients must be assessed for their adiposity-related risk. Unfortunately, healthcare providers and systems have not done a good job of assessing for excess adiposity even in its simplest form, such as measuring body mass index (BMI). It is for these reasons that we must emphasize the importance of assessing adiposity in clinical practices. Although it can be argued that the entire population should be targeted as an important public health issue with a goal of prevention of weight gain and obesity, there are currently so many "at risk" individuals that simple strategies to identify and treat those individuals are necessary. We must identify those individuals at highest risk of comorbidities in order to identify those who might benefit the most from aggressive weight management.

This scientific statement will first briefly review the epidemiology of obesity and its related comorbidities, supporting the need for improved assessment of adiposity in daily clinical practice. This will be followed by a discussion of some of the challenges and issues associated with assessing adiposity and then by a review of the methods available for assessing adiposity in adults. Finally, practical recommendations for the clinician in practice will be given with a goal of identifying more at-risk overweight/obese individuals.

Excess Adiposity: The Scope of the Problem

Classification of Overweight and Obesity

The Centers for Disease Control and Prevention classify obesity according to BMI[1] as summarized in Table 1.[2,2a] Among adults, a BMI between 18.5 and 24.9 kg/m^2 corresponds to a healthy weight, BMI between 25.0 and 29.9 kg/m^2 is overweight, and BMI of ≥30.0 kg/m^2 is obese. The degree of obesity is classified separately. A BMI of 30.0 to

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Table 1. Classification of Body Weight According to BMI in Adults and in Children[2,2a]

Adults
Underweight: BMI <18.5 kg/m^2
Normal or acceptable weight: BMI 18.5–24.9 kg/m^2
Overweight: BMI 25–29.9 kg/m^2
Obese: BMI ≥30 kg/m^2
Class 1: BMI 30–34.9 kg/m^2
Class 2: BMI 35.0–39.9 kg/m^2
Class 3: BMI ≥40 kg/m^2 (severe, extreme, or morbid obesity)
Children (youths between 2 and 18 y of age)
Overweight: BMI of 85th to 94th percentile
Obese: BMI of 95th percentile or BMI of ≥30 kg/m^2, whichever is lower
Severe obesity: 99th percentile BMI
≥30 to 32 kg/m^2 for youths 10–12 y of age
≥34 kg/m^2 for youths 14–16 y of age

BMI indicates body mass index.

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34.9 kg/m^2 is class 1 or mild obesity, 35.0 to 39.9 kg/m^2 is class 2 or moderate obesity, and ≥40.0 kg/m^2 is class 3 or severe obesity. The absolute value of BMI is not used to classify weight status in children because change in BMI is normal and expected as children grow and develop. Instead, BMI percentiles adjusted for age and sex and calculated based on a compilation of national survey data collected over a 30-year period are used. In children 2 to 19 years of age, a BMI between the 5th and <85th percentiles is healthy, between the 85th and <95th percentiles is overweight, and at or above the 95th percentile is obese.[3]

Epidemiology of Overweight and Obesity

On the basis of data collected as part of the 2007 to 2008 National Health and Nutrition Examination Survey, in the United States 72.3% of men, 64.1% of women, and 68.0% of adults overall were either overweight or obese, with 32.2% of men, 35.5% of women, and 33.8% of adults overall being obese. The rates were stable for women for the 10 years preceding the survey and showed a slight increase for men during that period.[4] Data from the same period revealed a prevalence of obesity of 16.9% and a combined overweight and obesity prevalence of 31.7% among children ages 2 to 19 years.[5] As among adults, there are encouraging data to suggest that these rates have stabilized, with the exception of an increase in the number of boys ages 6 to 19 years with a BMI percentile at or above the 97th.

There are significant racial and regional differences in the prevalence of obesity. Non-Hispanic white adults have an obesity prevalence of 32.8%, compared with 44.1% for non-Hispanic blacks and 38.7% for Hispanics. Racial differences are especially pronounced among women: 33.0% of non-Hispanic white women are obese compared with 49.6% and 43.0% of non-Hispanic black and Hispanic women, respectively. Similar racial differences are present among children: 15.3% of white children are obese, compared with 20.0% of non-Hispanic black children and 20.9% of Hispanic children. Regional data obtained from the Behavioral Risk Factor Surveillance System, which relies on self-reported height and weight, reveal a range of adult obesity prevalence by county of 12.4% to 43.7%. The highest rates of obesity are in the South, the western Appalachians, and coastal North and South Carolina. The lowest rates are in the West, the northern Plains, and New England.[6] Among states, according to the Behavioral Risk Factor Surveillance System, Mississippi has the highest adult obesity prevalence (32.8%), and Colorado has the lowest, with a rate of 18.5%.[7]

Complications of Excess Adiposity

A substantial body of evidence demonstrates a harmful effect of obesity and excess adiposity on cardiovascular health. Both abdominal obesity and general obesity are independently associated with cerebrovascular disease (odds ratio [OR] range 1.22–2.37)[8–14] and coronary heart disease (OR range 1.21–3.25).[14–18] Furthermore, obesity is associated with increased overall mortality[19–21] (OR range 1.9–2.42) and mortality after cardiovascular events (OR range 1.07–1.94).[22–25] Although some studies have shown a J-shaped curve between BMI and mortality, with higher mortality rates in individuals in both the highest and lowest BMI categories, often referred to as the "obesity paradox,"[12,26] comorbidities associated with excess adiposity appear to increase across the continuum of overweight and obesity. Furthermore, abdominal obesity, an important component of the metabolic or the cardiometabolic syndrome, has been shown to be associated with stroke,[27] coronary heart disease,[28] and overall mortality[29,30] independent of other cardiac risk factors. Overweight and obesity are also associated with increased risk of a number of other comorbid conditions, such as T2DM, systemic hypertension, dyslipidemia, obstructive sleep apnea, osteoarthritis, depression, gout, nonalcoholic liver disease, reproductive-endocrine disorders, and several cancers, to name a few.

Assessing Excess Adiposity: The Problems

Total Body Fat Versus Distribution of Body Fat Versus Body Composition Versus Ectopic Fat

Heterogeneity of Obesity

Although numerous population-based studies have shown that there is a clear relationship between BMI (the most common index of adiposity used in clinical practice) and the documented comorbidities associated with excess body fatness,[31–34] obesity has remained a puzzling condition for clinicians because of its remarkable heterogeneity. For instance, although obese patients are as a group at greater risk of comorbidities than normal-weight individuals, some obese patients may nevertheless show trivial or even no metabolic complications, the so-called metabolically healthy obese,[35–42] whereas others with the same level of obesity (on the basis of similar BMI values) could show numerous metabolic abnormalities, including insulin resistance, glucose intolerance, dyslipidemia, systemic hypertension, and a prothrombotic-inflammatory profile.[43–56] Thus, although BMI has been useful to describe secular changes in adiposity at the popu-

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lation level, BMI cannot always properly discriminate the risk of chronic disease at the individual level.

Body Shape Matters: The Pioneer

Numerous epidemiological and metabolic studies published over the past 3 decades have provided support to Jean Vague's early seminal observations[57,58] that the common complications of obesity, such as insulin resistance, atherogenic dyslipidemia, T2DM, and CVD, were more closely related to the distribution of body fat than to the absolute degree of fatness per se.[19,32,43–56,59–64] Vague coined the term "android" obesity (more frequently found in men) to describe the high-risk form of obesity, whereas he introduced the term "gynoid" obesity to describe the low risk typical of lower-body adiposity more frequently found in premenopausal women.[57]

The Renaissance of Regional Adipose Tissue Distribution

In the early 1980s, Björntorp and colleagues[59,60,65,66] in Gothenburg, Sweden, and Kissebah and collaborators[64,67] in Milwaukee, WI, reported that when the ratio of waist to hip circumferences (waist-hip ratio [WHR]) was used as an index of the relative accumulation of abdominal fat, this variable was related both to the risk of coronary heart disease and T2DM and to a diabetogenic/atherogenic metabolic risk profile. The rationale for this ratio was simple: The greater the relative accumulation of abdominal fat, the greater the waist circumference (WC) relative to the hip girth. This early work has had a tremendous impact on the field of body fat distribution and health, because it provided evidence that body fat distribution deserved more attention as a predictor of the comorbidities than had been, in the past, attributed to excess body fatness per se.

Imaging Techniques: A Major Advancement in the Study of Body Fat Distribution

In the mid-1980s, the introduction of imaging techniques such as computed tomography (CT) gave investigators interested in body fat topography a more sophisticated tool that allowed for more precise measurements of regional fat accumulation. CT was found to be particularly helpful in distinguishing the abdominal fat stored subcutaneously (ie, subcutaneous adipose tissue [SAT]) from the adipose tissue located in the abdominal cavity, including omental, mesenteric, and retroperitoneal adipose tissue, which has commonly been described as intra-abdominal or visceral adipose tissue (VAT). Studies that have measured SAT and VAT areas with CT have shown that although the size of both adipose depots is associated with a progressive deterioration in cardiometabolic risk profile, when matched for levels of SAT, individuals with excess VAT and deep SAT were characterized by a more diabetogenic/atherogenic risk factor profile.[43–56,68] These results have provided robust evidence that although excess fatness is associated with metabolic abnormalities, high levels specifically of VAT are characterized by the most severe metabolic abnormalities. More recent epidemiological studies that have used imaging techniques such as CT or magnetic resonance imaging (MRI) have been able to identify the respective contributions of SAT and VAT in very large study samples and have clearly shown that visceral adiposity is associated with more severe metabolic disturbances than subcutaneous adiposity.[53,69,70]

Table 2. Factors Associated With Increased Visceral Adiposity

Increasing age
Sex (men>women)
Menopause in women
Smoking
Nutritional factors (high-caloric diet)
Sedentary behavior
Race
↑ Asians
↓ in blacks

Factors Associated With Individual Differences in Visceral Adiposity

The factors that regulate regional body fat deposition have been investigated extensively (Table 2). Several factors are associated with differences in visceral adiposity, such as sex, age, genetic factors, hormonal profile, smoking, and nutritional factors, as well as vigorous endurance exercise.[71–73] Major sex differences are observed in visceral adiposity before menopause, with premenopausal women having on average 50% less VAT than men and with significantly more gluteal-femoral adipose tissue in women, which may be metabolically protective.[74,75] Such a sex difference in visceral adiposity has been shown to largely but not entirely explain the gender gap in cardiometabolic risk variables.[76] With age, there is also a selective deposition of VAT that is predictive of the age-related deterioration in the cardiometabolic risk profile,[75,77–80] particularly among those who have a family history of visceral obesity.[81]

Ethnicity and race are also associated with differences in susceptibility to the selective deposition of VAT.[82–87] For instance, blacks are more prone to subcutaneous adiposity than whites or Hispanics, whereas evidence available suggests that Asians may be more prone to visceral fat deposition.[82–87] Ethnic and racial differences in visceral body fat deposition are currently an area of intense study.

Visceral Adiposity and Metabolic Complications

An important question with considerable clinical implications is whether excess visceral adiposity is causally related to metabolic abnormalities. An extensive discussion of this issue is beyond the scope of this scientific statement, and the reader is referred to several comprehensive reviews on the topic.[71,88–91] Currently, 3 main theories have been proposed to explain the relationship between visceral adiposity and metabolic complications:

1. The portal free fatty acid model: Björntorp put forward the hypothesis that in visceral obesity, an uninterrupted overflow of free fatty acid from intra-abdominal or visceral adipocytes would expose the liver to high concentrations, leading to several impairments in hepatic metabolism.[92–94] These include reduced extraction and degradation of insulin that exacerbates systemic hyperinsulinemia, reduced degradation of apolipoprotein B that leads to hypertriglyceridemia, and increased

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hepatic glucose production that leads to impaired glucose tolerance and eventually to T2DM.[94,95] Therefore, under this model, one can explain the relationship between excess visceral adiposity and hypertriglyceridemia, hyperapolipoprotein B, hyperinsulinemia, and glucose intolerance that is found in at-risk overweight/obese patients. Although elegant work conducted in dogs supports this model,[96] the hypothesis has been under criticism since Jensen et al[97–99] provided evidence that most of the free fatty acid found in the portal circulation originates from SAT. Despite the fact that these investigators also found a relationship between visceral adiposity and portal free fatty acid levels coming from the visceral fat depot,[98] other scenarios may be involved in the full explanation of the dysmetabolic state of visceral obesity.

2. The "endocrine" function of VAT: Another advance in our understanding of adipose tissue biology was the discovery that adipose tissue is more than a triglyceride storage/mobilization organ. Indeed, numerous potentially important adipose tissue cytokines, commonly referred to as adipokines, could play a role in the dysmetabolic state associated with total/visceral adiposity.[100] For instance, leptin, which is produced by adipose cells, has been shown to be better correlated with total and subcutaneous adiposity than with visceral adiposity.[101–103] This is why circulating leptin levels are higher in women, who have on average more subcutaneous fat than men.[102,104,105] Another adipokine, adiponectin, appears to better reflect visceral than total adiposity.[49,52,106] Accordingly, adiponectin levels are generally lower in men than in women, and they are low in viscerally obese individuals and in patients with T2DM.[49,107,108] However, a key finding was the observation that hypertrophied adipose tissue is characterized by an infiltration of macrophages, some of which are a major source of inflammatory cytokines such as tumor necrosis factor-α and interleukin-6.[109,110] The cytokine interleukin-6 is a major driver of the production of C-reactive protein by the liver.[111] Therefore, in viscerally obese patients, the increased production of interleukin-6 by the expanded visceral adipose depot could contribute to expose the liver to high interleukin-6 levels, which could in turn stimulate hepatic C-reactive protein production and impair liver metabolism. Of course, the model is more complicated than the above oversimplification, but several adipokines and the role of the "inflamed" hypertrophied VAT are certainly under the radar screen and are the subject of considerable investigations.
3. Visceral obesity, a marker of dysfunctional adipose tissue leading to ectopic fat deposition: Finally, although visceral adiposity is clearly related to the metabolic abnormalities of overweight/obesity, whether there is a causal relationship between excess visceral adiposity and metabolic complications has been debated. In numerous recent papers and review articles, it has been proposed that excess visceral adiposity may not necessarily impair carbohydrate and lipid metabolism directly but rather may reflect the relative inability of SAT to properly adapt to positive energy balance and to expand by hyperplasia (multiplication of preadipocytes to an increase in the number of adipose cells), creating a "protective metabolic sink."[41,90,91,112] Under this model, a sedentary individual exposed to a surplus of calories would store this extra energy in SAT. To do so, the subcutaneous fat depot would undergo hyperplasia, if need be, to allow the safe storage of this extra energy. However, in situations in which subcutaneous fat could not undergo hyperplasia and therefore would have a limited ability to expand to store the caloric excess, as might occur in the setting of adipose tissue hypoxia,[113] these excess triglyceride molecules would accumulate at undesired sites such as liver, heart, pancreas, or skeletal muscle, a phenomenon referred to as "ectopic fat deposition." Substantial experimental evidence supports the view that excess visceral adiposity is a marker of dysfunctional adipose tissue and of ectopic fat. For instance, women, who have a lot more subcutaneous fat than men, are characterized by lower postprandial lipemia than men because their SAT can better handle the dietary fat load than men.[114] In addition, individuals with partial lipodystrophies have more visceral/ectopic fat because of their dysfunctional SAT.[115,116] Thiazolidinediones, which improve insulin sensitivity and decrease liver fat, have been shown to induce hyperplasia of SAT, and this is probably a key mechanism explaining how this class of drugs improves glycemia and the cardiometabolic risk profile.[117–119] Finally, a negative energy balance induced by diet or by endurance exercise has been shown not only to induce weight loss but also to induce a rapid reduction of liver fat and VAT.[120–123] Thus, under circumstances in which the "pressure" for storage of excess triglyceride molecules in SAT is decreased, there will no longer be a need to deposit triglyceride at undesired sites, and ectopic fat depot will be mobilized more readily than subcutaneous fat.

Liver Fat as a Key Feature of Ectopic Fat Associated With Dysfunctional Adipose Tissue and Visceral Obesity

The liver plays a central role in the regulation of carbohydrate and lipid/lipoprotein metabolism. Thus, any impairment in liver function is likely to have a major impact on risk factors/markers for prevalent complications such as T2DM and CVD. As for the study of visceral adiposity, the development of imaging techniques such as CT, MRI, and proton magnetic resonance spectroscopy (MRS) has allowed the study of individual differences in liver fat content and its relationship with cardiometabolic risk variables.[124–127] First, it has been found that the growing prevalence of obesity has had a major impact on the prevalence of nonalcoholic fatty liver disease,[128–130] a condition that could evolve to nonalcoholic steatohepatitis and cirrhosis. Studies that have examined the relationships between body composition, adipose tissue distribution, and liver fat content assessed by MRS have clearly shown that excess visceral adiposity is related to liver fat content even after controlling for total body fat.[70] However, liver fat content has generally been found to be more strongly related to insulin resistance and hypertriglyceridemia than visceral adiposity.[131] Thus, liver fat is closely related to features of the metabolic syndrome,[132] but visceral adiposity is the best adiposity predictor of liver fat content.[133] In the landmark Dallas Heart Study conducted on >2000 subjects, ethnic and racial differences (among Hispanic, whites, and blacks) were observed in liver fat content, with blacks having

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less liver fat than whites and Hispanics.[70] However, differences in visceral adiposity were also noted, with blacks having less VAT than the 2 other ethnic and racial groups. A major sex-based difference in the relationship of total adiposity to liver fat content has also been observed: Compared with men, women appear to be relatively protected from the liver fat accumulation expected from excess adiposity. However, this sex difference was entirely attributable to the fact that women had less visceral fat than men. On the other hand, men have greater liver fat content than women, a phenomenon that can be explained entirely by their greater accumulation of VAT compared with women.[70]

Another recently reported international study involving >4500 patients from 29 countries also provides evidence of a strong correlation between visceral adiposity and liver fat content.[69] This study also found that the greater accumulation of liver fat in men than in women was entirely accounted for by the greater visceral adiposity of men compared with women. Although such robust and consistent associations cannot be taken as evidence of a causal relationship between visceral adiposity and liver fat (as previously discussed), these observations provide highly concordant evidence that excess liver fat is commonly accompanied by excess visceral adiposity. Other ectopic fat depots (epicardial fat, skeletal muscle, pancreas) are also related to cardiometabolic risk,[90,91,134–137] but their specific contribution beyond visceral adiposity and liver fat is not clear. The evidence currently available suggests that excess liver fat is a key central feature predictive of cardiometabolic abnormalities,[131] which makes it a priority target for management of complications of overweight/obesity.

In summary, excess VAT may be related to cardiometabolic risk in part through a direct mechanism, but we need to keep in mind that another likely scenario is that excess visceral adiposity is a marker of dysfunctional SAT and of ectopic fat deposition. Under this model, 2 key features of ectopic fat may be excess visceral adiposity and liver fat.

"Normal-Weight" Obesity

Recent studies have suggested that individuals with normal body weight as defined by BMI might still be at risk for metabolic syndrome, insulin resistance, and increased mortality if they have a high body fat content.[138,139] A recent report from a sample of individuals representative of the adult US population showed that men of normal weight in the upper tertile of body fat percentage (>23% fat), as measured with electric bioimpedance, were 4 times more likely to have metabolic syndrome and had a higher prevalence of dyslipidemia, T2DM, systemic hypertension, and CVD than those in the lowest tertile.[139] Women in the highest tertile of body fat (>33% fat) were 7 times more likely to have metabolic syndrome. Interestingly, women with normal-weight obesity were almost twice as likely to die at follow-up as women in the lowest tertile of body fat. The prevalence of central obesity was low in this group of normal-weight individuals, so these associations were not explained by differences in measures of central obesity between those with normal-weight obesity and control subjects. Studies have also shown that people with normal BMI but enlarged WC have a higher rate of cardiovascular events and death (discussed further below). Although further research is needed to clarify these interesting results, it is clear that subjects with normal weight as defined by BMI may need more detailed classification to better define their adiposity-related risk.

Assessing Excess Adiposity: Methods

This section will review the most accepted methods available both to clinicians and researchers for assessing excess body fat. These methods include those for assessing total body fat mass, distribution of body fat, body composition (percent body fat), and ectopic fat.

Assessing Total Body Adiposity

Body Weight

Before the use of formulas and tables to adjust body weight for height, the diagnosis of obesity relied on the subjective interpretation of physical appearance and the absolute body weight. The use of weight alone to estimate adiposity, however, is inappropriate, because it fails to consider the fact that body weight is proportional to height, an observation first documented in the 19th century by a Belgian mathematician.[140] This relationship, originally known as the Quetelet Index, is now known as BMI. The first attempt to formally diagnose obesity on the basis of body weight indexed to height in modern times was the use of actuarial tables from the Metropolitan Life Insurance Company. These tables were used to estimate ideal weight and then determine the percentage of excess weight.[141,142] Because these tables were not based on a simple formula and required the subjective interpretation of an individual's constitution according to normal, thin, and big frame, their use is not practical or reproducible. Thus, a simple body weight is not sufficient in and of itself for the clinical assessment of body fatness.

Body Mass Index

BMI, calculated as body weight in kilograms divided by height in meters squared (kg/m^2), is one of the most commonly used anthropometric measures to assess for total body adiposity. Because of its simplicity as a measure, it has been used in epidemiological studies and is recommended as a screening tool in the initial clinical assessment of obesity.[143,144] Multiple epidemiological studies have demonstrated increased morbidity and mortality with BMI >30 kg/m^2.[145] Data from the Prospective Studies Collaboration, which analyzed 900 000 adults, demonstrated a 30% increase in all-cause mortality for every increase of 5 U in BMI above a BMI of 25 kg/m^2.[20]

Although the utility of BMI has been borne out in epidemiological data, there are limitations to the use of BMI alone to assess for adiposity in clinical practice, particularly among adults with BMI ≤30 kg/m^2.[146] The numerator in the BMI calculation is "total" body weight and does not distinguish between lean and fat mass. Thus, individuals with normal weight but excess body fat may not be diagnosed as overweight or obese. Conversely, adults with high levels of lean body mass may be misclassified as overweight or obese. Data from the National Health and Nutrition Examination Survey III were analyzed to compare BMI with the World Health

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Organization criteria for obesity (body fat >25% in men and >35% in women, as measured by bioelectrical impedance; discussed below). This analysis demonstrated that although a BMI ≥30 kg/m^2 had good specificity in men (95%) and women (99%) for detecting obesity, BMI had low sensitivity in men (36%) and women (49%) for diagnosing obesity.[146] In a meta-analysis that pooled 32 studies and included almost 32 000 individuals, BMI had a pooled sensitivity of 50% to identify excess adiposity and a pooled specificity of 90%, which demonstrates that half of the individuals with excess body fat were not identified as obese.[147]

The cut points of BMI used to diagnose overweight and obesity are assumed to be independent of age, sex, and ethnicity and race; however, because of age- and sex-related differences in body composition, BMI may not correlate as well with body fat in some age, sex, and ethnic groups. At similar levels of BMI, women may have higher percentages of body fat than men.[148] Hispanic women have a higher percentage body fat than black and white American women with similar BMIs,[149] and black women have a lower percent body fat than white women with the same BMI.[150] The most pronounced difference in the relationship between BMI, body fat, and disease risk is seen in Asian populations, in which a given level of BMI is associated with greater adiposity and comorbidities than in other populations. Although there are no population-dependent cut points for BMI, several studies have demonstrated that cut points between 23 and 27 kg/m^2 may more accurately identify obesity in Asian populations.[151,152]

Although BMI is more accurate than body weight alone and is simple to calculate, it does have limitations, including poor sensitivity in diagnosing excess body fatness, especially in some populations. Nevertheless, BMI should be considered as the primary tool for the assessment of body fatness in clinical practice because of its global acceptance and ease of calculation. The limitations of the BMI as discussed, however, must be considered when it is used alone as an index of adiposity in clinical practice.

Assessing Distribution of Body Fat

It is clear that simple measurements of body weight and BMI do not yield good assessments of either the body composition or distribution of body fat, especially in those with a BMI <30 kg/m^2. Tools are available to better assess the distribution of adiposity (Table 3).

Waist Circumference

WC has been shown to be a simple and inexpensive yet effective way to assess for central obesity, with excellent correlation with abdominal imaging[153] and high association with CVD risk and mortality.[154] As a result, definitions of the metabolic syndrome have adapted WC as a surrogate marker of abdominal or central obesity.[155] The WC is easily measured with a tape measure while the patient is standing, wearing light clothing, and at end expiration. Despite this, WC measurements have not been well adopted in clinical practice. One issue relates to issues that surround the measurement site. In a recent review of the literature, a panel of experts found 8 different measurement locations documented for WC: (1) halfway between the lowest rib and the iliac crest (midpoint); (2) point of minimal circumference; (3) immediately above the iliac crest; (4) umbilicus; (5) 1 inch above the umbilicus; (6) 1 cm above the umbilicus; (7) at the lowest rib; and (8) point of largest circumference around the waist.[156] This variability in measurements at different locations may be problematic, because as one might expect, all WC sites do not provide the same measurement estimate.[157–162] Although the umbilicus has been found to be the least reproducible site, most of these sites have very high reproducibility and do not appear to be influenced by age or BMI.[157] Although measurement of WC at the iliac crest has been shown to have lower precision and may require more training and experience to locate,[159] bony structures are stable landmarks that are not affected by changes in weight, which confers certain advantages, especially for longitudinal tracking of body composition. It is for these reasons that the iliac crest is currently recommended by the National Institutes of Health and National Heart, Lung, and Blood Institute. The World Health Organization recommends the use of the midpoint WC measurement; however, this method relies on the identification of 2 separate locations, the iliac crest and the lowest rib, and the need to calculate the midpoint of the distance between these 2 structures, which requires more skill and time than a measurement that relies on only 1 structure, such as the iliac crest.

Table 3. Potential Clinical Utility of the Methods for Assessing Body Fat Distribution

Method	Clinical Use
Waist circumference	+++
Hip circumference	+
Thigh circumference	+
Neck circumference	+
Ratios	
Waist-to-hip	++
Waist-to-height	+
Waist-to-thigh	+
Imaging	
CT	—
MRI	—

CT indicates computed tomography; MRI, magnetic resonance imaging; +++, widely accepted method; ++, accepted method; +, uncommonly used method; and —, not recommended for clinical use.

Another important consideration in establishing a standard site for WC measurement is the predictability of CVD morbidity and mortality associated with each measurement site. For example, WC cut points have been established based on their correspondence to a BMI of ≥25 kg/m^2 or ≥30 kg/m^2: 80 and 88 cm for women and 94 and 102 cm for men, respectively.[163] These cut points were established from WC measurements taken at the midpoint and were not based on risk of CVD or CVD morbidity and mortality. However, because studies have shown that WC is associated with CVD risk, it becomes important to establish the most appropriate measurement site for predicting CVD risk. Mason and Katzmarzyk[164] identified optimal WC thresholds for the prediction of cardiometabolic risk across 4 measurement sites: iliac

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crest, midpoint, umbilicus, and minimal waist. The authors found that more men and women met the criterion for abdominal obesity when WC was measured at the umbilicus, 34% and 55%, respectively, compared with 23% and 31%, respectively, for measurements taken at the minimal waist. Although the magnitude of the correlation between cardiometabolic risk and WC did not differ between measurement sites, optimal cut points to predict cardiometabolic risk differed: In men, optimal cut points were 100 cm at all sites except for the minimal waist, which was 97 cm; in women, cut points were 87 cm at minimal waist, 90 cm at midpoint, 93 cm at the iliac crest, and 95 cm at the umbilicus.[164] Similar observations have been noted by Bosy-Westphal et al,[159] in which 3 WC measurement sites (rib, midpoint, and iliac crest) had similar correlations with VAT and cardiometabolic risk factors.

In summary, WC is a simple and inexpensive tool for assessing body fat distribution. It correlates well with abdominal obesity as assessed by imaging methods (discussed below) and is associated with increased risk for adiposity-related morbidity and mortality. This tool requires only the purchase of an appropriate tape measure and simple training of health professionals and/or assistants. It can easily be incorporated in the vital sign assessment of patients at the time the body weight is obtained. We recommend performing the WC measurement at the iliac crest as the easiest and most consistent location, as described by the National Institutes of Health guidelines. This tool and its importance can be explained easily to patients. For these reasons, WC is an ideal inexpensive clinical complement to the BMI measurement.

Hip Circumference

Hip circumference (HC) is measured at the level of the widest circumference over the buttocks. This measurement is also used to calculate the WHR, which has been debated as a useful tool for assessment of body composition. Some may argue that a ratio does not provide information on whether the WC is large or the HC narrow, because, for example, a woman with a large WC of 100 cm and wide HC of 120 cm will have the same WHR as a woman with narrow WC of 75 cm and an HC of 90 cm, respectively. Based on differences in WC, these 2 women would be predicted to have a much different CVD risk profile. Others argue, however, that HC adds value to the measurement of WC because wider hips provide protection against CVD.[165,166] When examined with respect to all-cause mortality, however, HC does not appear to be a significant predictor of all-cause mortality.[167]

Lower Body Circumferences

Thigh and calf circumferences have also been assessed as predictors of metabolic risk. Thigh circumference has been measured on the right leg, 1 cm below the gluteal line,[167] on the left leg below the gluteal fold,[168] and at mid thigh,[169] whereas calf circumference has been measured at the maximum circumference of the calf.[167] Mason et al[167] have reported that, after adjusting for covariates, thigh and calf circumferences are negatively associated with mortality in men but not in women. A larger thigh circumference has been associated with lower risk of T2DM in both men and women, independent of BMI, age, and WC.[168] Most studies, however, have used thigh circumference in combination with WC to provide an index of upper- to lower-body adiposity (reviewed below).

Neck Circumference

Neck circumference is another anthropometric measure that may provide additional information for CVD risk. Neck circumference has been measured midway between the midcervical spine and midanterior neck, just below the laryngeal prominence. As early as 1989, data from Take Off the Pounds Sensibly (TOPS) participants indicated that neck circumference was related to the presence of T2DM in women.[170] In several studies, this measurement has been found to be correlated with WC, WHR, and BMI, as well as metabolic syndrome risk factors, in men and women.[171–174] A large neck circumference increases the odds of metabolic syndrome in men and women, even after adjustment for WC and smoking[173] or BMI and WC.[174] Moreover, the association may be stronger in women than in men.[174] Neck circumference also provides risk assessment for obstructive sleep apnea and has been found to be associated with the severity of obstructive sleep apnea independent of obesity.[175]

Ratios

Various ratios can be computed from anthropometric data. Some of the most common include WHR, waist-to-height ratio (WHtR), and waist-to-thigh ratio. These measurements have been examined for their ability to predict risk of metabolic disorders. In fact, Reis et al[176] compared the relative importance and joint association of overall obesity and abdominal adiposity with risk of total and cardiovascular mortality in the National Health and Nutrition Examination Survey III and found that men and women who died of CVD had greater WHR and thigh circumference at baseline, but only women also had greater WC and waist-to-thigh ratio. The authors concluded that the measurement of body fat distribution by WHR carries important information to identify adults at increased risk of mortality. Elsayed et al[177] also assessed WC and WHR as risk factors for CVD mortality in patients with chronic kidney disease. They found that WHR but not WC was associated with cardiac events in models adjusted for demographic and lifestyle characteristics, as well as baseline CVD and CVD risk factors. In the Monitoring Trends and Determinants in Cardiovascular Disease Augsburg (MONICA) study, BMI, WC, and WHR were all strongly and independently related to incident T2DM in both men and women.[178] Each measurement was equivalent in predicting T2DM in men but not in women, and WC and BMI had the greatest risk ratio. Taylor et al[179] also found that the magnitudes of the association between BMI, WHR, WHtR, and WC with CVD risk factors were all similar except that HC was less strongly associated with triglyceride and insulin levels. Other groups have also shown that BMI, WC, WHR, and WHtR are all closely related to CVD risk in 20- to 64-year-old Taiwanese men and women[180] and Asians in the Obesity in Asia Collaboration.[181] However, in non-Asians, WHR has a stronger association with dyslipidemia than BMI.[181] Ratios involving WC, such as WHR and WHtR, as well as WC alone, have also been shown to be superior to BMI at predicting coronary heart disease incidence in white

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middle-aged women.[182] This is supported by data from the European Perspective Investigating Into Cancer and Nutrition in Norfolk (EPIC-Norfolk) study[183] and data from the Physicians' Health Study and the Nurses' Health Study.[184]

The waist-to-thigh ratio has been reported to be a strong positive predictor of mortality in both men and women[167] and has the greatest discriminating power and strongest association with T2DM in men compared with WHtR, WHR, WC, and BMI.[169] In women, waist-to-thigh ratio performed better than BMI in discrimination for T2DM but was not different from WHtR, WHR, and WC. These data differ somewhat from those from the Hoorn Study, in which waist-to-thigh ratio was a better predictor of future T2DM than BMI in both men and women.[168]

Whether ratios, as indices of upper to lower body fat distribution, should be used rather than BMI or WC alone for predicting risk remains debatable and controversial. For example, although Gelber et al[184] found that WHtR had the strongest gradient in association with cardiovascular events in men and women from the Physicians' and the Nurses' Health Studies, they still concluded that there was no substantial or clinically meaningful difference between BMI and WHR in predicting cardiovascular events. Similarly, Taylor et al[179] concluded that because of similar associations between BMI, WC, WHR, WHtR, and CVD risk factors, recommendations to replace BMI with WC-based measurements are not warranted for routine public health surveillance. Page et al[182] suggested that ease of measurement should be a determining factor in establishing body composition indices that would predict CVD risk. Alternatively, Asian studies propose the use of WHtR[181,185] and WHR[181] in predicting CVD risk factors. In fact, ratios such as WHtR and WHR may provide the greatest value for uniform comparison of CVD between populations. Optimal BMI and WC values for predicting metabolic disorders differ between Mexicans, Asians, and blacks and whites,[185–187] but WHtR and WHR adjust for these ethnic differences in body shape.[187]

Despite all the evidence and the issue of practicality, we do not recommend the routine use of ratios to assess adiposity. WHtR and WHR, however, are promising measures for adjusting for ethnic differences in body shape when determining metabolic risk.

Sagittal Abdominal Diameter

As with WC, the sagittal abdominal diameter (SAD) has been shown to be a better marker of abdominal visceral adiposity, metabolic disorders, and coronary heart disease than the WHR.[153,188–190] SAD can be measured easily either with CT or MRI images or directly on a patient, generally in the supine position, as the distance between the examining table and the apex of the abdominal girth or the largest anteroposterior diameter between the xiphoid process and the umbilicus. Standardized methods for measuring SAD, however, have not been developed or validated. Some studies have found the SAD to be an even better predictor of metabolic syndrome, including dyslipidemia, high blood pressure, and insulin resistance,[191–194] and CVD[195] than WC. Other studies, though, have found no advantage of the SAD over WC.[196–198] Although they represent a promising measure of abdominal adiposity, SAD measurements need to be standardized and validated and normal thresholds identified.

Imaging Methods: CT and MRI

Although still primarily reserved for research purposes, imaging methods are available to assess adipose tissue distribution and body composition. Two commonly used methods, CT and MRI, have the advantage of distinguishing SAT and VAT. For example, although WC is generally a good predictor of abdominal adiposity, it cannot distinguish between SAT and VAT.

CT produces sliced images of the body from which areas occupied by selected tissues may be used to determine the surface or volume of these tissues in any given body area. Each pixel of each sliced image is assigned an attenuation value expressed as Hounsfield units (HU), ranging from −1000 HU (air) to 2000 HU (dense bone). Adipose tissue has attenuation values that range from −190 to −30 HU. Total body tissue and organ masses determined from repeated CT slices performed at 10-cm intervals from toes to fingers are highly reliable and reproducible, with an error <1% between paired scans.[199] The most significant advance in assessment of adiposity by CT scan has been the ability to dissect out the various adipose tissue depots in the body. To limit cost and radiation exposure, most CT scanning methods assess adiposity in the abdominal area with a single sliced image taken at the L4-L5 intervertebral space and estimation of total SAT and VAT content.[200] SAT and VAT areas can be separated by delineating the 2 depots on the densitometric scan. Abdominal SAT can be further subdivided into superficial and deep compartments by use of the fascia superficialis.[68] The deep SAT depot is also often referred to as the posterior SAT depot. VAT is found within the intra-abdominal cavity and is separated from the SAT by the muscle wall of the abdomen.[201] It remains unclear, however, whether assessment of SAT and VAT volumes derived from several sliced images of the abdomen by CT is more predictive of disease and dysmetabolic states than that derived from a single image.[202] In addition, universal definitions of excess SAT and VAT area have yet to be accepted.[200] CT assessments also allow for the measurement of lipids in nonadipose tissue compartments such as muscle and liver, the so-called ectopic fat.[203]

MRI is based on the interaction between protons present in all biological tissues and magnetic fields generated and controlled by the MRI system's instrumentation. Sliced images or a whole-body image are constructed according to the rate at which protons from various tissues return to their equilibrium state after exposure to various magnetic fields. Estimation of regional adipose tissue distribution by MRI compares well with values generated by CT. Because the radiation dose is virtually absent with MRI, this method is more appropriate than CT, particularly when several measurements are required over time in the same individual or when particular populations such as children are being investigated.[202] Other advantages of MRI scanning include access to information on other adipose tissue compartments, such as intermuscular adipose tissue, and segmentation of the body into lower- and upper-body regions. The use of MRI to assess adiposity, however, is limited by its high cost because

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of its sophisticated equipment and data processing.[202] Another limitation is that neither MRI nor CT can accommodate individuals with severe obesity.

A controversy in the field of body composition imaging is the ideal location of single-slice acquisitions. Because whole-body MRI scanning is time-consuming, requiring ≈30 minutes for a whole-body scan, and is very expensive, single-slice acquisitions are often preferred. Whether a slice obtained at the level of L4-L5 is most representative of total-body VAT or most associated with metabolic risk factors has been studied. Shen et al[204] used MRI data to determine which abdominal slice VAT was most correlated with total-body VAT and found that in men, the slice located 10 cm above L4-L5 was most correlated with total VAT. In women, the slice 5 cm above L4-L5 had stronger correlation with total VAT than L4-L5. The errors of prediction based on L4-L5 VAT were significantly larger than those based on the best slice: 10 cm above L4-L5 for men and 5 cm above L4-L5 for women. This group calculated that to achieve the same power to detect changes in VAT with a single slice compared with whole-body VAT, studies using the best slice would require 6% to 7% more participants, whereas studies using L4-L5 would require 24% more men or 16% more women. Similar observations were made by Liu et al,[205] who reported that in Chinese men and women, VAT at the lower costal margin, which is located above L4-L5, had the highest correlation with total VAT. Other locations assessed by this group included midway between the xiphoid process and the lower costal margin, the umbilicus, midway between the umbilicus and the pubic symphysis, and the pubic symphysis.

Shen et al[206] also examined the relationship between total VAT and single-slice VAT and metabolic risk factors. Compared with total VAT, VAT at L4-L5 had lower correlations with triglycerides, high-density lipoprotein cholesterol, fasting insulin, and diastolic blood pressure and equal correlation with fasting glucose and systolic blood pressure in men. Similarly, slices 5 cm above and 5 cm below had weaker correlations with fasting insulin and triglycerides and with systolic blood pressure (5 cm below only) than total VAT, whereas the slice 10 cm above L4-L5 had equal or higher correlations (with triglycerides and high-density lipoprotein cholesterol) than total VAT. In women, compared with total VAT, L4-L5 VAT had lower correlations with fasting glucose and high-density lipoprotein cholesterol and equal correlations with fasting insulin, triglycerides, and systolic and diastolic blood pressures. The slices 5 cm above and 5 cm below L4-L5 had similar correlations with metabolic risk factors as total VAT. This study showed that the highest correlations between VAT area and metabolic risk factors were 5 cm above or below L4-L5 in women and 10 cm above in men. These slice locations are the same locations that were most representative of total-body VAT.[204] These data in women are similar to those of Liu et al[205] showing that VAT at the lower costal margin was best correlated with Framingham risk score, whereas in men, VAT at the level of the umbilicus, somewhat equivalent to L4-L5, was most correlated with Framingham risk score.

In clinical settings, however, because of the limitations of imaging methods for assessing body composition, such as cost, availability, time of image acquisition for whole-body scans, and technical skill requirements for image analysis, anthropometric measurements are taken as estimates of adipose tissue distribution. Ludescher et al[207] reported that WC, WHR, and BMI were significantly correlated with total adipose tissue, VAT, and SAT; HC was correlated with SAT and total adipose tissue in men and also with VAT in women. Moreover, when Lee et al[208] assessed which measure (WC, abdominal fat mass by dual-energy X-ray absorptiometry [DEXA], or abdominal fat mass by CT) was most strongly associated with metabolic risk factors in Korean women, they concluded that all methods were of comparable utility. Whether similar results can be obtained in other ethnic groups remains to be determined.

Table 4. Potential Clinical Utility of the Methods for Assessing Body Composition

Method	Clinical Use
Anthropometry	++
Skinfold thickness	+
Ultrasound	+
Near-infrared interactance	+
Hydrostatic weighing	+
Air displacement plethysmography	+
DEXA	+
CT/MRI	—
Bioelectric impedance	+

DEXA indicates dual-energy X-ray absorptiometry; CT/MRI, computed tomography/magnetic resonance imaging; ++, accepted method; +, uncommonly used method; and —, not recommended for clinical use.

Assessing Body Composition

There is a clinical need to measure not only percent body fat but fat distribution, muscle mass, and bone mass as well. Whatever the reason for assessing body composition, healthcare providers and educators, fitness specialists, nutritionists, and other clinicians in health-related fields should have a general understanding of the most commonly used techniques for assessment of body composition. It is also important to understand the interpretation and limitations of body composition analysis techniques when applied to varied populations, such as older patients.

A range of techniques are available (Table 4). Some of those that produce the most accurate data, so-called "gold standard" or reference methods, have disadvantages of cost, limited availability, and the need to travel to research facilities. Simpler techniques are well tolerated and portable and therefore can be used in the clinic, at the patient's bedside, or in the community, although this may be less accurate. Some techniques also allow the assessment of regional as opposed to whole-body composition. Body composition measurement methods are continually being perfected, with the most commonly used methods being bioelectrical impedance analysis, dilution techniques, air displacement plethysmography, DEXA, and MRI or MRS. Collectively, these techniques allow for the measurement of fat, fat-free mass, bone mineral content, total-body water, extracellular water, total adipose

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tissue and its subdepots (visceral, subcutaneous, and intermuscular), skeletal muscle, select organs, and ectopic fat depots. Generally, the laboratory methods are more precise than the "field" methods; however, they are also more expensive, are more time intensive, and require a higher degree of technical training and skill. Numerous factors need to be considered before a method for body composition assessment is selected, including cost, ease of operation, technician training and skill, patient cooperation and comfort, number of participants and time available for assessment, body composition variables to be quantified and the purpose of the assessment, and whether or not the assessment will be conducted on multiple occasions to assess changes in body composition parameters.

Regardless of which instrument is chosen to assess body composition, the method is only as good as the measurement technique and prediction or conversion formula applied. Additionally, to remain valid, the conversion formulas and prediction equations selected for use must be restricted to the population from which they were derived. In clinical practice, bioelectrical impedance analysis and anthropometry are the most readily applicable in routine use, being easily applied in clinic, at the bedside, or in community settings.

Anthropometry

Assessment of muscle mass provides an indication of the body's protein reserves stored in the lean tissue.[209] Measurements of midupper arm and midthigh circumferences (also discussed above) can be used as indicators of muscle mass. Midupper arm circumference is measured midway between the acromion process and the olecranon process while the patient stands with elbows bent and palms facing upward. Sex-specific midupper arm and midthigh circumference reference data are available for adults ≥20 years of age.[210] On the basis of data from cadavers, midupper arm (r=0.896) and midthigh circumferences (r=0.990) are strongly correlated with total muscle mass.[211] In obese women, body weight and HC were significant predictors that explained 62% of the variance in lean tissue volume as measured by MRI.[212] In obese men, thigh circumference, WC, and body weight were significant predictors that explained 89% of the variance in lean tissue volume as measured by MRI. Limb circumference measurements, however, have shown inconsistent associations with CVD risk or outcomes.[213–218] In summary, although limb circumference measurements are considered simple methods for assessment of body composition, the accuracy and reliability of the measurements are contingent in part on the observer's skill, and the clinical importance is unclear.[219,220]

Skinfold Thickness

Because of its relatively low cost and simplicity, the measurement of skinfolds is a popular method of estimating body composition. Brozek and Keys published the first valid skinfold equations in 1951. Since that time, >100 prediction equations using various combinations of anthropometric variables have been reported in the literature.[221,222] The skinfolds technique involves pinching the skin with the thumb and forefinger, pulling it away from the body slightly, and placing the calipers on the fold. Thus, skinfolds measure the thickness of 2 layers of skin and the underlying subcutaneous fat, and sites have been located and measured as described by Jackson and Pollock[221] as follows:

- Chest: a diagonal fold taken on the anterior axillary fold as high as possible.
- Axilla: a vertical fold taken on the midaxillary line at the level of the xiphoid process.
- Triceps: a vertical fold measured on the posterior midline of the upper arm over the triceps muscle halfway between the acromion and the olecranon processes with the elbow extended and relaxed.
- Subscapular: a diagonal fold taken on the line coming from the vertebral border 1 to 2 cm below the inferior angle of the scapula.
- Abdominal: a vertical fold taken ≈2 cm lateral to the umbilicus.
- Suprailium: a diagonal fold taken above the iliac crest along an imaginary line extended from the anterior axillary line.
- Thigh: a vertical fold taken on the anterior aspect of the thigh midway between the hip and the knee joints.

A minimum of 3 skinfolds measurements are taken on the right side of the body at each site in rotational order by an experienced skinfolds technician. If the readings are not within 1 mm of each other, additional measurements should be taken.

Early models used the sum of 7 skinfold measurements (chest, midaxillary, triceps, subscapula, abdomen, suprailium, and thigh).[223] A high correlation (r=0.98) was found between the 7-skinfold model and one that used only 3 skinfolds (chest, abdomen, and thigh). Because of the enhanced feasibility of using only 3 measurements compared with 7, Jackson and Pollock have suggested using the 3-skinfolds model.[221] Using data compiled from 6 laboratories, Lohman[224] reported standard errors from skinfolds measurements to be 2.6 kg for fat-free mass and 3.5% for percent body fat, which were lower than for body weight or BMI. Some of the potential sources of error found in the skinfolds method included variation in subcutaneous in relation to total fat, variation in skinfolds thickness in relation to subcutaneous fat, and technical error in the skinfolds measurement.[222]

During the development of their equations, Jackson and Pollock made several observations.[223] First, the relationship between skinfolds and body density was quadratic. The prediction errors would be larger, especially at the extremes of body fatness, if a linear regression line were used to fit the data. In fact, underestimation of percent body fat with skinfold measurements has been found consistently.[221,225–228] Second, age is independently related to body composition and should be a factor in generalized equations.[221] The skinfolds method precisely measures body density; however, it requires a considerable amount of technical skill and being meticulous with site location and measurement, and it is restricted to the populations from which the prediction equation was derived. Although the skinfolds method is an excellent field method to use in lean participants, it is difficult to obtain reliable and accurate readings on older participants with loose connective tissue or obese individuals with large folds. Finally, because

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of racial differences in body composition, race-specific skinfolds equations should be used.[225,229,230]

Near-Infrared Interactance

Near-infrared interactance (NIR) was originally developed for use in agriculture to assess the composition of grains and seeds.[231] The major constituents of food (fat, protein, and water) could be estimated with diffuse reflectance spectrophotometry by the introduction of 2 wavelength signals, 1 peak and the other at minimum absorption, for each constituent. By decreasing the wavelengths that were used to assess agricultural products, it was found that the composition of human tissues could be measured.[232] The Futrex Corporation (Gaithersburg, MD) developed a wide-slit, commercial NIR analyzer (Futrex 5000) based on this research. It can be used to obtain optimal density (OD) measures at diverse sites, such as subscapular, abdominal, biceps, and thigh.[221] The NIR probe is placed firmly on the site and positioned perpendicular to the measurement site. The NIR light penetrates the tissues to a depth of 4 cm and is reflected back to the detector, which measures the optical density at wavelengths of 940 nm (OD_1) and 950 nm (OD_2). The underlying principle is that ODs are linearly and inversely related to percent body fat, and thus, the smaller the OD, the greater the absorption of NIR light and the higher the fat composition. Researchers have reported good test-retest and day-to-day reliability of the manufacturer's equation to predict percent body fat.

A cross-validation study comparing percent body fat obtained by NIR, skinfolds, and total-body water was conducted on 68 participants of different ages (range 20–61 years) and percent body fat (range 4.5%–40%).[233] The NIR-predicted percent body fat was highly related to the percent body fat obtained by other measures, but the standard errors (mt]2.5% body fat) were fairly large. Although the Futrex 5000 NIR equation has been reported to accurately estimate the average percent body fat of homogeneous samples of nonobese and lean women,[226,234] this equation overestimated percent body fat by >4% in very lean (<8% body fat) subjects but underestimated body fat by >4% in fatter (>30% body fat) subjects.[235] Elia et al[236] also noted that the degree of underestimation of percent body fat increased directly with the level of body fatness. The OD at the biceps site, however, may be a better predictor of total percent body fat than at other sites.[226,235] Race-specific NIR equations may also need to be developed to account for variability in skin color, because differences in skin tone among racial groups may affect OD measurements and possibly the slope and intercept of the relationship between OD and percent body fat.[237] In summary, numerous cross-validation studies have reported large, unacceptable prediction errors for NIR measurements, which suggests that they do little to improve the accuracy of estimating body composition beyond that obtained from other measures.

Hydrostatic Weighing

Hydrodensitometry, often referred to as underwater or hydrostatic weighing, is one of the oldest in vivo methods of analyzing human body composition as a 2-compartment (fat and fat-free mass) model.[238] It held the status of being the "gold standard" for body composition analysis for many years, but this had been challenged increasingly in the past decade as questions have been raised about the underlying assumptions. The specific gravity or "density" of the object can be determined from the weight of the object divided by the loss in weight when submerged in water. Fat-free body mass is assumed to be composed of constant proportions of water (73.2%), minerals (6.8%), and protein (19.5%), with residual amounts (<1%) of other chemical components (eg, glycogen). Human body densities generally vary between 1.08 g/cm^3 (very lean) and 1.03 g/cm^3 (moderately obese). Obese individuals will have body densities <1.03 g/cm^3, and severely obese people may have densities <1.00 g/cm^3. Thus, individual deviations from this value are mainly because of the amount of fat in the body. Because fat is less dense than water, the lower the body density, the greater the amount of body fat. Behnke and Wilmore[239,240] were the first to show that this method could be used to deduce the percentage of weight that is fat from body density using a simple 2-compartment model that assumes specific density for fat and fat-free fractions of body weight. The most commonly used 2-compartment model for estimating body composition from body density measured by underwater weighing was derived originally by Siri.[241] A revised model proposed by Brozek et al[242] gives slightly lower estimates in obese subjects because of somewhat different underlying assumptions about the densities of fat (0.8888 g/cm^3) and fat-free (1.1033 g/cm^3) components. Additional revised models have been proposed that adjust the coefficients in 2-compartment equations for systematic differences in the composition of fat-free mass associated with age, sex, ethnicity and race, and level of fatness.[243–245] None of these equations, however, consider human individuality or variability in the composition of fat-free mass that may occur independent of age, sex, ethnicity and race, or obesity.

There are a number of other limitations of underwater weighing. Because the composition of fat-free mass may change with weight loss, 2-compartment models based on body density alone may provide inaccurate estimates of the amount of fat lost.[246] Accurate measurements require active participation and effort by the subject being measured. In the conventional approach, subjects must submerge their body completely while exhaling maximally, and then hold their breath and body position for several seconds until a weight measurement is obtained. Some individuals cannot perform this task adequately, especially young children, frail elderly, or those with serious cardiovascular or pulmonary disease. In those who can perform the procedure, errors may occur because of body movement and the buoyant effects of air in the gastrointestinal tract and lungs. It is not feasible to measure the amount of air and gas in the stomach and intestinal tract, and a fixed value is usually assumed (≈100 mL). Adjustment is made for the larger air volume in the lungs by measuring residual lung volume when the subject is out of the water using a spirometer with helium dilution or nitrogen washout or during weighing with systems designed for this purpose. The simultaneous measurement of residual lung volume and underwater weight may be preferred because it controls for the effects of the increased pressure of water on the thorax during immersion.

Although feasible, underwater weighing of obese subjects may present special problems. Obesity is often associated with respiratory problems and reduced lung function, which may make it more difficult to obtain accurate measurements of residual lung volume. Because obese subjects have a strong

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tendency to float, it is necessary to use a weight belt or other tare weight system to completely submerge the body. The tare weights must be measured and recorded carefully to obtain an accurate underwater weight. Despite the various limitations reviewed above, high levels of precision can be achieved with underwater weighing. Moreover, underwater weighing may be the only practical method of measuring body fat in very obese subjects who cannot be evaluated by other methods. The minimum possible error from all sources (technical and biological) for percent body fat by underwater weighing has been estimated to be approximately ±1.5%.[224] If subjects are comfortable with water submersion, the hydrodensitometry method is very safe. Underwater weighing systems range in price and at the low end can be built quickly at low cost. Once built, the systems are usually not transportable.

Air Displacement Plethysmography

Air displacement plethysmography has been used to measure body composition for nearly a century. Only recently, however, has a practical, commercially available system (BodPod; Life Measurement Inc, Concord, CA) been developed that does not require stringent measures to maintain ambient conditions as a subject's body composition is assessed. The BodPod method is faster and easier to perform, is not associated with radiation exposure, and is much more comfortable for patients than other methods of assessing adiposity.[248] Air displacement plethysmography relies on the indirect measurement of the volume of an object from the volume of air it displaces. Body volume is calculated by subtracting the volume of air in a closed chamber with a subject inside it from the volume of air in an empty chamber. Measurement of actual volume depends on Boyle's Law, through which pressure and volume are inversely related at constant temperature. Adjustments to volume calculations are made to account for air in the lungs and isothermal air near skin or hair. Once the system calculates body volume, body density and body fat percentage are calculated by use of a subject's weight and a 2-compartment model. More than 30 papers have been published describing the reliability and validity of BodPod measurements. In general, the BodPod has been shown to be as reliable as hydrostatic weighing or DEXA in adults,[249] and its reliability is comparable in adults and children.[250,251] A disadvantage of this method is that it only gives a whole-body assessment of body composition and thus does not give information on fat distribution. Although this method has potential for clinical use in the future, more data on its ability to help risk stratify individuals are needed.

Dual-Energy X-Ray Absorptiometry

DEXA has been used extensively to study bone demineralization and osteoporosis and represents a significant advance in body fat assessment because of its ease of use in clinical settings and greater accuracy and precision for the differentiation of lean and fat tissues than earlier methods such as whole-body hydrodensitometry. DEXA defines a technology by which the attenuation of radiation at 2 energies is used to determine 2 components of the attenuating tissue, either bone and soft tissue or lean soft tissue and fat. Many now consider DEXA as one of the "gold standards" for body fat assessment. Validation studies have shown that body fat assessment by DEXA generally compares well with the 4-compartment model in which body fat is estimated from measurements of body density (hydrodensitometry), total-body water (usually by deuterium dilution), and DEXA bone mineral values.[252] However, studies suggest that DEXA may underestimate body fat at low body fat percentage and overestimate body fat at higher body fat percentage in both adults and children.[253,254]

More recently, DEXA has been used to assess regional body fat distribution. Abdominal fat is usually measured between the L1 and L4 vertebral bodies on the DEXA scan image.[255] Studies have shown that abdominal fat mass measured by DEXA and CT is highly correlated, although DEXA systematically underestimates the CT-derived abdominal fat mass.[256] However, DEXA cannot differentiate subcutaneous from visceral fat adiposity.

Assessment of body fat by DEXA requires very little radiation (1 μSv), which makes it appropriate for repeated measures in a clinical setting.[255] DEXA is also very quick and is easily applied for both healthy individuals and patients. Assessment of body fat by DEXA obviously requires specialized equipment that is moderately expensive but not too large to be easily accommodated within a small obesity clinic. Intermanufacturer and intramanufacturer differences have been raised as areas of concern, although these differences are of particular importance only in longitudinal and multicenter research settings.[252,255] DEXA is an attractive tool for measurement of body composition and potentially fat distribution but is reserved for research purposes at the current time until more data on risk prediction and cost-effectiveness are available.

CT and MRI

The use of CT and MRI has revolutionized not only the study of fat distribution as discussed in detail above but also that of body composition. These 2 methods are the only ones that provide reliable information on internal adipose tissue depots. CT and MRI are also considered to be the "gold standard" for calibration of field methods designed to measure adipose tissue and lean body mass.[200]

Bioelectric Impedance

Total body fat can also be assessed by electric techniques that take advantage of the principle that tissues conduct electricity based on their water and dissolved electrolyte content (fat and bone are relatively nonconductive). Bioelectrical impedance analysis (BIA) uses a small, alternating, single-frequency current that passes through electrodes applied to extremities of the body (usually wrists or ankles) to measure impedance between points of contact. An estimate of total body water is acquired, from which total body fat-free mass is calculated on the basis of the assumption that 73% of the body's fat-free mass is water.[257] A multisegmental BIA approach can be used to also provide estimates of fat-free mass distribution and hence body fat distribution based on the assumption that the body is made up of groups of cylinders (arms, legs, total body).[257] Multifrequency BIA (or bioimpedance spectroscopy) differentiates intracellular water from extracellular water compartments, which is particularly helpful in the exploration of variations in levels of hydration.[258] Unlike single-frequency BIA, multifrequency BIA may be used to evaluate leg skeletal muscle.[259]

The equipment required for BIA is generally very easy to use, portable, and much more affordable than other sophisticated

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methods such as DEXA, CT, and MRI.[260] BIA also poses no risk to patients (although it is not recommended for participants with a pacemaker) and provides instant results. However, studies have shown that the validity of body fat assessment by BIA is influenced by sex, age, disease state, race and ethnicity,[261] level of fatness, environment, phase of menstrual cycle, and underlying medical conditions.[262] Studies suggest that BIA measurements validated for specific ethnic and racial groups, populations, and conditions can be used to obtain accurate measures of body fat in those populations, but not others. This emphasizes the importance of using specific calibration equations for optimal use of this technique to assess body fat in clinical practice. The use of BIA to assess adiposity is also limited by the fact that it provides unreliable information on body fat distribution.

Other Important Issues to Consider

Assessing Fat Mass and Distribution in the Elderly

Changes in body composition occur as part of the normal aging process and are associated with important effects on health and function. Thus, it is important to understand the interpretation and limitations of body composition analysis techniques when applied to older patients with abnormal body composition, in whom some of the underlying assumptions of the techniques may not hold true. In particular, changes include loss of the skeletal muscle component of lean tissue (sarcopenia), changes in body fat content and distribution (including increased ectopic fat deposition), and their combination of sarcopenic obesity. Furthermore, changes in body composition with aging, particularly the altered composition of the constituents of fat-free mass, and changes in fat distribution may lead to measurement errors with standard body composition assessment methodologies. A curvilinear relationship between body fat and age was demonstrated in a cross-sectional study of 1324 individuals across the age range of 20 to 94 years.[263] A 10-year longitudinal study in elderly people also showed a decline in subcutaneous fat but an overall increase in total fat mass by densitometry.[264] WC and HC were the best anthropometric predictors of total fat mass change, with change in skinfolds having a far weaker relationship. Potential limitations of body composition techniques in older individuals include changes in composition of fat-free mass with age or altered distribution of fat, which could invalidate the underlying assumptions of the techniques. Also, predictive equations may have been derived in populations of younger ages and may be less valid in elderly individuals. Normal ranges of BIA data for different age groups from the National Health and Nutrition Examination Survey III have been published as reference data.[265] The same point applies to anthropometry, with inaccuracy in the elderly when existing equations are used and development of newer age-specific equations.[266] Techniques used for assessment should therefore be adapted or validated in this age group.

Ethnic and Racial Considerations

Because race may affect the composition of fat-free mass and regional fat distribution, race-specific prediction equations may need to be developed for some racial groups.[267] To date, race-specific skinfolds (American Indian women, black men, and Asian adults) and NIR (American Indian women and white women) equations have been developed.[268] It is readily apparent that the majority of published field method prediction equations have been developed and cross-validated for white populations. Hence, these equations may not be applicable to individuals from other racial groups.[269] Race may affect the composition of fat-free mass,[270–273] as well as the regional fat distribution,[225,229,274] thereby altering the relationship between reference measures and field measures of body composition, such as the sum of skinfolds, resistance index from BIA, and optical densities from NIR. As a result, race-specific equations may need to be developed. Research strongly suggests that multicomponent models need to be used to quantify differences in fat-free mass composition because of race so that accurate skinfolds and NIR prediction equations can be developed. Practitioners should carefully select and use only those prediction equations that have been developed and cross-validated for specific racial groups.

Assessing Ectopic Fat

The presence of increased triglycerides in nonadipose tissues, such as the liver, skeletal muscle, and cardiac muscle, is associated with metabolic and cardiac dysfunction.[275–279] Therefore, the assessment of triglycerides content in these organs has important physiological and clinical implications. Localized proton MRS provides a reliable assessment of intracellular triglyceride content. Moreover, MRS is noninvasive, does not involve ionizing radiation, and can be performed repeatedly without adverse effects in human subjects. The procedure usually takes <30 minutes for each tissue that is evaluated.

The MRS procedure involves the use of a strong magnet and nonionizing radiofrequency waves to acquire quantitative information on intracellular triglyceride content. This approach is based on the principle that the cellular chemical environment influences the oscillation frequency (resonance frequency) of nuclear protons (^{1}H). Therefore, protons present in intracellular water and triglycerides, as well as in intracellular and extracellular triglycerides, can be distinguished by their resonance frequencies. Fourier transformation is used to deconvolute the frequency data and generate spectra that provide information on the chemical nature and amount of the intracellular components. The strength of the external magnetic field influences resonance separation, so increasing the magnetic field can sometimes provide a more reliable assessment of individual water and triglyceride MRS peaks. For example, water and triglycerides are easily separated by use of a 1.5-T magnet, but a stronger magnet might be needed to reliably quantify the areas of both peaks in skeletal muscle.

The threshold for the normal amount of triglycerides in nonadipose tissues has only been established for the liver. An excessive amount of triglycerides in the liver (ie, steatosis) is defined "chemically" as an intrahepatic triglyceride (IHTG) content that exceeds 5% of liver by volume or weight, or "histologically" when 5% of hepatocytes contain visible intracellular triglycerides.[280,281] Recent data from a large population study that evaluated IHTG content by MRS in Hispanic, white, and black subjects support the notion that ≈5% of liver volume as triglycerides should be considered the upper limit of normal.[282] A normal amount of IHTG was estimated to be 5.6% of liver volume, because this value represented the 95th percentile in subjects who were considered to be at low risk for nonalcoholic fatty liver disease (ie, BMI <25 kg/m^2, no T2DM, and

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normal fasting serum glucose and alanine aminotransferase concentrations). Other methods for evaluating IHTG content are not as reliable or safe as MRS. Although IHTG can be determined by histological evaluation of liver tissue obtained by percutaneous biopsy, this procedure is prone to sampling error because of small sample size (≈50 mg of biopsy tissue compared with ≈25 g of tissue evaluated by MRS) and can cause discomfort and medical complications, such as bleeding and bile leakage. Ultrasound, CT, and MRI are noninvasive techniques that can be used to detect liver fat, but they do not provide a reliable quantification assessment of IHTG content.[283,284] The use of serum liver biochemistry panels to diagnose hepatic steatosis is not reliable, because up to 80% of subjects with increased IHTG content (≥5.6% IHTG content) have normal alanine aminotransferase concentrations.[285]

Assessing Changes in Adiposity

Assessing Changes in Total Fat Mass

The majority of longitudinal studies assessing changes in adiposity over time rely on the use of BMI or body weight. Reductions in body weight and BMI have been demonstrated to improve risk factors for CVD, including T2DM and systemic hypertension.[286,287] Findings from the Diabetes Prevention Program demonstrated that for every kilogram of weight loss with a lifestyle intervention, there was a 16% reduction in risk of T2DM.[288] Despite improvements in morbidity, reductions in body weight have not clearly demonstrated improvements in mortality. In fact, in several prospective studies, weight loss is associated with increased all-cause mortality. One concern in using weight loss or BMI change as a measure in predicting outcomes is that these measures do not differentiate between loss of fat mass and lean mass. Although ideally, weight loss should result in loss of fat mass, there is also loss of fat-free mass, and the percentage of weight lost as fat-free mass has been found to be different even among similar weight loss ranges.[289] Cachexia, or rapid weight loss, for example, may cause significant lean mass loss, whereas people engaged in intense exercise programs might gain weight at the expense of increased muscle mass without any increase in fat mass. Decreases in fat mass or lean mass may be better predictors of outcome than weight and BMI. In an analysis of 2 prospective population cohorts, weight loss was associated with increased mortality, whereas loss of fat (measured by skinfold thickness) was associated with decreased mortality.[290] Comparisons of 5 measures of adiposity suggested that although BMI and fat mass are both predictive of mortality, WHR and WC were stronger predictors.[291]

Assessing Changes in Distribution of Body Fat

In recent years, WC and WHR increasingly have become therapeutic goals in dietary interventions or weight loss trials, supported by the strong epidemiological evidence linking measures of body fat distribution with metabolic dysregulation, long-term cardiovascular events, and onset of T2DM; however, the advantages of assessing changes in WC or WHR over time are still controversial. The evidence linking changes in WC or WHR to cardiovascular events or mortality is nearly nonexistent. Several studies have shown an association between changes in WC and changes in lipids, blood pressure, fasting blood glucose, and other cardiometabolic risk factors. Most of the studies, however, have failed to adjust for concurrent changes in BMI, and when they did adjust for changes in BMI, the association between changes in WC and change in cardiometabolic factors disappeared.[292,293] One of the only exceptions is the DESIR study (Data from an Epidemiological Study on the Insulin Resistance Syndrome), in which the adjustment for BMI change did attenuate but did not take away the association between change in WC over 9 years and several cardiometabolic risk factors, including triglycerides, blood pressure, and fasting insulin in women.[294] At the moment, there is inconclusive evidence that changes in WC over time can accurately predict improvements in cardiometabolic risk factors beyond the effect predicted by changes in BMI, particularly among men.

Studies assessing the validity of serial measurements of WC or WHR to assess changes in abdominal visceral fat have shown conflicting results. One small study in women showed an excellent correlation between change in WC and change in abdominal visceral fat as measured by CT,[78] whereas 2 studies, 1 in Asian women and 1 in patients with chronic kidney disease, showed only a mild correlation between change in WC and change in abdominal visceral fat, which suggests that most of the variability in WC was attributable to changes in subcutaneous abdominal fat.[295,296] Changes in WHR appear to have a poor correlation with changes in abdominal visceral fat.[297] This might be due in part to a suboptimal interobserver variability on serial WHR measurements.[298]

Despite the limited evidence linking changes in WC to changes in cardiometabolic risk factors beyond the effect of BMI change, some reports suggest that there may be a role in measuring serial WC to assess the benefit of lifestyle interventions. In one clinical trial, patients assigned to intense exercise did not lose any significant amount of body weight, but their WC was significantly reduced at follow-up, which was associated with a benefit in regard to metabolic comorbidities.[120] In another study involving different doses of exercise, the reduction in WC was independent of changes in body weight in all exercise groups.[299] These results cannot be extrapolated to populations that are not purposely engaged in intensive exercise programs. The assessment of changes in WC in weight loss trials or observational studies may also help to reclassify people according to the presence or absence of central obesity or metabolic syndrome, and for that matter, it may help in the estimation of incidence rates of both conditions.

Assessing Changes in Body Composition

There is limited evidence assessing the value of measuring body composition over time to assess changes in adiposity. A recent report assessed the correlation between change in body weight and change in fat mass in a group of people attending a wellness center. It showed that changes in body weight "generally" reflect changes in body fat content. The study showed that a weight loss of >1 kg will have a specificity of 89% and sensitivity of 75% to detect a fat loss of more than 1 kg, with a positive predictive value of 90% and a negative predictive value of 75%. This study also showed that favorable improvements in body composition may have gone undetected in almost one third of the people whose weight remained unchanged at follow-up.[300] The reliability of assessment of body composition change has been tested in several studies. These studies have shown that air displacement

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plethysmography, DEXA, and BIA are all reliable techniques to assess changes in body composition over time compared with sophisticated methods used as a "gold standard."[301,302]

Several studies, however, have shown that weight change over time is due in part to changes in lean mass and not just to changes in body fat. This may depend on the manner in which the weight was lost. In one cohort of healthy individuals followed up for 8 years, lean mass accounted for 49% of the weight loss among those who lost any weight. Among those who gained weight at follow-up, the change in lean mass accounted for 32% of the weight change.[303] In another cohort of healthy volunteers 20 to 74 years old who were followed up for up to 3 years, almost half of the weight loss was because of loss in lean mass, and about half of the weight gain was attributed to change in lean mass.[304] Those relationships appeared to be independent of physical activity and age group. Data from the Healthy Aging and Body Composition Study showed that among those who lost weight in a 4-year period, 60% and 40% of the weight lost in men and women, respectively, was because of lean mass loss.[305] Among those who gained weight, approximately one fourth of the weight change was explained by an increase in lean mass in both sexes. These and other studies suggest that longitudinal assessment of body composition may be justified. Older individuals have a skeletal muscle mass decline of ≈1% per year, and this phenomenon affects the validity of the use of weight changes to assess changes in adiposity.[306] Longitudinal assessment of body composition also may be useful among those engaged in long-term exercise programs and among competitive athletes, particularly if resistance training is involved. Individuals attempting rapid weight loss, particularly those following ketogenic diets that promote diuresis or those undergoing bariatric surgery, should also consider longitudinal body composition assessment to determine the fat mass lost beyond excessive diuresis or loss in lean mass.

Unfortunately, there are no longitudinal studies assessing the effect of changes in body composition on incidence of clinical events or survival. There are no cohort studies assessing the association between changes in body fat composition and improvement in cardiometabolic parameters such as lipids, fasting blood glucose, insulin resistance, and blood pressure independent of changes in body weight.

Summary

The long-term deleterious consequences of excess adiposity are great and of clinical importance. Although the prevention of overweight and obesity in all individuals would be ideal, this is neither feasible nor realistic at the current time. We must therefore target those individuals at greatest risk (ie, those who already have excess or increasing levels of adiposity or those with disproportionate abdominal fat). The first step in targeting those at greatest risk is to identify those individuals (ie, to assess them for adiposity).

In 2009, the National Committee for Quality Assurance published Healthcare Effectiveness Data and Information Set (HEDIS) standards recommending the measurement and documentation of BMI in all adults.[307] Other groups and guidelines are in agreement,[143,308] and as such, the BMI should be used as a primary tool for assessing individuals for excess adiposity. It must be emphasized, however, that although BMI is generally well correlated with body fatness at a population level, there is significant heterogeneity in individual body fatness and ultimately risk for associated comorbidities at a given BMI. This heterogeneity not only is related to a number of different factors such as age, sex, genetics, and ethnicity or race but is also a result of differences in body fat distribution and composition. This has resulted in discussions of concepts such as "healthy obesity" and "normal-weight obesity." Furthermore, at any BMI or level of body fatness, the proportion of abdominal fat, particularly of VAT, and the amount of liver fat are highly correlated with metabolic disorders. Thus, although assessing for total fat mass with a BMI is a good and realistic start, it is also certainly not clinically sufficient.

It is therefore relevant to consider the use of simple clinical tools to help healthcare professionals find these high-risk individuals with excess visceral and liver fat. Recent data clearly indicate that at any BMI level, an increased WC is predictive of an increased risk of comorbidities and thus provides additional value in the assessment of an individual's level of excess adiposity and risk for associated comorbidities. As a result, measurement of WC has been recommended by the National Institutes of Health/National Heart, Lung, and Blood Institute and the National Cholesterol Education Program Adult Treatment Panel III[143,155] in addition to the BMI. Specifically, for a given BMI, individuals with an elevated WC will likely have more abdominal fat and thus more visceral, liver, and ectopic fat and more risk for obesity-related metabolic disorders, which warrants more aggressive intervention. A WC measurement would be especially valuable if BMI-specific cutoffs were available; unfortunately, such cutoffs have not been established in the literature and thus are desperately needed. Furthermore, proper age-, sex-, and race- or ethnicity-specific cutoff values for WC still need to be determined. Although we have discussed a number of other methods for measuring fat distribution and body composition, each of which has its merits and limitations, there is insufficient evidence or justification to apply these to daily clinical practice at the current time.

In summary, ideally, healthy lifestyle and body weight maintenance should be recommended to all individuals. More aggressive intervention, however, should be considered for those at higher risk; that is, those who already have excess adiposity, especially those with excess abdominal fat. BMI and WC measurements are the primary tools for assessing adiposity, and those individuals with an elevated BMI or with a disproportionally high WC for a given BMI should have other cardiometabolic risk factors evaluated for further risk stratification and should be targeted for a healthier lifestyle and body weight.

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*Modest.

†Significant.

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KEY WORDS: AHA Scientific Statements ■ obesity ■ overweight ■ body weight ■ metabolic syndrome ■ body fat

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