

REVIEWS

What aspects of body fat are particularly hazardous and how do we measure them?

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Introduction

There is a worldwide increase in the prevalence of obesity,¹ which contributes to a higher incidence of cardiovascular disease and type 2 diabetes mellitus.^{2,3} It has been projected that by 2020, type 2 diabetes and cardiovascular disease will account for almost three-fourth of all deaths worldwide.⁴

Since the 1950s it has been recognized that apart from overall obesity the distribution of body fat can influence disease risk.⁵ In particular an abdominal fat distribution is associated with metabolic disturbances and increased risk of cardiovascular disease and type 2 diabetes. In the present paper we will discuss different ways to measure body composition and focus on which aspects of body fatness (e.g. central vs total, subcutaneous vs visceral) are particularly hazardous in terms of morbidity and mortality.

How to measure body fat?

Body fat measurements

Numerous techniques are available to estimate body composition and fat distribution, and the method to use will depend on the aim of the study, economic resources, availability, time, and sample size.^{6–8} Multi-compartment models, such as underwater weighing, dilution techniques and dual-energy X-ray absorptiometry (DXA) are all reliable methods to obtain accurate measures of total body fat. However, because of their costs in terms of time and money, these methods are not practical in large epidemiological studies and for routine clinical use. In these situations, body mass index (BMI) is often used and assumed to represent the degree of body fat. BMI, however, does not distinguish between fat mass and lean (non-fat) mass. For example, well-trained body builders have a very low percentage of body fat, but their BMI may be in the overweight range because of their large lean (muscle) mass. In addition, in the elderly and non-Caucasian populations, the relationship between BMI and body fatness may be different as compared with younger Caucasian populations.^{9–14}

Another potential limitation of the BMI is that the distribution of fat over the body is not captured. Many studies have shown that an abdominal fat distribution, independent of overall obesity, is associated with metabolic disturbances and increased disease risk.^{15–23} An increased abdominal fat accumulation is largely caused by the accumulation of visceral (or intra-abdominal) fat (for distinction of these fat depots, see Figure 1). Owing to metabolic differences between different fat depots, they differ in their role of predicting metabolic disturbances and diseases. Table 1 summarizes the capability of the most commonly used methods to assess total adiposity and fat distribution. Abdominal obesity is usually assessed by the easily measured waist circumference, the waist-to-hip circumference ratio (WHR), or the less-commonly used sagittal abdominal diameter (SAD). By the use of sophisticated imaging techniques, such as magnetic resonance imaging (MRI) and computed tomography (CT), different fat depots can be distinguished at the waist level, and it has been shown that in particular the visceral fat depot is associated with metabolic disease risk.^{24–30} Because the SAD or waist circumference alone are more strongly correlated with visceral fat than the WHR,^{31–35} guidelines tend to focus on waist circumference to estimate disease risk as suggested by Lean *et al.*³⁶ These widely used cut-points (i.e. 102 cm for men and 88 cm for women) were originally based on a replacement of the classification of BMI,³⁶ but other cut-points have also been suggested on the basis of relationships with visceral fat area.³⁷



Figure 1 Cross-section of the abdomen in which subcutaneous and visceral fat can be distinguished. Lighter-coloured areas are muscles, bones, and organs

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Table 1 Capability of different body fat measurements to estimate total body fat and fat distribution

Method	Capability measuring total body fat	Capability measuring fat distribution	Applicability in large population studies
CT	Moderate	Very high	Low
MRI	High	Very high	Low
DXA	Very high	High	Moderate
Densitometry	Very high	Very low	Low
Dilution techniques	High	Very low	Moderate
BIA	Moderate	Very low	High
Anthropometry			
BMI	Moderate	Very low	Very high
WC, HC, WHR, SAD	Low	High	Very high
Skinfolds	Moderate	Moderate	High

CT, computed tomography; MRI, magnetic resonance imaging; DXA, dual-energy X-ray absorptiometry; BIA, bioelectrical impedance analysis; BMI, body mass index; WC, waist circumference; HC, hip circumference; WHR, waist-to-hip ratio; SAD, sagittal abdominal diameter.

These simple cut-points may be helpful for the classification of Caucasian adults, but they are probably less appropriate in other ethnic groups³⁸ or older age groups.³⁹ No large or consistent differences have been found between SAD and waist circumference in relation to visceral fat.^{31,33–35,40,41}

The waist circumference, however, is not always a stronger predictor of type 2 diabetes^{42,43} and other cardiovascular risk^{16,20,44–46} than the WHR. Because a higher WHR can be the result of a larger waist as well as a smaller hip, this suggests that a smaller hip (representing either lower muscle and/or fat mass at the hips) may be involved in determining the increased risk associated with an increased WHR. Hip circumference is more strongly associated with leg fat mass, but also with leg lean mass (particularly in men).⁴⁷ Indeed, WHR has been related to both a larger trunk fat mass, and a smaller leg fat mass (both sexes) and leg lean mass (men).⁴⁷ In another study, WHR has been related to both larger visceral fat and smaller leg muscle areas in men.⁴⁸ Several studies have found that a smaller hip circumference (for a given waist circumference) is associated with an increased risk.^{43,49–56}

Early studies on fat distribution often used skinfold measurements to characterize subcutaneous fat distribution.⁵⁷ Subcutaneous fat patterns were described using Z-score patterns, ratios of skinfolds (e.g. triceps/subscapular skinfold ratio and ratio of the sum of trunk skinfolds to the sum of skinfolds on extremities) and principal components analyses. The most promising and simple indicator of central fat distribution using skinfolds seems to be the subscapular skinfold. A prospective study showed that the subscapular skinfold predicted coronary heart disease in men independently of BMI and other cardiovascular risk factors⁵⁸ but studies that have compared the use of skinfold over and above the use of body circumferences or circumference ratios are rare. A few studies have compared the associations between skinfolds and circumferences in relation to components of the metabolic syndrome^{59,60} and these showed that correlations of waist circumference with risk factors were either similar or stronger compared with those of the subscapular skinfold. Misra *et al.* have proposed that the subscapular skinfold should be considered

as an indicator of central fat distribution separately of the waist circumference.⁶¹ It is, however, difficult to say with certainty that the measurements of skinfolds improve substantially the prediction of disease independently of body circumferences.

Anthropometry in specific groups: older persons

The composition of the body changes with age, and this may have serious implications for the interpretation of anthropometric data of older persons. First, older persons are generally shorter than younger persons owing to secular trends in height and owing to shrinkage of the spine because of vertebral bone loss, kyphosis, and scoliosis.^{62,63} Consequently, the BMI of older persons may be overestimated and it is, therefore, preferable to use a body height measured in early life to calculate the BMI of older persons. Second, with age the amount of lean body mass decreases, a process called sarcopenia.⁶⁴ Sarcopenia occurs even in weight stable persons owing to a concomitant increase in the amount of body fat.^{65,66} The relationship between BMI and percentage of body fatness has been shown to be dependent on age.⁹ Data from the Rosetta Study show that older adults have, on average, more fat than younger adults at any given BMI.⁶⁷ Prediction equations to estimate body composition from BMI will generally underestimate the amount of body fat in the elderly.⁶⁸ Also, a similar skinfold thickness in young and older persons represents a higher percentage of body fatness in older persons.⁶⁸ Age-specific prediction equations should be used to estimate body fatness from skinfold thickness.⁶⁹ A recent study in older men and women (mean age 60.4 years) showed that the change in skinfold thickness over time did not predict change in body fat mass, suggesting its limited use in longitudinal studies.⁷⁰ Finally, the distribution of body fat also changes with age because relatively more fat accumulates in the abdomen and less fat at the extremities.^{71,72} Waist circumference has been suggested as an indicator of overall body fatness in older persons.⁷³ Changes in waist and hip circumference were better anthropometric predictors of change in body fat mass over a 10 year period compared with changes in skinfold thickness.⁷⁰ However, in persons aged 70–79 years the explained variance in total body fat remained higher for BMI than for waist circumference.⁷⁴

The waist circumference has been shown to be similarly correlated with the amount of visceral fat in young and older persons.⁷⁵ In several studies, waist circumference was a better predictor of visceral fat in older persons compared with SAD or WHR.^{32,76} However, in very old men and women (>70 years) SAD was a better predictor of visceral fat compared with the waist circumference.⁷⁴ In that study the BMI performed as good as the waist circumference in predicting visceral fat.⁷⁴ An alternative, non-anthropometric method proposed to estimate the amount of visceral fat in older persons is subregional DXA.⁴⁰ The prediction of visceral fat by DXA was better compared with the waist circumference but was similar to the SAD.

For a given waist circumference, visceral fat has been shown to be higher in older persons compared with younger persons,⁷⁶ suggesting that absolute levels of waist circumference should be interpreted differently in younger and older persons. Prediction equations for visceral fat generally include age.⁷⁷ Whether the proposed waist circumference cut-points are useful for the prediction of cardiovascular disease risk factors in older persons is still unclear.^{78,79}

Anthropometry in specific groups: ethnicity

Several studies have shown a race difference in the association between BMI and percentage of body fat. For a given BMI, Chinese, Malay, Indian, Taiwanese, and Indonesian men and women have a higher percentage of body fat compared with Caucasians.^{10–14} Differences in trunk-to-leg-length ratio, slenderness, and muscularity may contribute to these racial differences in the percentage of body fat–BMI relationship.^{80,81} No clear differences in the relation between percentage of body fat and BMI have been observed for African-Americans vs Caucasians.⁶⁷ Based on these findings and the observed differences in the relation between BMI and disease risk, lower BMI cut-points have been suggested to define overweight and obesity for specific ethnic groups.^{10–12,82–84} However, the expert committee of the WHO has not redefined the cut-points for specific Asian populations, because available data do not necessarily indicate a clear BMI cut-off point for all Asian ethnic groups.⁸⁵

Ethnic differences in the relation between waist circumference and visceral fat have frequently been reported. Asian ethnic groups generally have a smaller waist circumference compared with Caucasians, although this is not necessarily true for Asian emigrants who are generally affluent and have more generalized and abdominal obesity.^{38,86} Despite the smaller waist circumference, the visceral fat mass is higher for Asians compared with Caucasians and African-Americans.^{87,88} Moreover, for specific Asian groups disease risks may already be increased at a lower level of waist circumference, suggesting that a lowering of the waist circumference cut-points should be considered for these ethnic groups.^{38,82,83} For a similar waist circumference (or WHR) and BMI, African-Americans have a lower visceral fat mass compared with Caucasians.^{89–91} Although a larger amount of visceral fat is associated with a higher disease risk in both African-Americans and Caucasians, similar amounts of visceral fat are associated with different levels of metabolic risk factors in these groups.⁹² The cause of the more diabetogenic profile in African-Americans as compared with Caucasians is currently unknown.⁹³

Epidemiology of body fat measures and associated disease risk

Time trends and prevalence of abdominal obesity

Secular changes in the prevalence of overweight and obesity as measured by BMI have been reported in many countries over the last decades.¹ Several studies have reported on secular changes in waist circumference and WHR. In German adults and in British adolescents, stronger increases over time in the average waist circumference than in relative weight were observed.^{94,95} A more rapid secular increase in WHR than in BMI was shown in Swedish women.⁹⁶ Lahti-Koski *et al.*⁹⁷ observed a similar secular change but did not compare this to the time trend in BMI. A more recent study from Sweden observed a significant increase in BMI but not in WHR in the period from 1985 to 2002.⁹⁸ A Dutch study showed similar secular changes in waist circumference as compared with BMI over a short period of time.⁹⁹ Large increases in the waist circumference were shown in the US adult population from 1960 to 2000 in all categories of BMI.¹⁰⁰ It has been suggested that the waist circumference is

more sensitive to changes in energy balance (e.g. decreased physical activity) than the BMI.⁹⁹ With decreasing physical activity muscle may be gradually replaced by fat mass and this may have less effect on overall body weight than on the waist circumference.

The prevalence of abdominal obesity according to these cut-points has been reported for several countries. In the US the age-adjusted prevalence of abdominal adiposity has tripled in men from ~13% in 1960–62 to 38% in 1999–2000. In women the prevalence increased from ~19 to 60% over the same period.¹⁰⁰ In The Netherlands the prevalence of abdominal obesity was ~15% in men and 21% in women in 1993–97.⁹⁹ These prevalences were similar to those of the US some 30 years earlier.

Body fat measures in relation to cardiovascular disease and type 2 diabetes

The worldwide increase in the prevalence of (abdominal) obesity is alarming because of the associated disease risk, in particular type 2 diabetes and cardiovascular diseases. Several studies were conducted to compare the contribution of measures of overall obesity (BMI) and abdominal obesity (waist circumference, WHR, SAD) with disease risk. Overall, it can be concluded that persons with a BMI in the normal weight range can still be at increased risk of metabolic disturbances if the WHR or waist circumference is increased, and that the combination of a high BMI and a high WHR results in a particularly high risk of an unfavourable metabolic profile, type 2 diabetes, and cardiovascular diseases.^{15–23}

In the elderly, few studies have directly compared BMI and waist circumference as predictors of metabolic abnormalities. The limited available data suggest that waist circumference and/or SAD are better indicators of cardiovascular risk factors in older men and women compared with BMI.^{21,101} However, in other studies waist circumference contributed little to the prediction of disease risk after BMI had been taken into account.^{102,103}

Regarding the comparison of waist circumference and WHR as predictors of metabolic disturbances and the risk of cardiovascular diseases, results have been inconsistent. Some studies have found waist circumference a stronger correlate of metabolic risk factors and cardiovascular disease than the WHR,^{31,104,105} whereas others found no difference,^{106–108} or found that the WHR was superior.^{16,20,42–46} The last observation resulted in several studies that investigated the separate contributions of waist and hip circumferences to disease risk. These studies consistently show that a smaller hip circumference, for a given waist circumference, is related to an increased risk for metabolic disturbances,^{49–51,53} type 2 diabetes,^{43,50,52,54} and cardiovascular disease and mortality.^{52,55,56} These results suggest that the measurement of hip circumference can contribute to the prediction of cardiovascular disease risk.

If waist circumference or WHR were compared with the SAD in the prediction of metabolic disturbances and disease risk, some studies found SAD a stronger correlate than waist circumference, WHR, and BMI.^{109–111} However, waist and SAD correlated similarly (but stronger than WHR) with metabolic variables in another study.³¹ In others, none of these three measures was superior in their association with metabolic disturbances or cardiovascular disease risk.¹⁰⁶

Considering more sophisticated body composition measurements, numerous studies have shown a consistent and strong association of CT-measured visceral fat area in relation to metabolic or disease risk.^{24–30} Results from the literature are not consistent on whether abdominal subcutaneous fat area contributes to an unfavourable metabolic profile and cardiovascular disease, independently of visceral fat area.¹¹² In the Health, Aging and body composition Study, a larger amount of abdominal subcutaneous fat was substantially and independently associated with higher glucose and lipid levels, although associations were stronger for visceral fat.³⁰ This independent association of subcutaneous abdominal fat with metabolic risk factors agrees with findings in earlier smaller studies.^{113,114}

Studies using DXA or CT to estimate fat and muscle content at the legs found that in particular more subcutaneous fat at the legs, and to a lesser extent muscle mass at the legs, was associated with a more favourable cardiovascular risk profile (for a given amount of abdominal fat).^{30,47,115,116} Thus, the association of a smaller hip circumference (for a given waist circumference) with increased disease risk can mostly be explained by larger peripheral fat mass.

Body fat distribution and premature mortality

Results for measures of body fatness and risk of premature mortality are more difficult to interpret than results for disease risk. First, causes of mortality can vary substantially for different populations and the effects of body fatness on these underlying causes will be different. Second, the induction time for effects of body fatness on mortality is likely to be longer than for effects on the development of diseases.¹¹⁷ Third, associations between anthropometry and mortality seem particularly prone to bias owing to ‘reverse causation’: (subclinical) diseases that are related to increased mortality can result in weight loss.^{117,118} Fourth, most studies of adiposity and mortality have used BMI as a measure of body fatness. Because BMI can reflect both fat and lean body mass, variation in lean body mass that may be associated with mortality can complicate the interpretation of results for BMI. Indeed, the U-shaped association between BMI and mortality that has been observed in some studies may reflect the opposite monotonous relations of lean mass (beneficial) and fat mass (detrimental) with risk of premature mortality.^{119,120} Overall, study findings have indicated that obesity (i.e. BMI ≥ 30 kg/m²) increases the risk of premature death.^{118,121} However, results for lower levels of BMI in relation to mortality have been less consistent, and methodological limitations of studies have undoubtedly contributed to variation in results.¹¹⁸

Studies of body fat distribution and premature mortality have been limited to studies of anthropometric measures of body fat distribution. In several studies, larger waist circumference,¹²² larger WHR,^{16,44,123} larger iliac-to-thigh circumference,¹²⁴ larger SAD,¹²⁵ and smaller hip circumference^{52,55,126} were substantially associated with risk of premature mortality after adjustment for BMI. Because BMI may also reflect variation in lean body mass, one could argue that these independent associations are owing to incomplete adjustment for overall body fatness. However, measures of central fat distribution also remained associated with premature mortality after adjustment for overall body fatness assessed by skinfold thickness^{44,127} or

bioelectrical impedance.^{128,129} These results are consistent with results for morbidity that suggest that given a certain degree of body fatness, it is preferable to have fat stored in the femoral-gluteal region instead of the abdominal region. It should be noted that studies of body fat distribution and mortality have mostly been conducted in white populations. Large waist circumference was a stronger predictor of premature mortality than BMI in black men,¹³⁰ but neither measure was clearly associated with mortality in black women¹³¹ possibly owing to the limited size of the study.

Pathophysiology

The role of free fatty acids

Although the concept that obesity, in particular abdominal obesity, is an important cause of metabolic disturbances is generally accepted, the exact pathophysiological mechanisms are not completely known. It is widely acknowledged that fatty acids play an important role in the development of type 2 diabetes.^{132–134} When free fatty acid levels in the circulation are high (as in abdominal obesity¹³⁵), glucose uptake and oxidation by muscle and other organs is inhibited through several mechanisms. The pancreas will compensate the diminished glucose uptake by increasing insulin secretion, but in many of the insulin resistant persons, the beta-cell eventually fails. In addition, free fatty acids will accumulate in organs (so-called ‘lipotoxicity’ or ‘ectopic fat storage’), particularly in the muscle and in the liver, but also in the pancreas. Accumulation of fat in non-adipose tissue may further promote insulin resistance and impair beta-cell function, which are the two key features in the development of type 2 diabetes.^{133,136}

Metabolic effects of different fat stores

Visceral fat is more sensitive to lipolytic stimuli, and less sensitive to anti-lipolytic stimuli (such as insulin), compared with subcutaneous fat. Therefore, visceral fat is more likely to release free fatty acids into the circulation causing increased free fatty acid levels, which may lead to ectopic fat storage in muscle, liver, and pancreas.^{133,137–139} It has been argued, however, that the quantitative contribution to circulating free fatty acid levels of subcutaneous fat is probably much larger because there simply is much more of it.^{112,140} However, the release of free fatty acids from visceral fat into the portal vein that directly leads to the liver, may cause reduced hepatic insulin clearance, increased gluconeogenesis and increased dyslipidaemia.^{141,142} Removal of visceral fat reversed hepatic insulin resistance and prevented age-induced insulin resistance and glucose intolerance in rats,^{143,144} whereas removal of equivalent amounts of subcutaneous fat had little effect.¹⁴⁴ And a pilot study in humans suggests that omentectomy (removal of part of visceral fat) might improve the metabolic profile.¹⁴⁵

From epidemiological studies (see above) it is unclear whether a larger abdominal subcutaneous fat mass also contributes to an increased disease risk, independently of visceral fat. In a study in six obese women, surgical removal of abdominal subcutaneous fat (55–65% of subcutaneous abdominal fat corresponding to 4.3 ± 1.1 litres) by liposuction, led to improvement of insulin sensitivity and glucose levels after 3–4 weeks.¹⁴⁶ Long-term consequences of subcutaneous liposuction are

inconsistent, however.^{147–149} Abdominal subcutaneous fat can be further divided into deep and superficial subcutaneous adipose tissue. It was demonstrated that the amount of deep subcutaneous adipose tissue had a much stronger association with insulin resistance than superficial subcutaneous fat, which may be due to differences in lipolysis.^{150,151} This difference between different types of subcutaneous fat may have contributed to the inconsistent results regarding removal of total abdominal subcutaneous fat and changes in insulin resistance.

As also described in a previous section, recent studies suggest that more peripheral subcutaneous fat in the legs, for a given amount of abdominal fat, may be associated with a more favourable cardiovascular risk profile.^{47,115,116} It has been suggested that the femoral-gluteal fat depot plays a protective role by acting as a 'sink' for circulating FFA.¹⁵² Adipocytes in the femoral region are relatively insensitive to lipolytic stimuli and have a high sensitivity for anti-lipolytic stimuli. The enzyme lipoprotein lipase (LPL) plays an important role in the uptake of free fatty acids from the circulation, and particularly in women, the femoral fat depot has a relatively high LPL activity and relatively low rate of basal and stimulated lipolysis.^{153,154} Therefore, the femoral-gluteal region is more likely to effectively take up FFA from the circulation and is less likely to release them readily. As a result of FFA uptake in the femoral-gluteal region, detrimental ectopic fat storage in the liver, skeletal muscle, and pancreas, may be prevented.¹³⁶

In line with this potential mechanism, transplantation of subcutaneous adipose tissue in lipoatrophic animals reversed elevated glucose levels¹⁵⁵ and subcutaneous lipectomy caused metabolic disturbances in hamsters.¹⁵⁶ In humans, the critical role of subcutaneous adipose tissue is illustrated by the observation that adipose tissue deficiency (lipodystrophy or lipoatrophy) is accompanied by ectopic fat storage, insulin resistance, and type 2 diabetes.¹³⁶ No studies have been conducted that compared the effects of liposuction in the femoral-gluteal region with liposuction in the abdominal region. The medical drug thiazolidinediones increases insulin sensitivity in insulin resistant patients, while a considerable amount of total body fat is accumulated. These drugs promote preadipocyte differentiation into mature adipocytes, in particular in the gluteal regions.¹⁵⁷ These new mature adipocytes have a better capacity to store lipids, which may result in reduced ectopic fat deposition, and consequently in improved insulin resistance and beta-cell function.

Alternative or additional explanations for the associations of fat depots and disease risk

Adipose tissue secretes many signalling proteins and cytokines with broad biological activity and critical functions. Some of these adipokines may be involved in the development of insulin resistance in obesity.¹⁵⁸ The secretory functions of adipose tissue is probably also subject to regional variations.¹⁵⁹ Therefore, the different associations of abdominal and femoral-gluteal subcutaneous fat depots with metabolic risk factors may be due to differences in the secretion of adipokines between the fat depots. There are known differences in endocrine secretion of leptin, adiponectin, and IL-6 between abdominal subcutaneous fat and visceral fat,^{160–162} whereas the existence of regional

differences in the secretion of plasminogen activator inhibitor-1 (PAI-1) and TNF-alpha is controversial.¹⁵⁹ Little is known about possible differences in the secretion of these adipokines between abdominal and femoral-gluteal subcutaneous fat. In addition, there are probably many more yet undiscovered proteins, differently secreted by different fat depots, which might influence metabolic function. Clearly, more research in this area is needed.

There are several factors that may influence body fat patterning as well as the development of metabolic disturbances and may, therefore, underlie or confound the associations between these phenomena. These factors include behavioural factors (smoking, physical activity, diet), hormonal factors (disturbances in glucocorticoid metabolism, sex hormones, growth hormone), and demographic factors such as age and gender.^{163,164} Recently, it has been shown that fat depots are also innervated by the parasympathetic nervous system, in addition to the earlier finding of a sympathetic innervation, and that stimulation of the parasympathetic nervous system promotes lipid accumulation (anabolic function).¹⁶⁵ Kreier *et al.*¹⁶⁶ have proposed an unbalanced and disturbed autonomic nervous system function as a major cause of changed body fat storage and the metabolic syndrome.

Conclusions

In conclusion, it is supported by mechanistic studies, studies of metabolic risk factors, and studies of cardiovascular disease and premature mortality, that body fat distribution is relevant for the risk of cardiovascular disease and mortality. Time trend studies have shown that there is a consistent increase over time in the prevalence of obesity and, particularly, abdominal obesity, which is likely to contribute to a higher incidence of type 2 diabetes, cardiovascular disease, and mortality.

Several methods are available to measure body fatness, and the choice largely depends on the purpose. For clinical applications it should be considered that usually no information on body fatness is collected at all and the health problems of being overweight are often not discussed by clinicians with their patients.¹⁶⁷ The systematic, repeated collection of a measure of body fatness in clinical practice may already be an important step forward and the simplicity of the measurement is an important consideration. For this purpose, BMI can be an adequate measure of body fatness in adults. However, waist circumference may be a simple alternative that also captures information on abdominal fat distribution and may be less affected by variation in lean mass. The WHR is more difficult to interpret because it may reflect an effect of larger waist as well as a smaller hip circumference. The SAD can be used instead of waist circumference but has not consistently been shown to be superior for the prediction of disease risk.

For large epidemiological studies the BMI can capture most of the relevant variation in body fatness depending on the age of the study population. However, many studies have shown that the collection of information on body fat distribution (waist circumference, WHR, SAD, DXA) can provide additional insights. For mechanistic studies and intervention studies with exposures that may affect body fat distribution, accurate methodology to assess fat depots (CT, MRI, DXA) is necessary.

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