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The site of waist measurement impacts the estimation of visceral fat: results from three-dimensional photonic body scanning

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Abstract

Currently, various protocols regarding the site of waist circumference (WC) measurement are in place. This study aimed to analyse the effect of the site of WC measurement on visceral adipose tissue (VAT) estimation. WC was obtained at 7 anatomical sites in 211 German volunteers (103 males) aged 23–81 years using three-dimensional photonic body scanning (PBS). At one site, WC was additionally measured by tape. The quantity of VAT was assessed by MRI. Models to estimate VAT based on WC were developed; the precision of the estimation is represented by R^2. The influence of the applied method of WC assessment (tape *v.* PBS) on the estimations is reported. Results show that the amount of estimated VAT and the precision of VAT estimation were dependent on the site of measurement. VAT was estimated most precisely by WC taken at the level of the lowest rib (WC_{rib}: $R^2 = 0{\cdot}75$ females; 0·79 males), the minimum circumference (WC_{min}: $R^2 = 0{\cdot}75$ females; 0·77 males) and at the narrowest part of the torso (WC_{nar}: $R^2 = 0{\cdot}76$ females; 0·77 males), and least precisely by WC assessed at the top of iliac crest (WC_{iliac}: $R^2 = 0{\cdot}61$ females; 0·60 males). VAT estimates based on WC obtained by PBS were smaller and estimations were slightly less precise compared to estimates based on tape measures. Our results indicate that the method and the site of waist measurement should be considered when estimating VAT based on WC. The implementation of a standardised protocol using either WC_{rib}, WC_{min} or WC_{nar} could improve the precision of VAT estimation.

Key words: Waist circumference: Visceral fat: Tape measurement: Site of waist measurement: Photonic body scanning

Overweight and obesity are associated with an increased risk for the development of metabolic disorders and CVD[1]. The pattern of fat distribution is particularly important for risk stratification: While ‘subcutaneous fat tissue’ or ‘subcutaneous adipose tissue’ (SAT) is located directly under the skin, ‘visceral fat tissue’ or ‘visceral adipose tissue’ (VAT) is located within the intraperitoneal and retroperitoneal space of the abdominal cavity. An increased amount of VAT is associated with type 2 diabetes mellitus[2], the occurrence of coronary artery disease[3] and cerebral small vessel disease[4], as well as with increased cardiovascular[5] and all-cause mortality[6]. Furthermore, evidence suggests that the ratio of VAT and abdominal SAT correlates with cardiometabolic risk[7].

The quantity of VAT and SAT is most accurately assessed by MRI or computed tomography[8]. Since computed tomography entails radiation and both methods are expensive and often not available in clinical practice or research settings, anthropometric parameters are commonly used to estimate the amount of VAT and the ratio of VAT/SAT. While waist circumference (WC), hip circumference (HC) and thigh circumference are all correlated with VAT and abdominal SAT[9], VAT is most accurately estimated by WC alone[10,11]. Abdominal SAT is strongly correlated with HC and thigh circumference, independent from WC[9].

Within the medical community, the measurement of WC is a widely accepted tool for the estimation of VAT and resulting

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Abbreviations: HC, hip circumference;; NIH, National Institutes of Health;; PBS, photonic body scanning;; SAT, subcutaneous adipose tissue;; SHIP, Study of Health in Pomerania;; VAT, visceral adipose tissue;; WC, waist circumference.

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cardiometabolic risk, and its use is recommended by leading health organisations[12]. However, cut-off values for WC identifying individuals with increased metabolic risks differ across recommending organisations. For Caucasians, three different recommendations for WC cut-offs are currently in place: 94 cm for males and 80 cm for females according to the protocol of the International Diabetes Federation (IDF)[13] and 102 cm for males and 88 cm for females according to the protocol of the National Institutes of Health (NIH)[12]. The WHO suggests using a graded risk assessment scheme proposing cut-off values of 94 cm (males) and 80 cm (females) to identify subjects with 'increased risk' and 102 cm (males) and 88 cm (females) to identify subjects with 'substantially increased risk'[14].

Furthermore, no unified measurement protocol determining the anatomical site of WC measurement is currently in place: The WHO[14], the European Society of Cardiology[15] and the IDF[13] recommend to measure WC midway between the iliac crest and the lower rib. The NIH[16], in contrast, recommends to measure WC on top of the iliac crest. In clinical practice and in research settings, further sites of waist measurement are in use, for example, the minimum WC[17], WC at the level of the lowest rib[18] or at the umbilicus[19].

Motivated by the widespread use of WC for the estimation of VAT, VAT/SAT and related cardiometabolic risk in the absence of a unified measurement protocol for WC, we used three-dimensional (3D) photonic body scanning (PBS) to acquire a variety of anthropometric parameters including WC at seven sites of waist measurement and MRI to quantify VAT and abdominal SAT. We analysed the impact of the site of WC measurement on the estimation of VAT and the VAT/SAT ratio. We further investigated the influence of sex, age, the extent of obesity and the method of WC measurement (PBS *v.* tape) on the precision of VAT estimation. Since this is the first study to use PBS for this purpose, we also present results from PBS validation. To allow for comparison of our results with studies that use manual tape measurements for the assessment of WC, we chose to only use WC measures that were obtained in reference to anatomic landmarks and can be reproduced by manual tape measurements.

Subjects and methods

Study population

The Study of Health in Pomerania (SHIP) is a population-based longitudinal study in north-eastern Germany that consists of two cohorts: SHIP and SHIP-Trend. Between 2008 and 2012, 2333 persons took part in the second follow-up examination of SHIP (SHIP-2) and 4420 persons took part in the baseline examinations of SHIP-Trend (SHIP-Trend-0)[20]. Both cohorts had been drawn from population registries, including subjects aged 20–79 years who held the German citizenship and had their main residence in the study region. All participants were Caucasian. The study was approved by the Ethics Committee of the University of Greifswald according to the principles of the Declaration of Helsinki and all participants gave their written informed consent.

All participants of SHIP-2 and SHIP-Trend underwent a set of exams including anthropometry. Whole-body MRI was offered as an optional exam to all participants of the SHIP. PBS was introduced as a pilot study in 2011 and was then offered as a further optional exam to participants on the day of their general SHIP examination. Out of 531 subjects who volunteered to undergo PBS, 221 had whole-body MRI scans within 60 d (median 8 d). Ten participants had to be excluded from the analyses due to incorrect PBS measures of WC, leaving a final study population of 211 participants (103 males) aged 23 to 77 years (online Supplementary Fig. 1).

Assessments

Anthropometry. Body height and weight were assessed using calibrated scales within the SHIP standard examination programme. Height was measured to the nearest centimetre, and weight of subjects in underwear was measured to the nearest 0·1 kg. The BMI was calculated: $BMI = weight(kg)/(height(cm))^2$.

WC and HC by manual tape measures and PBS were assessed by one out of three trained and certified examiners. For both procedures, subjects were asked to stand upright, feet shoulder-width apart, and to continue to breathe normally. WC and thigh circumference were measured directly on the skin; HC was measured over tight-fitting undergarments.

Manual tape measures and placement of physical markers. WC and HC were obtained according to the SHIP study protocol: The lowest (10th) rib and the iliac crest were palpated in the mid-axillary line. Standardised adhesive hemispheres (physical markers) were placed on these anatomical landmarks.

WC was measured with a flexible non-elastic tape at the narrowest part of the torso between the iliac crest and the lowest rib when regarding the upright standing participant from behind. In participants who did not have a recognisable narrowest part, $WC_{SHIP\text{-}tape}$ was measured midway between the iliac crest and the lowest rib. For tape measurement of HC, the iliac crest was palpated; $HC_{SHIP\text{-}tape}$ was measured midway between the iliac crest and the trochanter major. Measurement planes for $WC_{SHIP\text{-}tape}$ and $HC_{SHIP\text{-}tape}$ were marked with adhesive physical markers. Results of tape measurements were entered into the database before carrying out PBS.

Three-dimensional photonic body scanning. PBS was carried out using a VITUS Smart XXL body scanner with AnthroScan software (version 2·9·10; Human Solutions). The device has been validated for the measurement of body circumferences before[21,22].

PBS uses a system of laser emitters and cameras to obtain information on a person's body surface. Within the software, a 3D representation of the scanned person is constructed and subsequent identification of anatomical landmarks allow for the extraction of body circumferences at all commonly used sites of waist or hip measurement.

A full scan takes approximately 12 s and was conducted on the standing, upright subject. Arms were abducted 30–45° from the body to minimise the casting of shadows on the trunk. The resulting 3D images were checked for quality (position of the scanned person, integrity of the scan and potential shadows on scanned surface) after the scanning process. Physical markers that adhered to the participant's skin during the scan were identified on the 3D image by the examiner and matched to the corresponding measurement planes or anatomic landmarks, respectively.

Body circumferences were calculated at the height of the applied physical markers which corresponded to the level of manual hip ($HC_{SHIP\text{-}PBS}$) and waist measurements ($WC_{SHIP\text{-}PBS}$), to the iliac crest (WC_{iliac}) and to the lowest rib in the mid-axillary line (WC_{rib}). Additionally, WC was calculated midway between the iliac crest and the lowest rib (WC_{mid}), at the narrowest part of the torso between the lowest rib and the iliac crest when regarding the upright standing subject from behind (WC_{nar}), at the minimum circumference (WC_{min}), and at the maximum circumference (WC_{max}) between the iliac crest and the lowest rib. The maximum circumference of the hip (HC_{max}) between the iliac crest and the crotch was extracted. Thigh circumference was measured shortly below the crotch, according to a proprietary algorithm provided by the AnthroScan software.

Plausibility and quality control of anthropometric measures. Measures < 70 cm or > 120 cm for any WC and < 90 cm or > 120 cm for any HC were compared with tape measures that had been obtained of the participant on the same day during the standard examination programme of the SHIP. The procedure was repeated for $WC_{SHIP\text{-}tape}$ and $HC_{SHIP\text{-}tape}$ measures that deviated more than 3 cm from $WC_{SHIP\text{-}PBS}$ or $HC_{SHIP\text{-}PBS}$ measures, respectively. Finally, all measurement lines of PBS measures used for this analysis were displayed using the AnthroScan software and were checked visually for integrity from two perspectives to detect possible artefacts, on the surface of the 360° 3D model of the scanned person and in transversal slices. The last step allowed for detection of errors that were too discrete to be detectable by previously conducted plausibility control.

Assessment of visceral adipose tissue and subcutaneous adipose tissue by MRI. MRI examinations were performed on a 1·5-Tesla MR system (Magnetom Avanto, Siemens Healthcare AG, software version syngo MR B15), using a body-phased array coil.

Visceral and subcutaneous fat volumes were determined using a two-echo chemical shift-encoded gradient echo sequence in axial orientation acquired by covering the abdomen in three stacks (each with 64 slices) with the following imaging parameters: repetition time: 7·5 ms; echo time: 2·4/4·8 ms; flip angle: 10°; voxel size: 1·64 × 1·64 × 3·0 mm; slice gap: none; field of view: 420 × 288 mm; matrix: 256 × 120; bandwidth: 290 Hz per pixel; and parallel imaging with an effective acceleration factor of 2·0. The Automatic Tissue and Labelling Analysis Software (ATLAS), an in-house developed software at the University of Ulm, was then applied for quantification of VAT and abdominal SAT volume. The software first performs a fully automated scan[23] followed by a manual correction of the results. The manual correction included setting the upper (left diaphragm) and lower margins (bladder) for the abdominal fat analyses, correcting misclassified fat labels and removing fat labels that did not belong to the abdomen (i.e. arms, breast fat and parenchyma, bone marrow of pelvis and spine). It was performed by certified medical students (intraclass correlation coefficient > 0·997). VAT and abdominal SAT are presented as volumes in litres (l).The results of anthropometry were unknown to the students performing the validation and manual correction of VAT and SAT quantification, and VAT and SAT volumes were unknown to the examiners of anthropometry.

Statistical analyses

Participant's characteristics are presented as median with 25th and 75th percentiles; medians of males and females were compared using Mann–Whitney *U* test. All further statistical analyses were conducted stratified by sex. The means of WC obtained at different sites of waist measurement were compared by paired *t* tests.

Comparison of photonic body scanning with manual tape measurements. Due to one missing value in $HC_{SHIP\text{-}PBS}$, comparison of HC was conducted on 210 participants (103 males). WC measures obtained by PBS were compared with measures obtained by manual tape measurement using Bland–Altman plots[24]. A linear regression line was added to the plot to display the change of measurement differences depending on the mean of measurements from both methods. The means of $WC_{SHIP\text{-}PBS}$ and $WC_{SHIP\text{-}tape}$ and the means of $HC_{SHIP\text{-}PBS}$ and $HC_{SHIP\text{-}tape}$ were compared by paired *t* tests.

Estimation of visceral adipose tissue by waist circumference and estimation of visceral adipose tissue/subcutaneous adipose tissue by anthropometric ratios. Univariate regression models were used to investigate the relationship of WC with VAT and of anthropometric ratios with VAT/SAT. Fractional polynomials up to three DOF were tested at a level of significance of 0·1 to account for potential non-linear associations of the exposures with the outcomes[25]. Normal distribution of the residuals was checked using k-density plots and q-q plots, and homoscedasticity was checked using fitted values *v.* residuals plots. Since data proved to be heteroscedastic, the dependent variable was transformed according to the following transformations: $1/(VAT)$, $\log(VAT)$, $1/\log(VAT)$, $\ln(VAT)$, $1/\ln(VAT)$, $\sqrt{(VAT)}$, $1/\sqrt{(VAT)}$, $\sqrt[3]{(VAT)}$, $1/\sqrt[3]{(VAT)}$, $(VAT)^2$, $1/(VAT)^2$, $(VAT)^3$, $1/(VAT)^3$. Fractional polynomial regression analyses and analyses of residuals were repeated for the transformed outcomes. $Sqrt(VAT)$ showed a linear relationship with WC; residuals of linear regression associating WC with $sqrt(VAT)$were normally distributed and close to homoscedasticity and, thus, $sqrt(VAT)$ was used as dependent variable (online Supplementary Fig. 2 and 3). The coefficient of determination (R^2) was assessed to gain information on the accuracy of the models. The analyses were repeated adjusting the models for age. Sensitivity analyses were conducted, adjusting the models additionally for the period of time (in days) between anthropometry and MRI. In a further step, linear regression analyses were repeated stratified for age < 45 years and ≥ 45 years.

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Due to incomplete datasets of three subjects with missing values for either $HC_{SHIP\text{-}PBS}$, HC_{max} or SAT, analyses were conducted on 208 subjects (102 males). VAT/SAT was predicted by a variety of waist-to-hip ratios and by waist-to-thigh ratio. Fractional polynomial analyses associating anthropometric ratios with $sqrt(VAT/SAT)$ were conducted. Residuals were approximately normally distributed and homoscedastic. In case of non-linearity, the independent variable was transformed. R^2 was assessed.

To calculate estimates for VAT corresponding to values of WC obtained at different sites of waist measurement, the regression function $\widehat{E}(\sqrt{(VAT)}) = \beta * WC + b$ was transformed to $\widehat{E}(VAT) = (\beta * WC + b)^2$. The functions were plotted. VAT estimates with 95 % CI corresponding to cut-off values for WC (80 cm and 88 cm in females; 94 cm and 102 cm in males) were calculated.

To display the models' error depending on the extent of abdominal obesity, lower bound ($LB = (\beta * WC + b - (1.96 * RMSE))^2$) and upper bound ($UB = (\beta * WC + b + (1.96 * RMSE))^2$) of the 95 % CIs for the observed values were calculated and the functions were plotted. 95 % CI for and WC values corresponding to exemplary VAT estimates were calculated.

All statistical analyses were conducted using Stata/IC 16.1 (Stata Corporation).

Results and discussion

For the present study, we analysed data of 211 participants of the SHIP, 108 females aged 24–74 years and 103 males aged 23–77 years. Among male participants, 57·3 % were overweight (BMI > 25·0 kg/m^2) and 21·4% were obese (BMI > 30 kg/m^2) compared with 26 % overweight and 19·4% obese females. Males had significantly higher VAT volumes and larger WC than females (Mann–Whitney U test: $P < 0.001$), while females had slightly higher SAT volumes. Further characteristics of the study population are presented in Table 1.

The results of this study show that WC measurements vary considerably according to the site of waist measurement. With the exception of WC_{rib} and $WC_{SHIP\text{-}PBS}$ in males, mean WC obtained at the various sites of waist measurement were significantly different from each other (paired t tests: $P < 0.05$; online Supplementary Table 1). Maximum differences were more pronounced in females (WC_{min} = 84·3 cm; WC_{max} = 94·7 cm; difference = 10·4 cm) compared with males (WC_{min} = 97·0 cm; WC_{max} = 101·2 cm, difference = 4·2 cm) which is in line with observations from previous studies[26,27].

Estimation of visceral adipose tissue by waist circumference

Consequently, VAT estimates corresponding to given WC values can be expected to vary depending on the site of waist measurement and variation can be expected to be more pronounced in women than in men. These assumptions were confirmed by our analyses. Figure 1 shows VAT estimates plotted against WC obtained at different sites of waist measurement. While plotted VAT estimates are relatively close in men, they are distinctly spread in women.

To demonstrate the implications of these findings for the application of WC cut-offs and their ability to identify individuals with elevated VAT and entailed cardiometabolic risk, we calculated VAT estimates corresponding to established cut-off values for all sites of waist measurement (Table 2).

In males and females, the biggest differences in VAT estimates corresponding to a single WC cut-off value were found for VAT estimates based on WC_{min} compared with VAT estimates based on WC_{max}. Absolute differences were similar in females and males; however, due to the much smaller amount of VAT in females, proportional differences among VAT estimates were considerably more prominent in females than in males: In males, VAT estimates were up to 19 % higher at a WC of 102 cm (VAT(WC_{max}) = 4·76; VAT(WC_{min}) = 5·68 l; difference = 0·92 l) and 23 % at a WC of 94 cm (VAT(WC_{max}) = 3·27 l; VAT(WC_{min}) = 4·01 l; difference = 0·74 l) depending on the site of waist measurement. In females, VAT estimates were up to 84 % higher at a WC of 88 cm (VAT(WC_{max}) = 1·28 l; VAT(WC_{min}) = 2·36 l; difference = 1·08 l) and 114 % at WC of 80 cm (VAT(WC_{max}) = 0·69 l; VAT(WC_{min}) = 1·48 l; difference = 0·79 l) depending on the sites of waist measurement.

The observed sex-specific differences have further impact when applying the most commonly used measurement protocols for Caucasians; the IDF protocol (WC_{mid} and cut-off at 80 cm in females; 94 cm in males) and the NIH protocol (WC_{iliac} and cut-off at 88 cm in females; 102 cm in males). When strictly adhering to these protocols, resulting VAT estimates are similar in females (IDF: VAT = 1·13 (CI: 0·99, 1·28); NIH: VAT = 1·30 (CI: 1·14, 1·47)) but are significantly different from each other in males (IDF: VAT = 3·66 (CI 3·42, 3·90; NIH: VAT = 4·97 (CI: 4·69, 5·26)).

The opposite can be observed when using either WC_{mid} or WC_{iliac} in combination with one common cut-off value. When applying, for example, the IDF cut-off of 80 cm in females and 94 cm in males to WC obtained at both sites, resulting VAT estimates are comparable in males (WC_{mid}: VAT = 3·66 (CI: 3·42, 3·90); WC_{iliac}: VAT = 3·44 (CI: 3·16, 3·72)) while they are significantly different from each other in females (WC_{mid}: VAT = 1·13 (CI: 0·99, 1·28); WC_{iliac}: VAT = 0·70 (CI: 0·54, 0·88)).

These findings imply that the site of WC has more impact on VAT estimation in females compared with males. They underline the necessity of standardising the site of WC measurement to allow for a more reliable VAT estimation. During this process, the accuracy to estimate VAT should be considered. Until a unified protocol for the site of waist measurement is in place, a temporary solution to allow for comparison of waist measurements obtained by the two protocols might be to adhere strictly to the IDF and WHO protocols including the cut-off values mentioned above in females and to agree either on a 94-cm or 102-cm cut-off independent on the site of measurement in men. However, the feasibility of this 'work-around' should be tested in representative population-based studies first.

Accuracy of visceral adipose tissue estimation by waist circumference

In this study population, the accuracy of VAT estimations based on WC was dependent on the site of WC measurement. R^2 values

Table 1. Age, anthropometric characteristics, VAT and SAT of the study population

	Females (*n* 108)		Males (*n* 103)		
	Median	25th, 75th percentile	Median	25th, 75th percentile	*P*-value
Age (years)	46	40, 55	45	40, 57	0·98
Weight (kg)	66·9	59·9, 76·4	86·7	78·9, 96·8	< 0·001
Height (cm)	165	160, 169	179	173, 182	< 0·001
BMI (kg/m^2)	24·6	22·1, 28·3	27·7	25·6, 29·8	< 0·001
$WC_{SHIP\text{-}tape}$ (cm)*	80·5	74·0, 91·5	96·5	88·8, 104·0	< 0·001
$WC_{SHIP\text{-}PBS}$ (cm)*	83·7	76·0, 96·2	98·6	90·7, 106·1	< 0·001
WC_{rib} (cm)†	81·5	75·2, 93·1	99·1	90·8, 106·2	< 0·001
WC_{mid} (cm)‡	86·4	80·0, 98·0	99·3	91·3, 106·1	< 0·001
WC_{iliac} (cm)§	92·8	85·7, 101·8	100·2	93·5, 105·7	< 0·001
WC_{min} (cm)‖	81·0	74·7, 92·6	97·6	90·2, 104·0	< 0·001
WC_{nar} (cm)¶	81·5	74·7, 93·2	97·6	90·5, 105·4	< 0·001
WC_{max} (cm)**	92·9	85·6, 103·1	101	95·6, 107·6	< 0·001
$HC_{SHIP\text{-}tape}$ (cm)††	99·4	92·7, 106·6	100·5	97·0, 105·0	0·18
$HC_{SHIP\text{-}PBS}$ (cm)††	101·1	94·4, 108·7	102·7	98·1, 105·7	0·28
HC_{max} (cm)‡‡	105·3	100·7, 112·8	105·7	101·9, 110·5	0·89
TC (cm)§§	56·8	53·6, 60·5	56·8	54·7, 59·3	0·93
VAT (l)	1·8	0·9, 3·3	4·5	3·0, 6·1	< 0·001
Abdominal SAT (l)	7·1	5·4, 10·6	6·7	5·0, 8·7	0·09

VAT, visceral adipose tissue; SAT, subcutaneous adipose tissue; WC, waist circumference; HC, hip circumference; TC, thigh circumference.
Data are given as median, 25th and 75th percentile. *P*-values assessed by Mann–Whitney *U* test.
* $WC_{SHIP\text{-}tape}$ and $WC_{SHIP\text{-}PBS}$ were measured at the narrowest part between the lowest rib and the iliac crest. If no narrowest part was detectable, WC was measured midway between the lowest rib and the iliac crest.
† WC_{rib}: WC at level of lowest rib.
‡ WC_{mid}: WC midway between lowest rib and iliac crest.
§ WC_{iliac}: WC at level of iliac crest.
‖ WC_{min}: minimum WC.
¶ WC_{nar}: WC at narrowest part of torso.
** WC_{max}: maximum WC.
†† $HC_{SHIP\text{-}tape}$ and $HC_{SHIP\text{-}PBS}$ were measured midway between the iliac crest and the trochanter major.
‡‡ HC_{max} was measured at the maximum circumference between the iliac crest and the crotch.
§§ TC was measured shortly below the crotch.

from univariate linear regression analyses estimating $sqrt(VAT)$ by WC are presented in Table 3.

In females, the highest R^2 values were found in models based on WC_{nar} ($R^2 = 0{\cdot}76$), WC_{min} ($R^2 = 0{\cdot}75$) or WC_{rib} ($R^2 = 0{\cdot}75$), and the lowest R^2 were observed for analyses based on WC_{iliac} ($R^2 = 0{\cdot}64$). In males, the highest R^2 was observed for models associating $sqrt(VAT)$ with WC_{rib} ($R^2 = 0{\cdot}79$), WC_{min} ($R^2 = 0{\cdot}77$) or WC_{nar} ($R^2 = 0{\cdot}77$), while the lowest R^2 was observed for models using WC_{iliac} ($R^2 = 0{\cdot}66$) as the independent variable. Additional adjustment of the models for age lead to slightly higher R^2 in females independently of the site of waist measurement, and slightly increased R^2 of models based on WC_{iliac} and WC_{max} in males. In sensitivity analyses, additional adjustment for the time difference (in days) between anthropometric measurements and the MRI examination did not change the results substantially (difference in $R^2 \leq 0{\cdot}01$; online Supplementary Table 2).

Analyses stratified by sex and age confirmed the overall higher accuracy of VAT estimations based on WC_{rib}, WC_{min} or WC_{nar} compared with other sites of WC measurement (Table 4). Analyses showed that independent of the site of waist measurement, R^2 was higher for univariate linear regression models based on data of younger males (≤ 45 years) compared with models based on data of older males (> 45 years). In both age strata, the highest R^2 was attained by models based on WC_{rib}, while the lowest R^2 was observed for models based on WC_{iliac}. In females, the highest R^2 was observed for models associating WC_{min} or WC_{nar} with $sqrt(VAT)$ in both strata and was only slightly lower for females > 45 years. In contrast, R^2 of models based on WC_{max} or WC_{iliac} were considerately lower when based on data of older females (> 45 years) compared with models based on data of younger females (≤ 45 years). The distinct decrease of accuracy of VAT estimation for WC taken at the lower abdomen (WC_{max} and WC_{iliac}) in females might be explained by the slackening of connective tissue and abdominal muscles of the lower abdomen after giving birth. Sex differences were further observed when additionally adjusting the regression model for age: the accuracy in females increased while it was unchanged in males. These sex-specific differences might be explained by a more pronounced increase in WC[28] and VAT[29] with increasing age in females compared with males.

Anthropometric ratios only showed moderate model fit for the relation of visceral to abdominal subcutaneous fat (Table 5). Like for the estimation of VAT alone, estimations of VAT/SAT were more accurate when based on anthropometric ratios using WC_{rib}, WC_{nar} or WC_{min}: In females, the highest R^2 was observed for models associating $sqrt(VAT/SAT)$ with waist-to-hip ratio based on WC_{min} or WC_{nar} and HC_{max} ($R^2 = 0{\cdot}47$). In males, the highest R^2 was observed for models associating $sqrt(VAT/SAT)$ with weight-to-thigh ratio based on WC_{rib} and thigh circumference ($R^2 = 0{\cdot}40$).

To date, only few studies directly investigated the impact of different sites of WC measurement on the correlation of WC with VAT. Although results from these studies cannot be directly compared with this study or to each other due to heterogenous measurement protocols and study populations, it is of note that all the studies we

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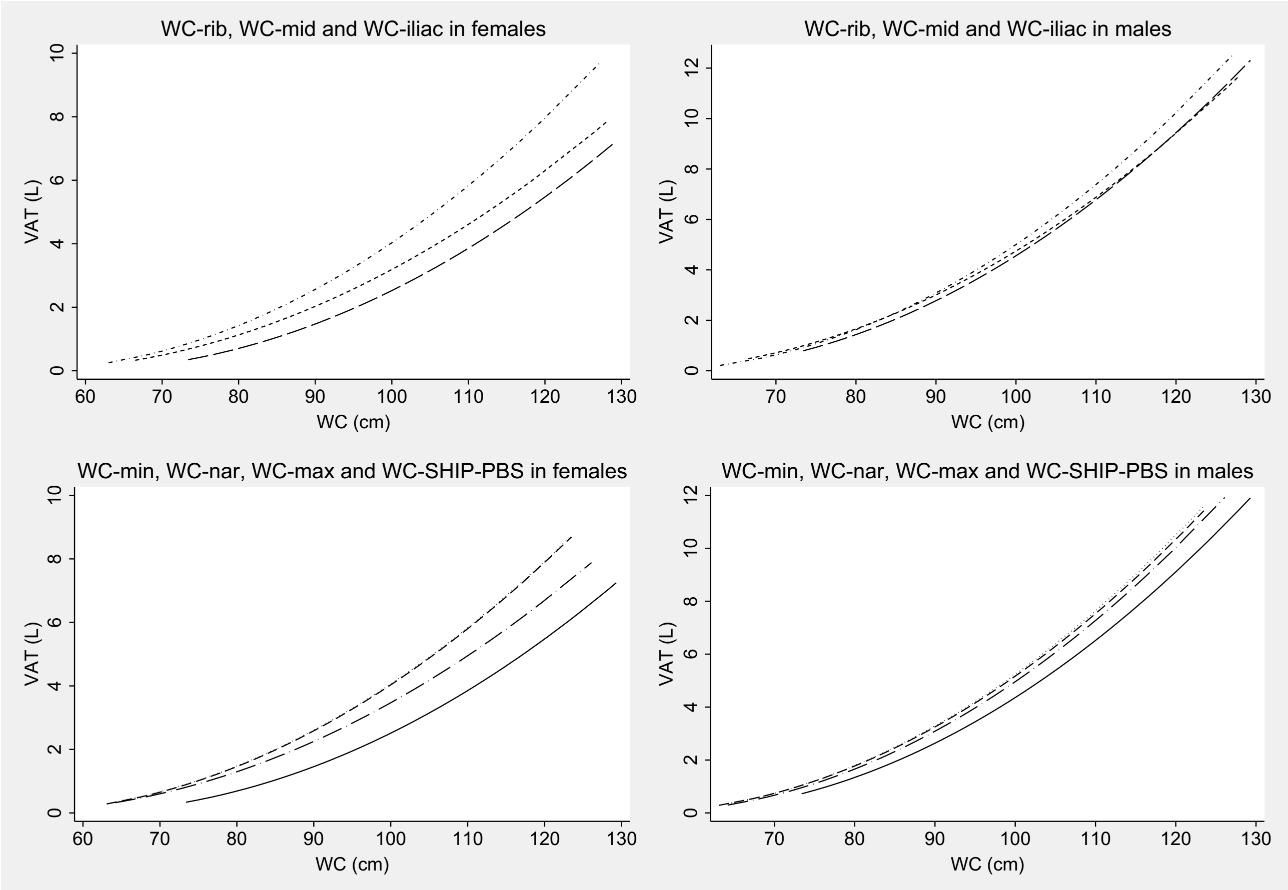

Fig. 1. VAT estimates corresponding to WC obtained at different sites of waist measurement. VAT estimates were obtained by transformation of the univariate regression function $\widehat{E}(\sqrt{(VAT)}) = \beta * WC + b$ to $\widehat{E}(VAT) = (\beta * WC + b)^2$. Line plots based on WC_{min} and WC_{nar} overlap. WC-rib ·····; WC-mid ·········; WC-iliac –––; WC-min ; WC-nar ----; WC-SHIP-PBS – –; WC-max ——. VAT, visceral adipose tissue; WC, waist circumference; SHIP, The Study of Health in Pomerania; PBS, photonic body scanning

Table 2. VAT estimates with 95 % CI corresponding to cut-off values of WC

	Females (*n* 108) VAT estimates (l) corresponding to:				Males (*n* 103) VAT estimates (l) corresponding to:			
	WC of 80 cm		WC of 88 cm		WC of 94 cm		WC of 102 cm	
	VAT	95 % CI	VAT	95 % CI	VAT	95 % CI	VAT	95 % CI
$WC_{SHIP\text{-}tape}$	1·55	1·41, 1·69	2·45	2·28, 2·63	4·12	3·91, 4·34	5·87	5·58, 6·16
$WC_{SHIP\text{-}PBS}$	1·30	1·16, 1·44	2·04	1·88, 2·20	3·78	3·55, 4·02	5·39	5·12, 5·66
WC_{rib}	1·43	1·29, 1·57	2·31	2·15, 2·48	3·80	3·59, 4·01	5·44	5·20, 5·70
WC_{mid}	1·13	0·99, 1·28	1·83	1·67, 1·99	3·66	3·42, 3·90	5·14	4·88, 5·41
WC_{iliac}	0·70	0·54, 0·88	1·30	1·14, 1·47	3·44	3·16, 3·72	4·97	4·69, 5·26
WC_{min}	1·48	1·34, 1·61	2·36	2·19, 2·53	4·01	3·80, 4·23	5·68	5·41, 5·96
WC_{nar}	1·46	1·33, 1·60	2·34	2·17, 2·50	3·96	3·75, 4·18	5·60	5·34, 5·88
WC_{max}	0·69	0·53, 0·84	1·28	1·12, 1·45	3·27	3·01, 3·54	4·76	4·50, 5·01

VAT, visceral adipose tissue; WC, waist circumference.
Values for VAT are given in litres (l).
VAT estimates and 95 % CIs for VAT estimations are based on univariate regression analyses.

reviewed for this article found either WC_{iliac} or WC at the level of the umbilicus to be the least correlated with VAT. In three of these studies, WC_{min}[27,30], WC_{rib}[26] and WC_{mid}[26] demonstrated the strongest correlations with VAT and two studies that assessed neither WC_{min} nor WC_{rib} found VAT to be better correlated with WC_{mid}[31,32] or WC_{nar}[32] compared with WC_{iliac} or WC obtained at the level of the umbilicus.

Studies that investigated the correlation of the amount of VAT with WC obtained at one site of waist measurement observed correlation coefficients ranging from 0·73 ($R^2 = 0·55$) to 0·87

Table 3. Coefficient of determination (R^2) of linear regression models estimating $sqrt(VAT)$

	Females (*n* 108)		Males (*n* 103)	
	WC*	WC and age†	WC*	WC and age†
WC$_{\text{SHIP-tape}}$	0·74	0·80	0·77	0·78
WC$_{\text{SHIP-PBS}}$	0·72	0·78	0·74	0·75
WC$_{\text{rib}}$	0·75	0·80	0·79	0·79
WC$_{\text{mid}}$	0·70	0·77	0·72	0·73
WC$_{\text{iliac}}$	0·64	0·72	0·66	0·70
WC$_{\text{min}}$	0·75	0·80	0·77	0·77
WC$_{\text{nar}}$	0·76	0·80	0·77	0·78
WC$_{\text{max}}$	0·65	0·73	0·70	0·72

WC, waist circumference.
* R^2 of univariate linear regression analyses using WC as independent variable.
† R^2 of linear regression analysis using WC & age as independent variables.

Table 4. Coefficient of determination (R^2) of univariate linear regression models estimating $sqrt(VAT)$ by WC, stratified by age

	Females		Males	
	≤ 45 years (*n* 51)	> 45 years (*n* 57)	≤ 45 years (*n* 53)	> 45 years (*n* 50)
WC$_{\text{SHIP-tape}}$	0·75	0·72	0·80	0·70
WC$_{\text{SHIP-PBS}}$	0·72	0·70	0·76	0·67
WC$_{\text{rib}}$	0·74	0·72	0·81	0·71
WC$_{\text{mid}}$	0·71	0·67	0·74	0·66
WC$_{\text{iliac}}$	0·68	0·57	0·68	0·64
WC$_{\text{min}}$	0·75	0·73	0·80	0·70
WC$_{\text{nar}}$	0·75	0·73	0·80	0·70
WC$_{\text{max}}$	0·69	0·59	0·71	0·66

WC, waist circumference.

($R^2 = 0{\cdot}76$) depending on the applied measurement protocol and the study population[10,11,17,18,19,33,34]. Among the identified studies, highest correlation coefficients were observed in studies using WC at the level of the lowest rib[10,18] or the minimum waist[34].

The plausibility of the results of this study is further supported by studies that used computed tomography to directly assess the amount of VAT and SAT at different levels of the abdomen. In both sexes, SAT was found to be more prevalent in the lower abdomen (L3–L5) compared with the upper abdomen (L1–L3)[35,36]. Contrary to the abdominal SAT distribution, the observed VAT distribution differed notably among the sexes[35,36]. While it was more evenly distributed in females peaking slightly at L4/5, in males VAT was distinctly more prevalent in slices obtained at the upper and middle abdomen (L1/2–L3/4) compared with the lower abdomen (L4–L5). When using WC obtained at the lower abdomen to estimate VAT, for example, at the level of the iliac crest which corresponds roughly to the level of L4/5, the higher proportion of SAT in the lower abdomen might contribute to increased error of the estimation. In males, the higher proportion of VAT in the upper abdomen might additionally increase the correlation of WC$_{\text{rib}}$ and WC$_{\text{mid}}$ with VAT.

Impact of the extent of central obesity on visceral adipose tissue estimation

To investigate how the extent of abdominal obesity affects the precision of VAT estimation, we analysed the distribution of residuals, that is, the difference between VAT estimates and the measured VAT values. We found that residuals of the linear regression model increased with increasing WC (online Supplementary Fig. 2 and 3: 'residuals *v.* fitted values plots'). This implicates that VAT estimation is more precise in slender individuals compared with centrally obese individuals. Commonly used linear models assume residuals and CI to be constant over the whole range of WC, which simulates equal precision of VAT estimation in individuals of all sizes. These findings indicate that a linear model might not be appropriate to estimate VAT.

Our relatively small sample size allowed only for limited exploration of alternative mathematical models, but we found that the transformation of the outcome VAT to $sqrt(VAT)$ enabled us to perform a simple linear regression resulting in normally distributed residuals that were approximately evenly distributed over the whole range of WC. In the next step, the retransformation of the regression function $sqrt(VAT) = \beta \times WC + b$ to $VAT = (\beta \times WC + b)^2$ permitted us to calculate and display the VAT estimates and corresponding CI for the observed values of VAT (online Supplementary Fig. 4 and 5) in a more realistic way than a linear regression model would allow for. Furthermore, we

Table 5. Coefficients of determination (R^2) of univariate regression models estimating $sqrt(VAT/SAT)$ using waist-to-hip ratio (WHR) and waist-to-thigh ratio (WTR)

	Females (*n* 106)	Males (*n* 102)
WC$_{\text{SHIP-tape}}$/HC$_{\text{SHIP-tape}}$	0·45	0·24
WC$_{\text{SHIP-PBS}}$/HC$_{\text{SHIP-tape}}$	0·39	0·19
WC$_{\text{rib}}$/HC$_{\text{SHIP-tape}}$	0·43	0·27
WC$_{\text{mid}}$/HC$_{\text{SHIP-tape}}$	0·34	0·17
WC$_{\text{iliac}}$/HC$_{\text{SHIP-tape}}$	0·21	0·10
WC$_{\text{min}}$/HC$_{\text{SHIP-tape}}$	0·44	0·24
WC$_{\text{nar}}$/HC$_{\text{SHIP-tape}}$	0·44	0·24
WC$_{\text{max}}$/HC$_{\text{SHIP-tape}}$	0·24	0·14
WC$_{\text{SHIP tape}}$/HC$_{\text{SHIP-PBS}}$	0·40	0·23
WC$_{\text{SHIP PBS}}$/HC$_{\text{SHIP-PBS}}$	0·36	0·18
WC$_{\text{rib}}$/HC$_{\text{SHIP-PBS}}$	0·39	0·26
WC$_{\text{mid}}$/HC$_{\text{SHIP-PBS}}$	0·32	0·16
WC$_{\text{iliac}}$/HC$_{\text{SHIP-PBS}}$	0·19	0·09
WC$_{\text{min}}$/HC$_{\text{SHIP-PBS}}$	0·41	0·23
WC$_{\text{nar}}$/HC$_{\text{SHIP-PBS}}$	0·42	0·23
WC$_{\text{max}}$/HC$_{\text{SHIP-PBS}}$	0·22	0·12
WC$_{\text{SHIP tape}}$/HC$_{\text{max}}$	0·45	0·31
WC$_{\text{SHIP PBS}}$/HC$_{\text{max}}$	0·43†	0·26
WC$_{\text{rib}}$/HC$_{\text{max}}$	0·46†	0·33
WC$_{\text{mid}}$/HC$_{\text{max}}$	0·37	0·24
WC$_{\text{iliac}}$/HC$_{\text{max}}$	0·30	0·19
WC$_{\text{min}}$/HC$_{\text{max}}$	0·47†	0·31
WC$_{\text{nar}}$/HC$_{\text{max}}$	0·47†	0·31
WC$_{\text{max}}$/HC$_{\text{max}}$	0·31	0·22
WC$_{\text{SHIP-tape}}$/TC	0·44	0·39*
WC$_{\text{SHIP-PBS}}$/TC	0·40	0·31
WC$_{\text{rib}}$/TC	0·44	0·40*
WC$_{\text{mid}}$/TC	0·38	0·30
WC$_{\text{iliac}}$/TC	0·30	0·28
WC$_{\text{min}}$/TC	0·45	0·38*
WC$_{\text{nar}}$/TC	0·45	0·38*
WC$_{\text{max}}$/TC	0·31	0·29

WC, waist circumference; HC, hip circumference.
R^2 assessed using linear univariate regression analysis with exception of:
* Transformation of the independent variable: WTR → $1/(\text{WTR})^2$.
† Transformation of the independent variable: WHR → $(\text{WHR})^3$.

calculated VAT estimates with 95 % confidence VAT values for exemplary WC values (online Supplementary Tables 3 and 4). According to our models, CI for VAT estimation broadened with increasing WC independent from the site of measurement but were narrower over the whole range of WC when based on WC_{rib}, WC_{min} or WC_{nar} compared with estimations based on WC_{mid}, WC_{max} or WC_{iliac}. This could be expected due to the overall more precise performance of WC_{rib}, WC_{min} and WC_{nar}.

We believe that the finding of a better fitting mathematical model might be possible within a population-based study with a bigger sample size. More realistic CI for VAT values could facilitate the finding of more reliable cut-off values for WC, help to reduce misclassifications and facilitate the decision-making progress on when to introduce further diagnostic or therapeutic interventions in individuals.

Photonic body scanning v. *tape measures*

WC is traditionally obtained by manual tape measures. The manual assessment of a large variety of WC, which is needed for comparative studies, is technically difficult and time-consuming. PBS facilitates this process: Once the markers to identify anthropometric reference points are placed and the scans conducted and stored, a multitude of highly standardised anthropometric measures can be extracted whenever needed. This way PBS enabled us to perform the present analyses at a time when we would not have had the personal resources to perform the measures manually.

To ensure comparability of results, measures obtained by PBS were contrasted with measures obtained by tape at one site of waist and hip measurement.

Means of anthropometric measures obtained by PBS differed significantly from means of anthropometric measures obtained by manual tape measurements (paired *t* tests: $P < 0{\cdot}001$). In males, mean $HC_{SHIP\text{-}PBS}$ was 1·5 cm higher; in females, mean $HC_{SHIP\text{-}PBS}$ was 1·4 cm higher than mean $HC_{SHIP\text{-}tape}$. Means of $WC_{SHIP\text{-}PBS}$ were 1·9 cm higher in males and 3·3 cm higher in females compared with mean $WC_{SHIP\text{-}tape}$. The difference between the two methods increased with increasing WC or HC values and was most pronounced in WC of females (Fig. 2).

These results are in line with a previously conducted study by Heuberger *et al.*[22] which compared waist and hip measures obtained by tape to measures obtained by the VITUS smart PBS device in a cohort of young females. In this study, WC and HC measures obtained by PBS were about 2·5 cm higher when compared with measures obtained by tape. This suggests that PBS might lead to systematically higher measures when compared with measures obtained by tape. In addition, we were able to show that the differences between manual and PBS measurements depended on the measured values themselves, which had not been investigated before: The differences between the methods increased with increasing body circumferences, particularly in WC in females.

With regard to its ability to estimate VAT, manual tape measures were slightly more accurate than measures obtained at the same site using PBS. In both, stratified and non-stratified analyses, linear regression models using WC obtained by tape to estimate $sqrt(VAT)$ had slightly higher R^2 than models using WC obtained at the same site of measurement using PBS (Tables 3 and 4). The ratios of VAT and abdominal SAT were estimated slightly more accurately by anthropometric ratios based on $WC_{SHIPtape}$ and $HC_{SHIPtape}$ than by ratios based on $WC_{SHIP\text{-}PBS}$ and $HC_{SHIP\text{-}PBS}$ (Table 5).

Although this observation might be attributed to chance, factors that lead to tape measures being systematically smaller than measures obtained by PBS might also have contributed to the improved discrimination between SAT and VAT by tape measures:

When horizontally applying the tape around the participant's body, a slight tightening of the tape is necessary to prevent it from slipping. According to examiners of the SHIP, WC measurement in subjects with larger body circumference is at times particularly challenging. In these cases, a horizontal application of the tape can only be achieved with increased pressure on the tape which may at times lead to the impression of abdominal SAT and skin which would reduce the measured WC. We further assume that the impression of tape measures is more pronounced with increasing amount and softness of the subcutaneous tissue. Especially in subjects with substantial amount of SAT, the tape might slip into skinfolds that are not recognised by PBS. Both the slipping of the tape into skinfolds and the impression of subcutaneous tissue by tape could accidently increase the discrimination between individuals with high amount of SAT and high amount of VAT.

The logistics of PBS examination might have further contributed to random error and thus led to decreased accuracy of VAT estimations when based on WC obtained by PBS: While both exams were conducted according to the same study protocol, examiners could correct the participants' posture and remind them to continue breathing calmly when taking the tape measurements. This possibility was limited during the 12-s body scan and possibly leads to waist being randomly scanned between maximum inspiration and expiration.

Furthermore, a contraction of the abdominal muscles might have occurred among a fraction of the participants during the manual measurement of WC, either as a reaction to being touched or as an attempt to reduce the measured WC values to conform to the ideal of a narrow waist. Although this might impact the systematic differences between manual and PBS measures, it should not increase accuracy of tape measures compared with measures obtained by PBS.

Logistic limitations

Due to logistic constraints, several methodological limitations related to data collection had to be accepted: Being a pilot study introduced during a running data collection, PBS examinations could only be offered to a limited number of participants of the SHIP and are thus not strictly representative for the general population. Though the study sample used for the analyses represents all age and BMI groups investigated in the population-based SHIP cohorts, this sample has a higher proportion of overweight and obese participants compared with the general north-eastern German population. Moreover, MRI examinations could only be scheduled on the same day of anthropometric examinations for 28 % of the participants which led to time differences

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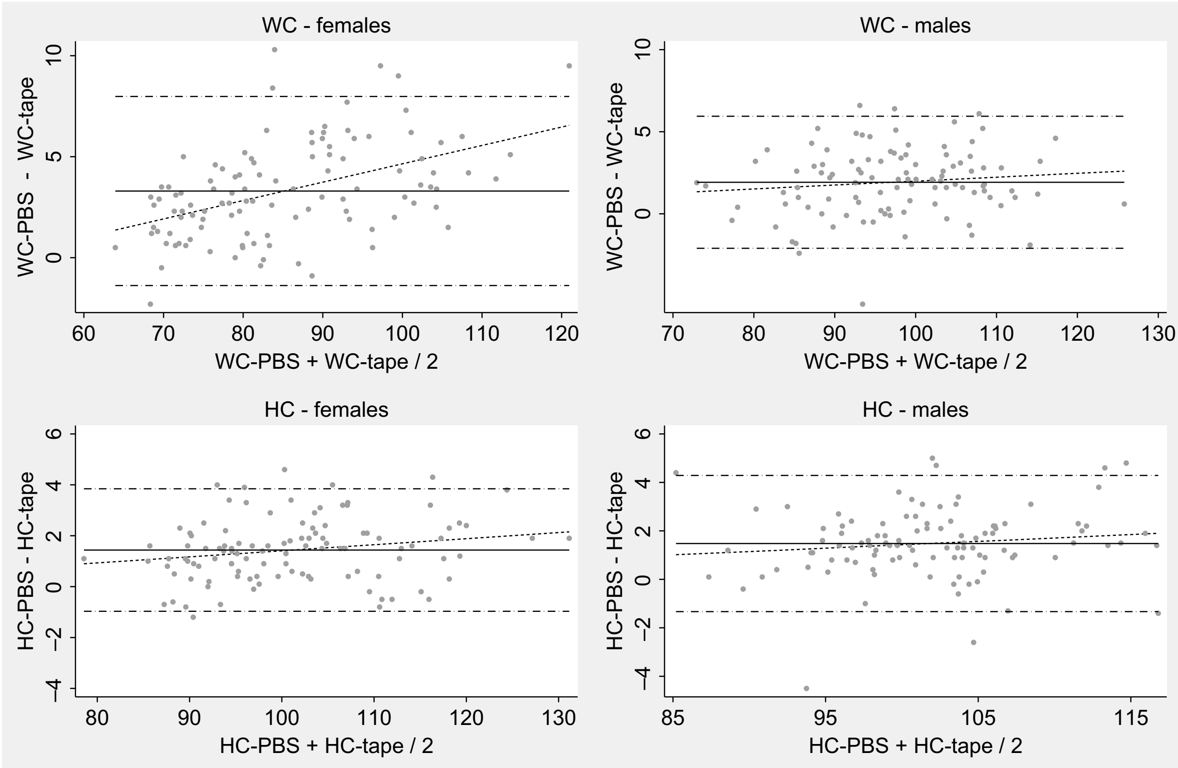

Fig. 2. Bland–Altman plots illustrating the point differences, mean differences and limits of agreements ($mean \pm 1.96 * SD$) between WC and HC measures obtained by PBS and WC and HC measures obtained by tape. A linear regression line was added to the plots to display the change of mean differences depending on the mean of measurements from both methods. Fitted values ········; Observed point differences ●; Mean ——; −1·96 SD – –; +1·96 SD – –. WC, waist circumference; HC, hip circumference; PBS, photonic body scanning

between the examinations for all others. However, sensitivity analysis showed that this did not influence the results of this study.

Although it is likely that constraints during data collection and measurement differences of PBS and tape measures resulted in random error and decreased the precision of VAT estimations, it is unlikely that the analysis of the impact of the site of waist measurement on the accuracy of VAT estimation was systematically biased.

Conclusion

The results of this study underline the importance of a standardisation of the site of measurement for WC. Until a standardised protocol is in place, WC cut-off values should only be used for VAT estimation when developed for or adapted to the applied protocol of waist measurement to prevent systematic over- or under-estimation of VAT and possibly cardiometabolic risk. Due to female body shape, this risk is particularly elevated in females.

The results of this and previously conducted studies strongly suggest that WC_{min} and WC_{nar} are more accurate estimators of VAT than WC_{max} and WCs obtained at the upper abdomen are more accurate VAT estimators than WCs obtained at the lower abdomen ($WC_{rib} > WC_{mid} > WC_{iliac}$).

Furthermore, WC obtained by manual tape measures proved to be a slightly more precise estimator of VAT than WC obtained by PBS at the same site. PBS was also susceptible to incorrect measures due to the casting of shadows and incorrect arm posture that were only detectable by thorough and time-consuming quality control. However, the possibility to assess WC at the narrowest part of the torso or the minimum circumference without needing to manually identify anatomic landmarks could, once stable and transparent algorithms are provided, facilitate methodological studies and promote the standardisation of WC measurement in multicentre studies and similar settings.

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K. R.: research design; quality control of anthropometric measures including PBS; data analysis; writing of the manuscript, primary responsibility for final content. D.R.: research design; supervision and quality control of anthropometric measurements including PBS, preparation and analysis of PBS data; writing of the manuscript. T. I.: data analysis and methodological consultation, review and editing of the manuscript. M. A.: data analysis and methodological consultation, review and editing

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of the manuscript. M. R. P. M.: research design and medical consultation, writing of the manuscript. E. T. S. H.: research design and methodological consultation, writing of the manuscript. N. F.: Supervision of VAT and SAT quantification, review and editing of the manuscript. R. B.: Supervision of MRI examinations and quality control of MRI data, review and editing of the manuscript. H.V.: research design and writing of the manuscript.

There are no conflicts of interest.

Supplementary material

For supplementary material/s referred to in this article, please visit https://doi.org/10.1017/S0007114521003123

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