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How to best assess abdominal obesity

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Abstract

Purpose of review—Abdominal obesity, especially the increase of visceral adipose tissue (VAT), is closely associated with increased mortality related to cardiovascular disease, diabetes, and fatty liver disease. This review provides an overview of the recent advances for abdominal obesity measurement.

Recent findings—Compared to simple waist circumference, emerging three-dimensional (3D) body-scanning techniques also measure abdominal volume and shape. Abdominal dimension measures have been implemented in bioelectrical impedance analysis to improve accuracy when estimating VAT. Geometrical models have been applied in ultrasound to convert depth measurement into VAT area. Only computed tomography (CT) and MRI can provide direct measures of VAT. Recent advances in imaging allow for evaluating functional aspects of abdominal fat such as brown adipose tissue and fatty acid composition.

Summary—Waist circumference is a simple, inexpensive method to measure abdominal obesity. CT and MRI are reference methods for measuring VAT. Further studies are needed to establish the accuracy for dual-energy X-ray absorptiometry in estimating longitudinal changes of VAT. Further studies are needed to establish whether bioelectrical impedance analysis, ultrasound, or 3D body scanning is consistently superior to waist circumference in estimating VAT in different populations.

Keywords

computed tomography; MRI; three-dimensional body scanning; visceral adipose tissue

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INTRODUCTION

Obesity has grown into a global health issue [1]. Obesity, especially abdominal obesity, is associated with metabolic syndrome and cardiovascular disease and also an independent risk factor of all-cause mortality [2–4]. In the third National Health and Nutrition Examination Survey study, normal-weight central obesity, as defined by high waist-to-hip ratio, was associated with higher cardiovascular mortality than BMI-defined obesity [4]. In the Dallas Heart Study of 1200 obese participants undergoing MRI, amount of visceral adipose tissue (VAT) was associated with a more severe metabolic, dyslipidemic, and atherogenic obesity phenotype compared to amount of subcutaneous adipose tissue [5]. Quantitative analysis of abdominal fat distribution, specifically VAT, is integral to understanding obesity-related comorbidities and treatment of obesity. This review provides an overview of the most popular methods to measure abdominal obesity and describes the advantages and limitations of each method.

ANTHROPOMETRY

Anthropometry has been widely used in large-scale epidemiology studies and clinical settings because of its low cost, favorable safety profile, ease of use, and applicability to all body sizes. Anthropometric measures of abdominal obesity include waist circumference, waist-to-hip ratio, and waist-to-height ratio. In a study of 168 159 participants from countries, waist circumference showed higher odds ratio with cardiovascular disease and type 2 diabetes than BMI in participants from most regions of the world [6]. Waist circumference trended for a higher correlation with MRI measured VAT than BMI ($n = 1192$; $r = 0.80$ vs. r ¼ 0.75) [7].

Waist circumference is an index of central obesity recommended by the National Institutes of Health, WHO, the American Heart Association, and the International Diabetes Foundation for screening for risk of metabolic and cardiovascular disease. However, there are limitations to this assessment mode. Cutoff points of waist circumference vary with sex and ethnic groups. There is no consensus on the best anatomic location to measure waist circumference; WHO recommends the midpoint between the last palpable rib and the iliac crest and the National Institutes of Health recommends the level of the umbilicus.

THREE-DIMENSIONAL BODY SCANNING TECHNOLOGY

Three-dimensional (3D) body scanning is a fast-growing technology that projects laser and other forms of light on the body surface and captures the reflected contour of the body with camera systems [8]. These systems can rapidly acquire hundreds of linear, circumferential, and volumetric body dimensions. Low-cost devices even for home use are now being introduced. The accuracy of laser-based 3D body scanning is higher than optical camera based, whereas the latter is much less expensive. Previous adult studies reported that the correlation between tape measured and 3D laser scanner measured waist circumference is higher than 0.99, with excellent intraobserver agreement. In a study of 473 children and adolescents, the concordance correlation coefficients were higher than 0.9 between 3D laser scanner and waist circumference and hip circumference, with intraobserver concordance correlation coefficients higher than 0.9 [9]. Soileau *et al.* [8] found a (mean ± standard deviation) 2.1 ± 1.8% difference between the waist circumference measured by structured light vs. laser light 3D scanning. 3D scanners that utilized a higher number of cameras produced more consistent waist circumference measurements (i.e., 16 stationary cameras vs. one oscillating camera or stationary camera) [10]. The authors suggested that the limitations including low resolution of the optical-based systems were mostly correctable when building next-generation devices. Popular media have reported smart phone apps that can perform 3D scans of objects; however, there are no peer-reviewed publications describing the efficacy of these consumer-based products. Using 3D scan apps may be a future direction for abdominal obesity evaluation when technology improvements make accurate quantification feasible.

3D body scanning can be used to derive new central obesity indices such as abdominal volume and body shape. Future studies are needed to compare abdominal volume and body shape measures with waist circumference in predicting VAT and obesity-related health risks.

BIOELECTRICAL IMPEDANCE ANALYSIS

Dual abdominal bioelectrical impedance analysis was developed for quantification of VAT by combining information on impedance and abdominal shape, which can be measured by built-in calipers to assess abdominal dimensions in the sagittal and coronal planes or by built-in laser to measure waist circumference. Impedance is measured by electrodes placed on the abdominal wall. Bioelectrical impedance analysis estimates were more highly correlated with total abdominal fat than VAT ($r = 0.92–0.94$ vs. 0.64–0.65) [11]. Dual abdominal bioelectrical impedance analysis estimates showed a higher correlation with computed tomography (CT)-measured VAT than whole-body bioelectrical impedance analysis estimates ($r = 0.89$, $r = 0.64$, respectively, $P < 0.001$). Some studies showed that bioelectrical impedance analysis better or equivalently estimates VAT amount compared to tape-measured waist circumference [12,13], but other studies found the opposite [11,14]. Dual abdominal bioelectrical impedance analysis seems to underestimate or has a large margin of error for VAT when VAT is high [12,14]. Large-population, multiethnic studies are needed to demonstrate whether abdominal bioelectrical impedance analysis is consistently superior to waist circumference to estimate VAT across populations.

ULTRASOUND

Ultrasound can be used to measure tissue thickness in various planes to develop novel geometric models that estimate abdominal VAT calculated from measured depths at various points around the abdominal circumference [15■]. The correlation coefficient between abdominal VAT measured by ultrasound compared with CT-measured VAT was 0.766–0.781, $P < 0.001$, with intrarater and inter-rater reliability of ultrasound-assessed abdominal fat thickness greater than 0.98 [15■]. There are no consistent findings on whether ultrasound estimates VAT more accurately than waist circumference [16,17]. Currently, B-mode ultrasound is more commonly used than A-mode ultrasound in obesity studies [18]. In a study of six cadavers comparing dissected tissue thickness with ultra-sound-detected thickness using A-mode and B-mode, the mean difference in subcutaneous adipose tissue thickness between A-mode and B-mode was less than 0.7 mm at the abdomen, thigh, and triceps sites [18]. No validation studies have been published examining VAT detection by A-mode ultrasound compared to CT or MRI. In summary, ultrasound can reliably estimate abdominal fat thickness, whereas the validity and reliability of ultrasound for measurement of adipose tissue areas needs further study.

DUAL-ENERGY X-RAY ABSORPTIOMETRY

Dual-energy X-ray absorptiometry (DXA) projects two beams of different energy X-rays that are collected by detectors after attenuation by the body tissues through which they have passed. The low dose of X-ray is considered safe for children and adults but most institutions prohibit its use in pregnant women.

DXA does not directly discriminate visceral from subcutaneous fat as it is a two-dimensional imaging technique, but DXA-estimated VAT volume was strongly correlated with MRI-measured VAT volume ($r = 0.902$, $P < 0.0001$) and CT-measured VAT area ($r = 0.83$, $P < 0.0001$) [19]. The Dallas Heart Study showed DXA-measured and MRI-measured VAT area correlate well, with R^2 ranging from 0.82 to 0.86 ($n = 2689$). The inter-reader correlation was excellent (interclass correlation coefficient 0.997); however, DXA tended to underestimate VAT mass at low VAT levels and overestimate it at high VAT levels [20]. A cross-sectional study of 4950 participants showed that DXA-determined VAT mass has stronger odds ratios for type 2 diabetes and cardiovascular disease than waist circumference (i.e., 1.69–3.64 vs. 1.07–1.83) [21■].

In summary, with the high correlation between DXA and MRI to measure VAT, it is reasonable to believe that DXA is superior to waist circumference in measuring VAT in cross-sectional studies. Future studies, ideally validated by MRI or CT, are needed to establish whether DXA effectively detects longitudinal changes of VAT.

COMPUTED TOMOGRAPHY AND MAGNETIC RESONANCE IMAGING

CT and MRI directly measure VAT areas or volumes and are considered reference methods for evaluating abdominal adiposity. Compared to MRI, CT is less likely to be influenced by breathing artifact. The ionizing radiation from CT limits its use in children and in longitudinal studies. Most MRI systems have 60 cm bores, which may not accommodate individuals with severe obesity, although individuals with up to an approximate BMI of 47 have been scanned with 60 cm bore size scanners [22,23]. Larger 70 cm bore MRI facilities are becoming increasingly accessible and can accommodate patients of almost all sizes. Comprehensive discussions of the use of MRI for fat compartment measurement can be found in earlier reviews [24,25].

Single-slice images are often used to measure abdominal adiposity for its simplicity and to reduce radiation exposure in CT. Although single-slice imaging is a good compromise between accuracy and cost in cross-sectional studies, it may not be as accurate as total volume imaging to detect longitudinal changes in abdominal adiposity. Earlier studies used the L4–L5 intervertebral disk to localize single-slice imaging, but investigators increasingly use L2–L3 or L3–L4 disks because these sites have been found to better estimate total VAT volume. Using quantitative CT, Cheng *et al.* [26] confirmed that the L2–L3 location best estimates total VAT volume ($r = 0.98$, $P < 0.001$) in a healthy Chinese population, which is consistent with previous findings in western populations. Future studies of more diverse populations are needed to verify the power and generalizability of a single slice image to predict the risk for obesity-associated morbidity and mortality. Figure 1 shows that a single slice may be misleading in estimating VAT changes when breath hold is not consistent between baseline and follow up. Therefore, single slice imaging should be used cautiously in interpreting VAT changes for individual patients.

Brown adipose tissue (BAT), as a metabolically active tissue, is closely related to energy regulation and obesity in humans. PET-CT, MRI, and dual energy CT can distinguish BAT from white adipose tissue [27]. A recent study of PET-CT reported that obese men with cold exposure had less activated BAT overall and less abdominal activated BAT than lean men with cold exposure (obese vs. lean, 4.9 ± 7.6 vs. 45.5 ± 43.3 ml, $P = 0.02$) [28■■]. Activated BAT was not detected in abdominal subcutaneous adipose tissue nor omental or mesenteric VAT. BAT-activation images included in the article show that activated BAT was found predominantly in the peri-renal and para-renal fat. Further investigation could explore whether abdominal BAT has different metabolic characteristics compared to BAT in other body regions. MRI fat fraction changes in the neck under thermal challenges correlated with hypermetabolic BAT volume ($r -0.55$, $P = 0.04$ during activation and $r = 0.72$, $P = 0.003$ during deactivation) and with¼ BAT activity ($r = 0.69$, $P = 0.006$ during deactivation) as measured by PET-CT [29]. Given that PET-CT involves exposure to ionizing radiation, MRI may serve as an alternative method to study BAT, although there are still technical challenges for quantification of BAT based on fat fraction [30].

Proton magnetic resonance spectroscopy can be used to assess polyunsaturated fatty acids in subcutaneous adipose tissue, VAT, and bone marrow adipose tissue. A significant negative correlation was observed between unsaturated fat content and VAT amount; however, there was no correlation with unsaturated fat content and other adipose tissue compartments [31]. Further studies in larger cohorts are needed to gain further insight into whether the composition of fatty acids of adipose tissue is related to metabolic health risks.

Most studies use Hounsfield Unit of about −190 to −30 for subcutaneous adipose tissue and VAT quantification in CT studies. There is no consistent threshold that can be applied for MRI adipose tissue segmentation; however, there has been tremendous growth in automation of the analysis process in recent years [32–35]. The automatic analysis of water-fat imaging methods and the conventional T1-weighted MRI has been shown to be comparable [35]. Some studies automatically separated VAT from subcutaneous adipose tissue and bone marrow adipose tissue [32–35], other studies further removed intermuscular adipose tissue in addition to using $R2_*$ mapping to remove bowel content and bone marrow fat [34]. Semiautomated segmentation is considered the reference method until fully automated segmentation methods are validated across diverse populations including infants and children. Growth in the fields of artificial intelligence and deep learning may be a future direction for fully automated, accurate 3D segmentation of adipose tissue depots [36].

ABDOMINAL ORGAN FAT QUANTIFICATION

CT and MRI have been utilized for quantifying fat contents of abdominal organs including liver, pancreas, and adrenal glands [37]. Routine CT measurement of fat content is nonspecific and may be influenced by confounding factors that alter tissue density. However, with quantitative CT technology, liver fat content measured by CT is comparable to that measured by MRI in studies validated with a postmortem biochemical fat analysis in goose [38■,39]. MRI can specifically quantify fat content and utilize a variety of pulse sequences and scan parameters to create multidimensional imaging and high resolution for soft tissues. Fat-selective MRI, chemical-shift-encoded water-fat MRI, and magnetic resonance spectroscopy are the most popular fat quantification technologies [24,25].

Substantial evidence indicates that intrahepatic fat is a major driver of metabolic complications of obesity. The fatty acid composition of liver fat can also be estimated by both magnetic resonance spectroscopy and custom-designed MRI sequences [40■], which could be applied to distinguish subtypes of nonalcoholic fatty liver disease. In a study comparing histology and MRI in 32 patients with nonalcoholic fatty liver disease, the saturated fatty acid fraction was higher in patients with nonalcoholic steatohepatitis than in patients with simple steatosis (48 ± 2% vs. 44 ± 4%; $P < 0.05$) [40■]. Future studies could evaluate whether fatty acid composition in different depots (i.e., liver, VAT, and subcutaneous adipose tissue) plays different roles in metabolism and development of metabolic syndrome.

Magnetic resonance spectroscopy-measured pancreatic fat has previously been reported in association with insulin resistance. Using water-fat MRI, a recent population study of 685 healthy Chinese adults reported that fatty pancreas was related to central obesity defined by waist circumference, hypertriglyceridemia, and elevated serum ferritin [41]. A recent meta-analysis reported that the presence of nonalcoholic fatty pancreas disease was associated with a significantly increased risk of arterial hypertension, type 2 diabetes, and metabolic syndrome [42].

CONCLUSION

Advances in imaging technology increase the accuracy and efficiency of abdominal obesity measurement. Although tape-measured waist circumference fits the needs of large-scale epidemiological studies, 3D body scanning provides more detailed information that reflects body shape and volume. Recent improvements in dual abdominal bioelectrical impedance analysis and ultrasound are promising, particularly because ultrasound may be used to assess abdominal subcutaneous adipose tissue thickness [43] and VAT depth [44] during pregnancy. Future large-scale studies are needed to prove that bioelectrical impedance analysis or ultrasound is more accurate than waist circumference in estimating VAT in different populations. DXA is more accurate than waist circumference in estimating VAT, but future studies are needed to validate DXA's capacity to detect VAT changes over time. CT and MRI provide multidimensional visualizations of anatomy and are reference methods for abdominal adipose tissue quantification. The versatile image acquisitions and postprocessing protocols available, especially in MRI, promote evaluating abdominal adiposity through a range of perspectives from simple morphology to functional studies.

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KEY POINTS

- Waist circumference is the simplest and most economical measure of abdominal obesity.
- Only CT and MRI can provide multidimensional visualizations of the anatomy and directly measure abdominal adipose tissue depots.
- The emerging 3D body scanning technique measures abdominal volume and shape.
- Further evidence is needed to support that bioelectrical impedance analysis, ultrasound, or 3D body scanning is consistently superior to waist circumference in evaluating abdominal obesity.

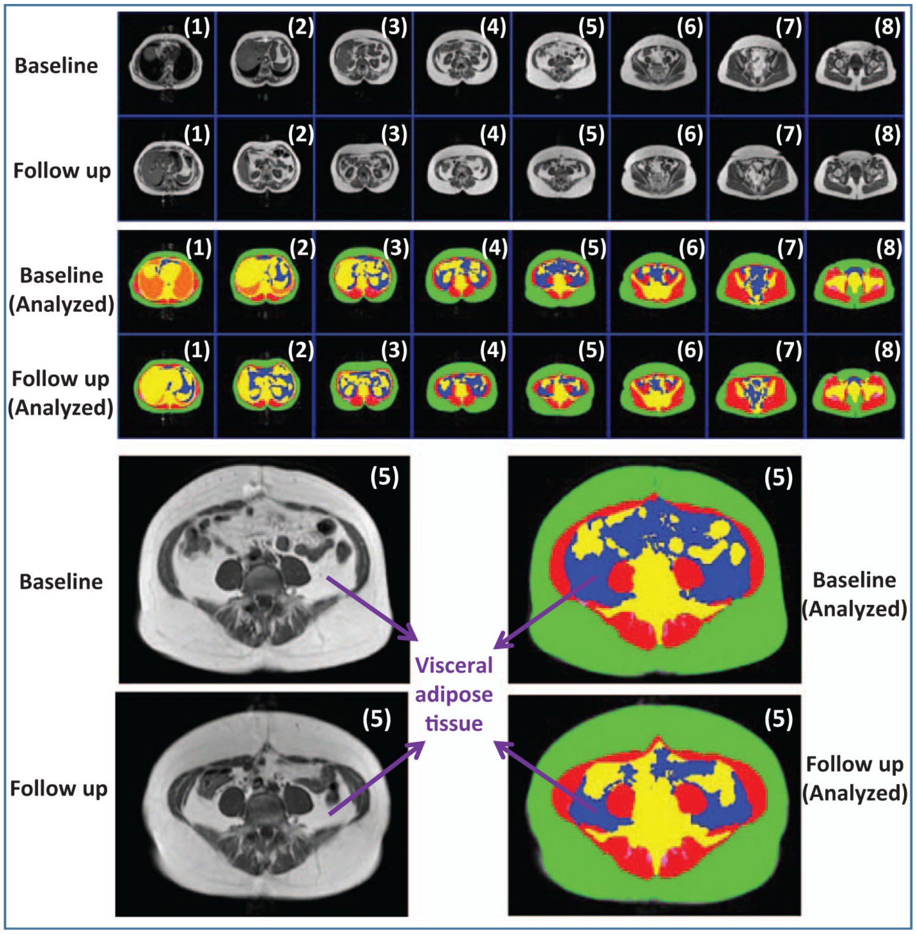

FIGURE 1.

Upper panel: Original and analyzed multislice MRI from the dome of the liver to the femoral head. Although the total VAT volume is similar between baseline and follow up, the VAT area in one MRI slice (5) is larger at baseline than at follow up. This difference is influenced by breath holding: the participant is likely inhaling during the baseline measurement but exhaling during the follow up measurement.