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Measurement Site for Waist Circumference Affects Its Accuracy As an Index of Visceral and Abdominal Subcutaneous Fat in a Caucasian Population[1,2]

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Abstract

Following experts' consensus, waist circumference (WC) is the best anthropometric obesity index. However, different anatomic sites are used, and currently there is no universally accepted protocol for measurement of WC. In this study, we compare the associations between WC measured at different sites with total visceral adipose tissue (VAT) volume and cardiometabolic risk. Cross-sectional data were obtained from 294 adults and 234 children and adolescents. In addition, longitudinal data were provided in 75 overweight adults before and after dietary-induced weight loss. WC was measured below the lowest rib (WC_{rib}), above the iliac crest ($WC_{iliac\ crest}$), and midway between both sites (WC_{middle}). Volumes of VAT and abdominal subcutaneous adipose tissue (SAT) were obtained using MRI. Cardiometabolic risk included blood pressure, plasma lipids, glucose, and homeostasis model (HOMA index). WC differed according to measurement site as $WC_{rib} < WC_{middle} < WC_{iliac\ crest}$ ($P < 0.001$) in children and women, and $WC_{rib} < WC_{middle}$, $WC_{iliac\ crest}$ ($P < 0.001$) in men. Elevated WC differed by 10–20% in females and 6–10% in males, dependent on measurement site. In men and children, all WC had similar relations with VAT, SAT, and cardiometabolic risk factors. In women, WC_{rib} correlated with weight loss-induced decreases in VAT ($r = 0.35$; $P < 0.05$). By contrast, $WC_{iliac\ crest}$ had the lowest associations with VAT and cardiometabolic risk factors in women. Each WC had a stronger correlation with SAT than with VAT, suggesting that WC is predominantly an index of abdominal subcutaneous fat. There is need for a unified measurement protocol. J. Nutr. 140: 954–961, 2010.

Introduction

Measurement of waist circumference (WC)[6] has been recommended in clinical guidelines (1–3) by leading health authorities and societies to assess obesity-associated cardiometabolic risk in clinical practice (4), as well as in epidemiological studies (5,6). However, there is no consensus on the measurement protocol to use, which is due to a lack of data that provide a scientific rationale. In a recent systematic review of 120 studies, a panel of experts identified 8 different protocols for WC measurement (7). As a primary effort to develop an internationally accepted standard for measurement of WC, these experts emphasized the need for the use of bony landmarks [fixed skeletal site(s)] to guide measurement and for the ease of measurement. Three protocols comply with these requirements: *1*) the superior border of the iliac crest as recommended by the NIH guidelines (8) and applied in NHANES III; *2*) just below the lowest rib; and *3*) midway between lowest rib and iliac crest as described in the WHO and International Diabetes Federation guidelines (1,3,10). Studies comparing different protocols have shown a profound influence of the measurement site on absolute WC values (11–20). These discrepancies are sizable and especially important for applying cutoffs in clinical decision-making. It is therefore questionable if the existing protocols can be used interchangeably for identification of obesity-associated health risk.

Reviewing the available data, Ross et al. (7) did not find a substantial influence of WC measurement protocol on the relationship between WC and morbidity or mortality. However,

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[6] Abbreviations used: HDL-C, HDL cholesterol; HOMA, homeostasis model assessment; SAT, abdominal subcutaneous adipose tissue; TG, triglyceride; WC, waist circumference; WC_{rib}, waist circumference measured below the lowest rib; $WC_{iliac\ crest}$, waist circumference measured above the iliac crest; WC_{middle}, waist circumference measured between both sites; VAT, visceral adipose tissue.

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a quantitative meta-analysis could not be performed because of heterogeneity among studies and also small sample sizes for some outcomes.

It is generally assumed that WC is an indirect measure of visceral fat mass (which is again associated with cardiometabolic risk). Thus, comparing WC measured at different sites should be based on its association with visceral fat mass. To the best of our knowledge, no study has addressed associations among multiple WC measurement sites, visceral fat mass, and cardiometabolic risk. The present study sets out to provide a biological rationale of an optimal WC measurement protocol. WC was measured above the iliac crest ($WC_{iliac\ crest}$), below the lowest rib (WC_{rib}), and midway between both sites (WC_{middle}) in a sample of 540 participants aged between 6 and 78 y. Across age and sex groups, we investigated which WC is most closely associated with total visceral adipose tissue (VAT) volume and cardiometabolic risk factors. In a subgroup of 75 overweight and obese adults, we analyzed which WC best identifies weight loss-induced loss in VAT.

Participants and Methods

Subject eligibility and recruitment. The study group was recruited from 2007 to 2009 by local advertisement and consisted of 528 healthy, weight-stable Caucasian participants (nonpregnant or lactating) aged 6–78 y with a BMI range of 12.3–25.7 kg/m^2 in prepubertal children, 13.8–38.6 kg/m^2 in pubertal children and adolescents, and 16.8–40.2 kg/m^2 in adults. Exclusion criteria were smoking; taking any medication influencing body composition; and using lipid-lowering, hypoglycemic, or antihypertensive medication. Self-assessment of pubertal stage according to Tanner (21) was used in children and adolescents older than 10 y.

Intervention group. The substudy was designed to investigate longitudinal changes in body fat distribution and insulin sensitivity before and after diet-induced weight loss. A total of 8 overweight and 53 obese women (BMI 28.2–46.8 kg/m^2) aged 19–46 y and 1 overweight and 13 obese men (BMI 29.4–41.8 kg/m^2) aged 27–47 y were selected for participation. All participants had a normal physical examination and ECG recording, no history of cardiovascular or metabolic disease, and a normal thyroid function.

Both study protocols (cross-sectional and intervention) were approved by the medical ethics committee of the Christian-Albrechts-University Kiel. All participants provided their fully informed and written consent before participation. In addition, parents assented for underage children.

Measurement of WC. The bony landmarks of the lowest rib and the iliac crest were located and palpated by the examiner at the level of the midaxillary line. The measurement tape was placed in a horizontal plane around the abdomen at the level just above the uppermost lateral border of the iliac crest (superior border of the iliac crest, $WC_{iliac\ crest}$), just below the lowest rib (i.e. distal border of the lowest rib, WC_{rib}), and midway between both sites (measured distance, WC_{middle}). Special attention was paid to ensure the tape was parallel to the floor. The measurement was made at the end of normal expiration with the nonelastic plastic tape adjacent to but not compressing the skin and the participant standing well erect. For each anthropometrical point considered, 1 measurement was obtained. All measurements were performed by 4 well-educated and trained nutritionists who regularly compared their results in training to minimize within and between-observer variation. In a subset of 16 lean and obese participants, intra- and inter-observer CV for 3 nonconsecutive measurements and 4 observers were: WC_{rib}, 0.59 and 1.29%; $WC_{iliac\ crest}$, 1.43 and 2.64%; and WC_{middle}, 1.19 and 2.52%. The technical error of measurements, which is the square root of measurement error variance (22), was also used for the calculation of the intra- and inter-evaluator variation: WC_{rib}, 1.2 and 2.4 cm; $WC_{iliac\ crest}$, 2.2 and 5.5 cm; and WC_{middle}, 2.0 and 5.1 cm.

Cutoffs for the definition of abdominal obesity were WC > 88 cm in women and >102 cm in men according to the National Cholesterol Education Program Adult Treatment Panel III and WHO (2,3) and >80 cm in women and >94 cm in men according to the International Diabetes Federation (1).

Quantification of visceral and abdominal subcutaneous adipose tissue by MRI. Measurements of visceral and abdominal subcutaneous adipose tissue (SAT) volumes were performed in a supine position with their arms extended above their heads using a Magnetom Avanto 1.5-T scanner (Siemens Medical Systems). The entire abdomen from the diaphragm (top of the liver or the base of the lungs, T10) to the femur heads was scanned using continuous axial images with an 8-mm slice thickness and 2-mm interslice gaps. Images were obtained using a T1 weighted gradient-echo sequence (TR 157 ms, TE 4 ms, flip angle 70°, voxel size 3.9 × 2 × 8 mm^3), during which the participants were required to hold their breath. All images were segmented manually using Slice-O-Matic, Tomovision 4.3 Software. The software employed knowledge-based image processing to label pixels as fat and nonfat components using a threshold for adipose tissue on the basis of the gray-level histograms of the images. Each slice was manually reviewed and voxels arising from fatty bowel content were deleted. Total VAT and abdominal SAT were determined from the sum of all adipose tissue areas (cm^2) multiplied by the slice thickness. CV for repeated measurements of VAT and SAT were 1.5 and 0.9%, respectively.

Risk factor measurements. Body weight was measured to the nearest 0.1 kg on an electronic Tanita scale. Height was measured on a stadiometer (seca, Vogel & Halke) to the nearest 0.5 cm. Blood pressure measurements were obtained while the participant was in a seated position, using a standard manual sphygmomanometer. Blood samples were taken after an 8-h overnight fast and analyzed following standard procedures. Briefly, plasma glucose was assayed using a hexokinase enzymatic method (Konelab kit, Thermo Clinical Labsystems). Plasma insulin was measured by RIA showing no cross-reactivity with C-peptide and only 14% with proinsulin (REF 10624, Adaltis S.p.A). The homeostasis model assessment (HOMA) was used to calculate insulin resistance (IR) as HOMA-IR = fasting insulin (μU/mL) × fasting glucose (mmol/L)/ 22.5 (23). CRP was measured turbidimetrically using a latex-agglutination test (CRP-Dynamik/ -Hit917, BIOMED Labordiagnostik). Cholesterol and triacylglycerol concentrations were measured enzymatically (VITROS 5,1 FS, Ortho-Clinical Diagnostics).

Weight loss intervention. During 12.7 ± 2.3 wk of weight loss intervention, participants received a low-energy, nutritionally balanced diet (BCM-Diät, PreCon) containing 3350–4200 kJ/d, as described elsewhere (24,25). All participants obtained weekly individual counseling in the principles of the hypocaloric diet by a registered dietitian. Three-day food records were obtained if necessary for dietary counseling (i.e. unsuccessful or slow weight loss) and compliance was also monitored by weekly measurement of losses in weight and fat mass by Air-Displacement Plethysmography (BOD-POD, Life Measurement).

Statistical analysis. Group data are given as mean ± SD or median and interquartile range in case of nonnormal distribution. For categorical analysis, we grouped BMI as follows: 18.5 to <25 (normal weight), 25 to <30 (overweight), and ≥30 (obese) kg/m^2. In children and adolescents, overweight and obesity were determined using corresponding actual German BMI percentiles (>90th and >97th percentile, respectively) (26). Because of significant sex differences in visceral and SAT, WC data for males and females were analyzed separately. Unpaired Student's *t* tests were used to examine sex differences in normally distributed variables and Mann-Whitney U test in nonnormally distributed variables. Comparisons among 3 WC were performed by repeated-measures ANOVA using a Tukey-Kramer multiple comparison post hoc test (calculation with NCSS, 2007). Differences between pre- and postweight loss measures of variables were determined using a paired Student's *t* test. Triglycerides (TG) and HOMA-IR, volumes of VAT and SAT, were normalized by logarithmic transformation. Because the relations between WC and cardiometabolic risk or WC and VAT are influenced by

age (27), partial correlations adjusted for age were used to quantify the association between WC and cardiometabolic risk factors, VAT, or SAT. The strength of correlation coefficients $r(\times 1,y)$ and $r(\times 2,y)$ was compared using the method of Meng et al. (28), which considers intercorrelation ($r(\times 1,\times 2)$) between both correlations tested. Analyses were conducted using SPSS statistical software (SPSS 13.0). Levels of significance were set at $P < 0.05$.

Results

Participant characteristics are presented in **Table 1**. In prepubertal children, there were no sex differences in age, BMI, WC, VAT, SAT, and cardiometabolic risk except for a slightly lower diastolic blood pressure in girls ($P < 0.05$). Pubertal girls had lower height, weight, and systolic blood pressure and a higher HDL cholesterol (HDL-C) concentration than pubertal boys, but BMI and abdominal adipose tissue volumes did not differ between sexes. Compared with adults, children and adolescents had very low VAT in relation to SAT. Women were younger and had more SAT, less VAT, and lower cardiometabolic risk factors compared with men. WC_{rib} was lower in pubertal girls and women ($P < 0.001$), but there were no sex differences for the other WC.

Comparing mean WC values at 3 sites showed that in men, WC_{rib} was smaller than the other 2 sites (-2.5 ± 2.8 cm for WC_{middle} and -2.6 ± 3.8 cm for $WC_{iliac\ crest}$; $P < 0.001$). In women and in prepubertal and pubertal boys and girls, each site for WC differed from the other, with $WC_{rib} < WC_{middle} < WC_{iliac\ crest}$ ($P < 0.001$). The greatest differences were observed in women, with -6.9 ± 5.5 cm for $WC_{rib} - WC_{middle}$, -12.2 ± 7.5 cm for $WC_{rib} - WC_{iliac\ crest}$, and 5.3 ± 6.8 cm for $WC_{iliac\ crest} - WC_{middle}$.

Figure 1*A* illustrates the differences in WC measured at different sites across groups of normal weight, overweight, and obese women. With increasing BMI, the shape of the trunk remained constant in women, with the lowest WC just below the lowest rib and the highest WC just above the iliac crest. In men, the shape of the trunk depended on BMI (Fig. 1*B*), with the highest WC midway between the lowest rib and the iliac crest in obese men.

Influence of measurement site for WC on its correlation with VAT and cardiometabolic risk. All relationships between WC measured at different sites and VAT in adults were nonlinear and the slopes were higher in men when compared with women (**Fig. 2**). The lowest sex difference between the slopes was observed for WC_{rib} and the highest for $WC_{iliac\ crest}$. In prepubertal and pubertal children and men, all 3 WC had a similar correlation with VAT (**Table 2**), and cardiometabolic risk factors (data not shown). There were no differences in the *r*-values except for prebubertal boys, where the relationships between $WC_{iliac\ crest}$ and VAT ($r = 0.65$) or $WC_{iliac\ crest}$ and HOMA index ($r = 0.13$) were lower ($P < 0.05$) compared with *r*-values of the other WC (WC_{middle} vs. VAT, $r = 0.74$ and WC_{middle} vs. HOMA index, $r = 0.35$; WC_{rib} vs. VAT, $r = 0.76$ and WC_{rib} vs. HOMA index $r = 0.33$). By contrast, in women, the WC_{rib} had the highest *r*-value with VAT compared with *r*-values of WC_{middle} ($P < 0.05$) and $WC_{iliac\ crest}$ ($P < 0.001$). In this group, WC_{rib} and WC_{middle} had similar associations with cardiometabolic risk, but the magnitude of correlations between $WC_{iliac\ crest}$ and diastolic blood pressure, HOMA index, plasma TG, and HDL-C was lower (all $P < 0.05$).

The influence of measurement site on its association with VAT and SAT was also investigated in subgroups of normal weight, overweight, and obese adults (**Table 3**). Generally, all WC were closer or more similarly related to SAT than VAT across BMI groups and in both sexes (with the exception of WC_{rib} in normal weight men). Compared with $WC_{ileac\ crest}$, WC_{rib} had a tendency toward the lowest correlation with SAT in normal weight ($P = 0.09$), overweight ($P = 0.10$), and obese

TABLE 1 Anthropometrics and plasma biochemistry of the participants and prevalence of overweight and obesity[1]

	Prepubertal children		Pubertal children		Adults	
	Female, *n* = 35	Male, *n* = 39	Female, *n* = 86	Male, *n* = 74	Female, *n* = 177	Male, *n* = 117
Age, *y*	8.8 ± 1.5	9.3 ± 1.6	14.8 ± 2.1	15.0 ± 1.9	37.9 ± 13.3	44.7 ± 14.5***
Height, *m*	1.34 ± 0.89	1.39 ± 0.12	1.64 ± 0.09	1.71 ± 0.11***	1.68 ± 0.07	1.79 ± 0.06***
Weight, *kg*	30.3 ± 7.0	33.3 ± 10.0	63.1 ± 18.7	69.8 ± 24.0*	82.4 ± 20.9	87.8 ± 16.0*
BMI, kg/m^2	16.7 ± 2.4	16.7 ± 3.0	23.3 ± 5.7	23.3 ± 5.9	29.0 ± 6.7	27.5 ± 4.6*
Overweight, %	8.6	2.6	7.6	3.8	22.0	41.9
Obese, %	0.0	7.7	26.1	26.3	42.4	25.6
SBP,[2] *mm Hg*	113 ± 13	115 ± 10	119 ± 9	124 ± 12**	122 ± 13	127 ± 13***
DBP,[2] *mm Hg*	72 ± 9	68 ± 8*	74 ± 9	74 ± 10	79 ± 9	83 ± 9***
FPG,[2] *mmol/L*	4.82 ± 0.30	4.90 ± 0.44	5.17 ± 1.29	5.13 ± 0.50	5.17 ± 0.59	5.63 ± 0.59***
HOMA-IR	1.69 (1.32–2.51)	1.63 (1.17–2.23)	2.65 (1.98–3.43)	2.76 (2.14–3.84)	2.77 (1.93–4.66)	2.16 (1.62–3.48)***
TG, *mmol/L*	59.0 (39.5–75.0)	62.0 (48.0–83.3)	88.5 (64.5–128.5)	81.2 (63.0–103.0)	97.5 (77.0–133.3)	114.0 (87.8–159.5)*
TC,[2] *mmol/L*	159.6 ± 31.6	159.3 ± 24.1	164.3 ± 34.2	159.7 ± 39.0	190.8 ± 38.2	203.1 ± 47.3*
HDL-C,[2] *mmol/L*	62.0 ± 14.2	63.8 ± 11.6	57.6 ± 12.9	54.3 ± 15.9*	63.2 ± 18.0	51.0 ± 17.2***
LDL-C,[2] *mmol/L*	84.9 ± 24.3	81.6 ± 24.7	86.8 ± 29.0	85.7 ± 35.6	104.7 ± 34.9	121.8 ± 38.4***
WC_{rib}, *cm*	57.0 ± 6.3	59.7 ± 7.5	73.8 ± 12.0	77.9 ± 13.4*	87.8 ± 13.8	94.6 ± 12.7***
WC_{middle}, *cm*	58.0 ± 7.5	60.4 ± 7.9	78.5 ± 14.8	80.1 ± 15.6	94.6 ± 16.5	97.1 ± 13.4
$WC_{iliac\ crest}$, *cm*	60.8 ± 8.3	63.2 ± 10.6	84.5 ± 16.2	83.2 ± 16.4	100.0 ± 17.0	97.2 ± 12.4
VAT, cm^3	24 (21–38)	27 (18–40)	67 (42–757)	58 (38–682)	1,934 (1,253–3,035)	4,421 (2,409–6,229)***
SAT, cm^3	231 (172–314)	200 (137–282)	590 (361–7,547)	345 (284–5,715)	10,106 (6,658–13,957)	5,998 (4,179–8,122)***

[1] Values are mean ± SD, median (interquartile range), or percent. Asterisks indicate different from corresponding female, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[2] DBP, diastolic blood pressure; FPG, fasting plasma glucose; LDL-C, LDL cholesterol; SBP, systolic blood pressure; TC, total cholesterol.

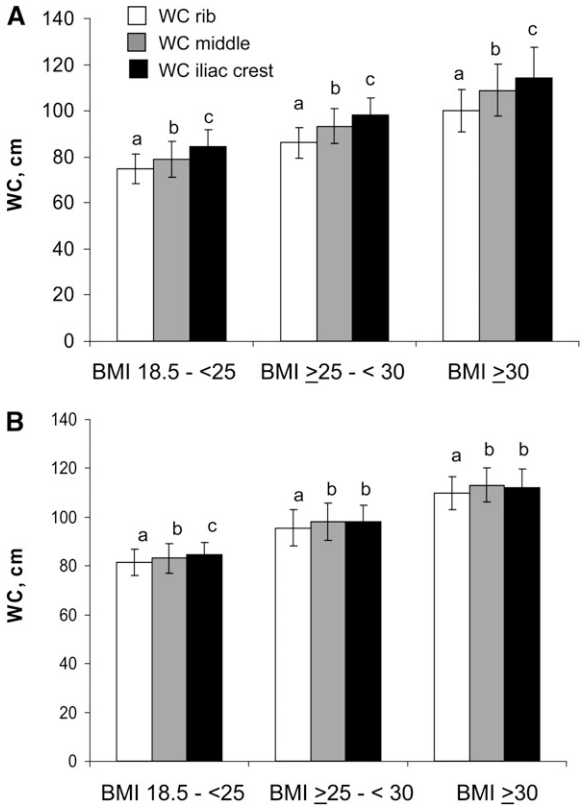

FIGURE 1 WC measured at different sites in women (*A*) and men (*B*) grouped by BMI. Values are means ± SD, n = 59 women/35 men (normal weight), n = 37 women/47 men (overweight), and n = 78 women/33 men (obese). Within a BMI category, means without a common letter differ, $P < 0.05$.

women ($P = 0.07$). Furthermore, in obese women, the WC_{rib} was more closely related with VAT than the other 2 WC ($P < 0.05$). All WC were equal correlates of VAT in the other groups.

Influence of measurement site for WC on the prediction of cardiometabolic risk. The differences in absolute WC measures have a substantial influence on the prevalence of elevated morbidity defined by using the same WC cutoffs (**Table 4**). In women, the prevalence of elevated values was 20% higher using $WC_{iliac\ crest}$ compared with WC_{rib}. Considering the lower absolute differences between WC measures in men, these discrepancies were only 6–10% using 102 or 92 cm as a cutoff.

Influence of measurement site for WC on its correlation with decreases in VAT and SAT. **Table 5** presents the characteristics of before and after the weight loss program. In men and women, the intervention reduced ($P < 0.001$) body weight by 12 and 8%, BMI by 12 and 9%, WC_{rib} by 10 and 6%, WC_{middle} by 12 and 7%, $WC_{iliac\ crest}$ by 9 and 5%, VAT by 34 and 16%, and SAT by 27 and 19%, respectively.

Correlations between WC measured at different sites and volumes of VAT and SAT showed similar patterns before and after intervention (**Table 6**). These data are in line with our cross-sectional results (Table 2). Because of the smaller sample size in men, some relationships did not reach significance.

However, the relationships between decreases in WC and decreases in VAT volume were moderate and only significant for WC_{rib} in women ($r = 0.35$; $P < 0.05$) and WC_{middle} in men ($r = 0.57$; $P < 0.05$). Both WC also had a similar relationship with the decrease in SAT (Table 6).

Discussion

The main finding of this study was that WC had a stronger correlation with SAT than with VAT. This was independent of the site of measurement. These data suggest that WC is a better index of abdominal subcutaneous rather than visceral fat. Minor differences were observed between WC measurement sites; WC_{rib} seemed to be a better index for VAT in overweight and obese women than $WC_{iliac\ crest}$, whereas in men and underage children, all WC protocols yielded similar results. More importantly, absolute values also differed among all measurement sites in all age groups and both genders. These data add to clinical practice (e.g. risk assessment in the context of the metabolic syndrome). It is evident that there is a need for a standardized protocol. Our data also have an impact on recent epidemiological studies on obesity-related risks. The recent longitudinal data of the EPIC study showed that WC is a better index of mortality

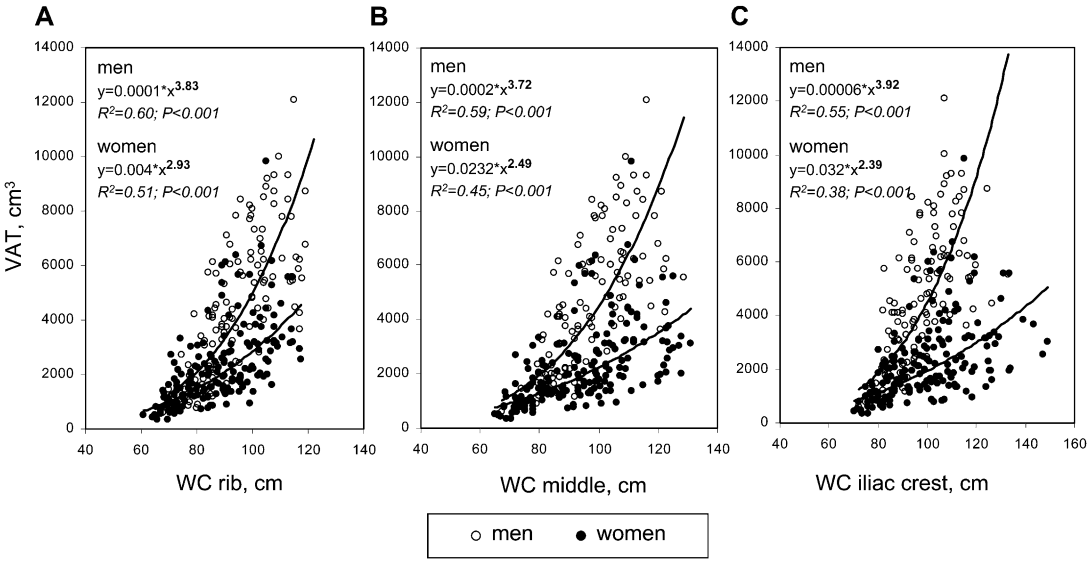

FIGURE 2 Relations between VAT and WC measured at WC_{rib} (*A*), WC_{middle} (*B*), and $WC_{iliac\ crest}$ (*C*) in men and women.

TABLE 2 Partial correlations adjusted for age between WC measured at different sites, VAT, and cardiometabolic risk by sex

	Female					Male				
	lnVAT	WC_{rib}	WC_{middle}	WC_{icrest}	*n*	lnVAT	WC_{rib}	WC_{middle}	WC_{icrest}	*n*
Prepubertal children										
ln VAT	–	0.73***	0.70***	0.70***	35	–	0.76***	0.74***	0.65***	39
ln SAT	0.80***	0.89***	0.86***	0.87***	35	0.85***	0.85***	0.86***	0.75***	39
Pubertal children										
ln VAT	–	0.83***	0.82***	0.83***	86	–	0.87***	0.86***	0.86***	74
ln SAT	0.98***	0.87***	0.86***	0.88***	86	0.94***	0.93***	0.91***	0.92***	74
Adults										
ln VAT	–	0.70***	0.66***	0.62***	177	–	0.74***	0.74***	0.71***	117
ln SAT	0.75***	0.87***	0.88***	0.87***	177	0.76***	0.83***	0.87***	0.87***	117
SBP[1]	0.39***	0.40***	0.41***	0.37***	177	0.43***	0.51***	0.51***	0.51***	117
DBP[1]	0.39***	0.39***	0.38***	0.31***	177	0.37***	0.50***	0.51***	0.48***	117
FPG[1]	0.13	0.10	0.05	0.06	168	0.30***	0.34***	0.36***	0.34***	116
ln HOMA-IR	0.37***	0.45***	0.42***	0.39***	163	0.41***	0.47***	0.50***	0.49***	98
ln TG	0.36***	0.35***	0.35***	0.29***	169	0.46***	0.41***	0.39***	0.42***	112
Cholesterol	0.08	−0.02	−0.00	−0.02	169	0.34**	0.27**	0.25**	0.25**	116
HDL-C	−0.40***	−0.40***	−0.36***	−0.34***	169	−0.38*	−0.37***	−0.36***	−0.32***	116
LDL-C[1]	0.24**	0.13	0.12	0.13	168	0.32**	0.24**	0.22*	0.21*	116

$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[1] DBP, diastolic blood pressure; FPG, fasting plasma glucose; LDL-C, LDL cholesterol; SBP, systolic blood pressure; TC, total cholesterol.

risk than BMI (5). In this study, WC was measured either at the narrowest circumference of the torso or midpoint between the lowest rib and the iliac crest. In addition, measurements were performed with clothing. The results of this study may be weakened, because pooling data on WC obtained by different protocols without correcting for differences in absolute measures will likely lead to erroneous results (Table 1; Fig. 1). Likewise, the use of a nonstandard protocol (WC measured at the narrowest point between the costal margin and iliac crest) may also have added to the low value of WC in the INTERHEART Study (29). These authors proposed that the waist:hip ratio, not WC, is the best adiposity risk marker for acute myocardial infarction (6).

WC reflects abdominal fat tissue and cannot differentiate between visceral and subcutaneous fat depots. However, regarding risk assessment, WC should be an index of visceral obesity. This is supported by the finding that VAT but not SAT was a significant predictor of diabetes in men and women of the Diabetes Prevention Program (30). Comparing different WC, WC_{rib} was most specific for VAT in women (i.e. WC_{rib} had the lowest relationship with SAT) (Tables 2 and 3). In contrast, the $WC_{iliac\ crest}$ had a lower association with VAT (Table 2, especially in obese women; Table 3) but had the highest relationships with SAT. This is consistent with significantly lower associations between $WC_{iliac\ crest}$ and cardiometabolic risk factors in women (Table 2). This might be explained by the finding that VAT in the upper abdomen correlates more closely to total VAT volume and health risk factors than VAT at the iliac crest level (31,32). Thus, WC_{rib} or WC_{middle} in women appear to be better correlated with cardiometabolic risk than $WC_{iliac\ crest}$. In addition, only WC_{rib} predicted weight loss-associated decreases in VAT in women (Table 6). In men, all WC measures yielded similar results.

Another drawback of $WC_{iliac\ crest}$ was its lower precision (see Methods). This was confirmed by Wang et al. (15) and was especially true in females, because the waist shape superior to the iliac crest decreases more than the waist shape in other regions of the trunk, making it difficult to stabilize the tape on a sharply curved skin surface (15). In accordance with Wang et al. (15), WC_{rib} had the highest reproducibility, maybe because it is the

TABLE 3 Partial correlations adjusted for age between WC measured at different sites and VAT or SAT volume stratified by sex and BMI groups

	Female				Male			
BMI group	WC_{rib}	WC_{middle}	WC_{icrest}	*n*	WC_{rib}	WC_{middle}	WC_{icrest}	*n*
18.5 to <25 kg/m^2								
ln VAT	0.67***	0.61***	0.66***	59	0.52**	0.61***	0.53**	35
ln SAT	0.70***	0.72***	0.77***	59	0.40*	0.66***	0.63***	35
≥25 to <30 kg/m^2								
ln VAT	0.32*	0.30	0.15	37	0.58***	0.54***	0.52**	47
ln SAT	0.30*	0.38*	0.51**	37	0.67***	0.72***	0.74***	47
≥30 kg/m^2								
ln VAT	0.66***	0.51***	0.32***	78	0.16	0.05	0.08	33
ln SAT	0.70***	0.73***	0.70***	78	0.54**	0.65***	0.67***	33

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

TABLE 4 Prevalence of elevated WC measured at different anatomic sites and using cutoffs by WHO/NCEP ATP III and IDF[1]

	Women		Men	
	>80 cm	>88 cm	>94 cm	>102 cm
	n (%)			
WC_{rib}	118 (66.7)	87 (49.2)	54 (46.2)	36 (30.8)
WC_{middle}	134 (75.7)	109 (61.6)	62 (53.0)	43 (36.8)
$WC_{iliac\ crest}$	153 (86.4)	123 (69.5)	66 (56.4)	42 (35.9)

[1] IDF, International Diabetes Federation; NCEP ATPIII, National Cholesterol Education Program Adult Treatment Panel III.

TABLE 5 Characteristics of participants before (T0) and after weight loss (T1) and changes in anthropometric variables, VAT and SAT[1,2]

	Women, n = 61			Men, n = 14		
	T0	T1	Δ T1−T0	T0	T1	Δ T1−T0
Age, *y*	32.9 ± 6.8	–	–	38.0 ± 6.0$^{\#}$	–	–
Weight, *kg*	100.5 ± 16.7	92.2 ± 16.3*	−8.3 ± 3.8	111.9 ± 13.1$^{\#}$	98.6 ± 11.9*	−13.3 ± 4.2$^{\#\#\#}$
BMI, *kg/m^2*	35.2 ± 4.4	32.2 ± 4.3*	−3.0 ± 1.3	34.6 ± 3.7	30.5 ± 3.1*	−4.1 ± 1.4$^{\#\#}$
WC_{rib}, *cm*	99.4 ± 9.4	93.6 ± 9.9*	−5.8 ± 4.8	110.8 ± 6.0$^{\#\#\#}$	100.1 ± 5.8$^{\#\#}$*	−10.6 ± 3.1$^{\#\#\#}$
WC_{middle}, *cm*	109.0 ± 11.5	101.1 ± 11.4*	−7.9 ± 6.9	114.5 ± 7.4$^{\#}$	101.1 ± 7.9*	−13.4 ± 4.4$^{\#\#}$
$WC_{iliac\ crest}$, *cm*	114.4 ± 13.0	108.9 ± 12.0*	−5.5 ± 8.6	113.9 ± 8.7	103.9 ± 8.0*	−10.0 ± 4.0$^{\#\#}$
VAT, *cm^3*	2,391 ± 1,190	1,986 ± 1,013*	−363 ± 550	5,496 ± 1,174$^{\#\#\#}$	3,637 ± 754$^{\#\#\#}$*	−1,770 ± 1,187$^{\#\#}$
SAT, *cm^3*	14,866 ± 4,286	11,889 ± 4,269*	2,737 ± 1,977	10,184 ± 3,853$^{\#\#}$	7,475 ± 2,813$^{\#\#\#}$*	−2,580 ± 1,533

[1] Values are mean ± SD. Asterisks indicate different from T0: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Number symbols indicate different from corresponding female: $^{\#}$ $P < 0.05$, $^{\#\#}$ $P < 0.01$, $^{\#\#\#}$ $P < 0.001$.
[2] The intervention duration was 12.7 ± 2.3 wk.

most easily located. WC_{middle} is more cumbersome to obtain, because it requires the identification of 2 bony landmarks, a measured distance between the 2, and the calculation of the midpoint. Because the measurement error limits the minimal detectable change of a parameter, weight loss-induced improvements of WC may be better detected just below the lowest rib.

In prepubertal and pubertal children, none of the WC measures was consistently better than the other. However, the prevalence of overweight and obesity was low in these groups (Table 1) and significant differences in absolute values between WC measurement sites were already seen in prebubertal and pubertal boys and girls (see Results). These led to a discordant prevalence when defining abdominal obesity as previously reported by our group (19). Although we found reasonable correlations between all WC and VAT in prepubertal and pubertal children, absolute amounts of VAT and the VAT:SAT ratio was very low (Table 1). This is in agreement with WC being a better index for abdominal subcutaneous than for visceral adiposity in underage individuals (Table 2).

Because of the absolute difference in WC measure, especially in women, the percentage of patients above or below the recommended threshold values differs considerably among WC measurement protocols and leads to under- or overestimation of obesity-related health risk, depending on the WC protocol used (Table 4). As long as there are no reference values generated specifically for the WC protocol below the lowest rib, this protocol cannot be used for clinical identification of abdominally obese individuals at increased health risk. A simple conversion of different measures by adding or subtracting a constant amount would be inappropriate, because the absolute difference between WC measures depends on weight status (Fig. 1) and probably also on age (27).

In addition, the current cutoffs for WC have to be revised, because they are based on cutoffs for BMI (33). Future WC cutoffs should be based on VAT, because BMI is only an imprecise measure of central obesity, especially in the normal weight and overweight range. This was shown previously; in postmenopausal women at a normal BMI (19.5–24.9 kg/m^2), 30% already had an elevated WC > 80 to < 88 cm and 10% even had a WC > 88 cm (34). Likewise, in overweight women (25–29.9 kg/m^2), 9% had a normal WC < 80 cm, whereas 57% already had a WC > 88 cm and only 33% were classified as having an elevated WC > 80 to < 88 cm. Notably, at both cutoff levels (80 or 94cm and 88 or 102cm), men had ~3.8 times more VAT than women (Fig. 2). This observation may partly account for the higher morbidity and mortality associated with the same BMI in men than in women.

Knowledge about the relationship between WC and VAT is a precondition for understanding the relationship between WC and morbidity or mortality. Some studies have shown a similar predictive value of a large WC and a high BMI (35–37). If WC is a more accurate index for visceral obesity than BMI, these results are at odds with our understanding that measures of fat distribution are superior at predicting risk of death (38). However, considering the high colinearity among obesity indices like BMI and WC, WC measured at the wrong site may be only marginally better than BMI at estimating visceral fat (39). In line with this speculation, the correlation between BMI and VAT was r = 0.62 in women and r = 0.64 in men (both $P < 0.001$) is only slightly different from the associations observed between $WC_{iliac\ crest}$ and VAT (r = 0.62 and 0.71) (Table 2). Previous studies have also shown similar correlations between WC and VAT and between BMI and VAT in women (40,41). Moreover, all WC (especially WC_{middle} or $WC_{iliac\ crest}$) were more strongly correlated with abdominal SAT compared with VAT (Table 2 and 3). Hence, we conclude that WC regardless of the measurement site is predominantly an index of abdominal subcutaneous, not visceral, fat.

Compared with Caucasians of the same WC or BMI, African Americans have a lower VAT and Asians have a higher VAT

TABLE 6 Correlations between WC measured at 3 sites and volumes of VAT and SAT before (T0) and after weight loss (T1) and between changes in response to weight loss[1]

	Women (n = 61)			Men (n = 14)		
	WC_{rib}	WC_{middle}	WC_{icrest}	WC_{rib}	WC_{middle}	WC_{icrest}
vs. WC at T0						
ln VAT	0.77***	0.64**	0.42**	−0.31	−0.35	−0.32
ln SAT	0.72***	0.76***	0.73***	0.78**	0.79**	0.87***
vs. WC at T1						
ln VAT	0.75***	0.69***	0.67***	0.40	0.54*	0.32
ln SAT	0.74***	0.73***	0.82***	0.83***	0.77**	0.92***
vs. ΔWC T1-T0						
ΔVAT	0.35**	0.04	−0.02	0.52	0.57*	0.48
ΔSAT	0.36**	0.09	0.12	0.49	0.63*	0.61*

[1] Significant at * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

(30,42–47). Because ethnic differences in body fat distribution may therefore alter the associations between WC sites and VAT, our results apply to Caucasians only.

In conclusion, WC is predominantly an index of abdominal SAT. The measurement site of WC plays a minor role when looking for the best index for visceral fat volume. However, WC_{rib} seemed to be a better index for visceral fat volume and cardiometabolic risk than $WC_{iliac\ crest}$. This measure can be applied in both sexes. However, specific cutoffs for WC_{rib} need to be established before it can be used in clinical decision-making.

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Literature Cited

1. Alberti KG, Zimmet P, Shaw J. IDF Epidemiology Task Force Consensus Group. The metabolic syndrome-a new worldwide definition. Lancet. 2005;366:1059–62.
2. Executive Summary of The Third Report of The National Cholesterol Education Program Expert Panel on Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III). JAMA. 2002;258:2486–97.
3. WHO. Definition, diagnosis and classification of diabetes mellitus and its complications: report of a WHO consultation. Geneva: WHO; 1999.
4. Klein S, Allison DB, Heymsfield SB, Kelley DE, Leibel RL, Nonas C, Kahn R. Waist circumference and cardiometabolic risk: a consensus statement from Shaping America's Health: Association for Weight Management and Obesity Prevention; NAASO, the Obesity Society; the American Society for Nutrition; and the American Diabetes Association. Am J Clin Nutr. 2007;85:1197–202.
5. Pischon T, Boeing H, Hoffmann K, Bergmann M, Schulze MB, Overvad K, van der Schouw YT, Spencer E, Moons KG, et al. General and abdominal adiposity and risk of death in Europe. N Engl J Med. 2008;359:2105–20.
6. Yusuf S, Hawken S, Ounpuu S, Bautista L, Franzosi MG, Commerford P, Lang CC, Rumboldt Z, Onen CL, et al. INTERHEART Study Investigators. Obesity and the risk of myocardial infarction in 27,000 participants from 52 countries: a case-control study. Lancet. 2005;366:1640–9.
7. Ross R, Berentzen T, Bradshaw AJ, Janssen I, Kahn HS, Katzmarzyk PT, Kuk JL, Seidell JC, Snijder MB, et al. Does the relationship between waist circumference, morbidity and mortality depend on measurement protocol for waist circumference? Obes Rev. 2008;9:312–25.
8. National Institute for Health and Clinical Excellence. Obesity guidance on the prevention, identification, assessment and management of overweight and obesity in adults and children [cited 2009 Feb 6]. Available from: http://www.nice.org.uk/guidance /CG43/?c=91500.
9. NIH. The practical guide identification, evaluation, and treatment of overweight and obesity in adults. Bethesda (MD): NIH; 2000. (NIH publication no. 00–4084.)
10. Physical status. The use and interpretation of anthropometry. Report of a WHO Expert Committee. World Health Organ Tech Rep Ser. 1995;854:1–452.
11. Seidell JC, Cigolini M, Charzewska J, Ellsinger BM, Contaldo F. Regional obesity and serum lipids in European women born in 1948. A multicenter study. Acta Med Scand Suppl. 1988;723:189–97.
12. Seidell JC, Cigolini M, Charzewska J, Ellsinger BM, Deslypere JP, Cruz A. Fat distribution in European men: a comparison of anthropometric measurements in relation to cardiovascular risk factors. Int J Obes Relat Metab Disord. 1992;16:17–22.
13. Houmard JA, Wheeler WS, McCammon MR, Wells JM, Truitt N, Hamad SF, Holbert D, Israel RG, Barakat HA. An evaluation of waist to hip ratio measurement methods in relation to lipid and carbohydrate metabolism in men. In J Obes 1991;15:181–188.
14. Carson CA, Meilahn EN, Caggiula AW. Comparison of waist measurements: a methodologic issue in longitudinal studies. J Am Diet Assoc. 1994;94:771–2.
15. Wang J, Thornton JC, Bari S, Williamson B, Gallagher D, Heymsfield SB, Horlick M, Kotler D, Laferrère B, et al. Comparisons of waist circumferences measured at 4 sites. Am J Clin Nutr. 2003;77:379–84.
16. Onat A, Avcı GŞ, Barlan MM, Uyarel H, Uzunlar B, Sansoy V. Measures of abdominal obesity assessed for visceral adiposity and relation to coronary risk. Int J Obes Relat Metab Disord. 2004;28:1018–25.
17. Rudolf MCJ, Walker J, Cole TJ. What is the best way to measure waist circumference? Int J Pediatr Obes. 2007;2:58–61.
18. Willis LH, Slentz CA, Houmard JA, Johnson JL, Duscha BD, Aiken LB, Kraus WE. Minimal vs. umbilical waist circumference measures as indicators of cardiovascular disease risk. Obesity (Silver Spring). 2007;15:753–9.
19. Hitze B, Bosy-Westphal A, Bielfeldt F, Settler U, Mönig H, Müller MJ. Measurement of waist circumference at four different sites in children, adolescents, and young adults: concordance and correlation with nutritional status as well as cardiometabolic risk factors. Obes Facts. 2008;1:243–9.
20. Edwards LA, Bugaresti JM, Buchholz AC. Visceral adipose tissue and the ratio of visceral to subcutaneous adipose tissue are greater in adults with than in those without spinal cord injury, despite matching waist circumferences. Am J Clin Nutr. 2008;87:600–7.
21. Duke PM, Litt IF, Gross RT. Adolescents' self-assessment of sexual maturation. Pediatrics. 1980;66:918–20.
22. Ulijaszek SJ, Kerr DA. Anthropometric measurement error and the assessment of nutritional status. Br J Nutr. 1999;82:165–77.
23. Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC. Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. Diabetologia. 1985;28:412–9.
24. Goele K, Bosy-Westphal A, Lagerpusch M, Müller MJ. Influence of changes in body composition and adaptive thermogenesis on the difference between measured and predicted weight loss in obese women. Obes Facts. 2009;2:105–9.
25. Bosy-Westphal A, Kossel E, Goele K, Later W, Hitze B, Settler U, Heller M, Glüer C-C, Heymsfield SB, et al. Contribution of individual organ mass loss to weight loss-associated decline in resting energy expenditure. Am J Clin Nutr. 2009;90:993–1001.
26. Kromeyer-Hauschild K, Wabitsch M, Kunze D, Geller F, Geiß HC, Hesse V, von Hippel A, Jaeger U, Johnsen D, et al. Perzentile für den Body-mass-Index für das Kindes- und Jugendalter unter Heranziehung verschiedener deutscher Stichproben. Monatsschr Kinderheilkd. 2001;149:807–8118.
27. Kuk JL, Lee SJ, Heymsfield SB, Ross R. Waist circumference and abdominal adipose tissue distribution: influence of age and sex. Am J Clin Nutr. 2005;81:1330–4.
28. Meng X-L, Rosenthal R, Rubin DB. Comparing correlated correlation coefficients. Psychol Bull. 1992;111:172–5.
29. Han TS, Sattar N, Lean M. Assessment of obesity and its clinical implications. BMJ. 2006;333:695–8.
30. Bray GA, Jablonski KA, Fujimoto WY, Barrett-Connor E, Haffner S, Hanson RL, Hill JO, Hubbard V, Kriska A, et al. Diabetes Prevention Program Research Group. Relation of central adiposity and body mass index to the development of diabetes in the Diabetes Prevention Program. Am J Clin Nutr. 2008;87:1212–8.
31. Shen W, Punyanitya M, Chen J, Gallagher D, Albu J, Pi-Sunyer X, Lewis CE, Grunfeld C, Heymsfield SB, et al. Visceral adipose tissue: relationships between single slice areas at different locations and obesity-related health risks. Int J Obes (Lond). 2007;31:763–9.
32. Shen W, Punyanitya M, Wang Z, Gallagher D, St-Onge MP, Albu J, Heymsfield SB, Heshka S. Visceral adipose tissue: relations between single-slice areas and total volume. Am J Clin Nutr. 2004;80:271–8.
33. Lean MEJ, Han TS, Morrison CE. Waist circumference indicates the need for weight management. BMJ. 1995;311:158–61.
34. Kanaya AM, Vittinghoff E, Shlipak MG, Resnick HE, Visser M, Grady D, Barrett-Connor E. Association of total and central obesity with mortality in postmenopausal women with coronary heart disease. Am J Epidemiol. 2003;158:1161–70.
35. Flegal KM, Graubard BI. Estimates of excess deaths associated with body mass index and other anthropometric variables. Am J Clin Nutr. 2009;89:1213–9.

36. Janssen I, Katzmarzyk PT, Ross R. Body mass index is inversely related to mortality in older people after adjustment for waist circumference. J Am Geriatr Soc. 2005;53:2112–8.
37. Baik I, Ascherio A, Rimm EB, Giovannucci E, Spiegelman D, Stampfer MJ, Willett WC. Adiposity and mortality in men. Am J Epidemiol. 2000;152:264–71.
38. Kuk JL, Katzmarzyk PT, Nichaman MZ, Church TS, Blair SN, Ross R. Visceral fat is an independent predictor of all-cause mortality in men. Obesity (Silver Spring). 2006;14:336–41.
39. Moore SC. Waist versus weight: which matters more for mortality? Am J Clin Nutr. 2009;89:1003–4.
40. Heymsfield SB, Martin-Nguyen A, Fong TM, Gallagher D, Pietrobelli A. Body circumferences: clinical implications emerging from a new geometric model. Nutr Metab (Lond). 2008;5:24.
41. Shen W, Punyanitya M, Wang Z, Gallagher D, St-Onge MP, Albu J, Heymsfield SB. Total body skeletal muscle and adipose tissue volumes: estimation from a single abdominal cross-sectional image. J Appl Physiol. 2004;97:2333–8.
42. WHO Expert Consultation. Appropriate body-mass index for Asian populations and its implications for policy and intervention strategies. Lancet. 2004;363:157–63.
43. Deurenberg-Yap M, Schmidt G, van Staveren WA, Deurenberg P. The paradox of low body mass index and high body fat percentage among Chinese, Malays and Indians in Singapore. Int J Obes Relat Metab Disord. 2000;24:1011–7.
44. Razak F, Anand SS, Shannon H, Vuksan V, Davis B, Jacobs R, Teo KK, McQueen M, Yusuf S. Defining obesity cut points in a multiethnic population. Circulation. 2007;115:2111–8.
45. Lear SA, Toma M, Birmingham CL, Frohlich JJ. Modification of the relationship between simple anthropometric indices and risk factors by ethnic background. Metabolism. 2003;52:1295–301.
46. Carroll JF, Chiapa AL, Rodriquez M, Phelps DR, Cardarelli KM, Vishwanatha JK, Bae S, Cardarelli R. Visceral fat, waist circumference, and BMI: impact of race/ethnicity. Obesity (Silver Spring). 2008;16:600–7.
47. Zhu S, Heymsfield SB, Toyoshima H, Wang Z, Pietrobelli A, Heshka S. Race-ethnicity-specific waist circumference cutoffs for identifying cardiovascular disease risk factors. Am J Clin Nutr. 2005;81:409–15.