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PRACTICE

Quantification of fat and skeletal muscle tissue at abdominal computed tomography: associations between single-slice measurements and total compartment volumes

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Abstract

Purpose Body composition is of great prognostic value in several severe diseases, including different types of cancer as well as cardiometabolic disorders. We aimed to investigate the correlations of skeletal muscle mass and abdominal adipose tissue compartments between volumetric and single-slice measurements to study the usefulness of several anatomical landmarks for estimation of total compartment volumes using abdominal CT-scans.

Methods In this retrospective study volumetric quantifications of paraspinal skeletal muscles (SM) and adipose tissue compartments (visceral adipose tissue, VAT; subcutaneous adipose tissue, SAT) were performed in 50 consecutive patients (26 male; mean age, 63 ± 15 years) who underwent abdominal multislice-CT for diagnostic purposes using an in-house software. Associations between total volumes of SM, VAT, and SAT with single-slice measurements at eight predefined anatomical landmarks (median intervertebral disk spaces T12/L1 to L5/S1; level of the umbilicus (U); level of the radix of the superior mesenteric artery (SMA)) were studied using correlation coefficients.

Results Statistical analysis revealed a strong association between single-slice measurements of adipose tissue compartments with total VAT and SAT volume (VAT: all $r > 0.89$, $P < 0.001$; SAT: all $r > 0.95$, $P < 0.001$). The strongest associations with total SM volume were found for single-slice measurements obtained at L3/4 ($r = 0.94$, $P < 0.001$) and were further improved by normalization to height ($r = 0.98$, $P < 0.001$).

Conclusions Single-slice measurements of SM, VAT, and SAT at several anatomical landmarks are strongly associated with total compartment volumes and therefore allow for easy and simultaneous assessment of skeletal muscle mass and adipose tissue compartment volumes.

Keywords Sarcopenia · Obesity · CT · Abdomen

Abbreviations

BMI	Body mass index
CT	Computed tomography
ROI	Region of interest
SAT	Subcutaneous adipose tissue
SMA	Superior mesenteric artery
SM	Paraspinal skeletal muscle mass
SMVH	Paraspinal skeletal muscle mass normalized to volume of interest height
VAT	Visceral adipose tissue

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Introduction

Population aging and overall increase in the prevalence of obesity are expected to raise global burden of several chronic diseases and are therefore currently recognized as central issues of healthcare [1, 2]. For the United States it is estimated that by 2050 the total number of people with an age of 65 years and above will be more than doubled to a number of about 89 million. Currently, about 92 percent of those people are reported to suffer from at least one chronic disease [1]. The overall prevalence of obesity among the general population is steadily increasing with about 604 million adults being affected worldwide in 2015. Increased body weight was identified as an independent risk factor for adverse outcome in several chronic diseases, including cardiometabolic, oncologic, and musculoskeletal disorders [3–5]. Sarcopenia,

broadly defined as onward decline of skeletal muscle mass, is a central part of "frailty syndrome", which is also known to be related to age and has a strong prognostic value in severe diseases, including different types of cancer [6–9].

Conventional anthropometric measurements such as body mass index (BMI) or waist-to-hip ratio are well established to determine general body composition in clinical routine but lack to distinguish between connective tissue compartments such as adipose and skeletal muscle tissue, which are known to comprise prognostic information in severe diseases [4, 5, 7–9]. Abdominal computed tomography (CT) is applied for manifold indications in daily clinical practice and allows for easy quantification of these compartments based on densitometric thresholds. It is increasingly realized that additional information beyond the primary addressed question, for example amount and composition of connective tissue compartments, can opportunistically be obtained from CT-scans [10, 11]. Several studies have demonstrated that single-slice measurements obtained at different anatomical landmarks show high correlations with total compartment volumes [12–14]. Total amounts of visceral and subcutaneous fat are typically estimated at the level of the intervertebral disk space L4/5, while the third lumbar vertebra is a common reference point for estimation of skeletal muscle mass [6]. From a clinical point of view, it would be desirable to estimate all relevant connective tissue compartments from only one anatomical landmark. Some previous studies measured the amount of visceral and subcutaneous fat as well as skeletal muscle mass simultaneously [7, 8, 15]. These measurements were typically performed at the level of the third lumbar vertebra. However, anatomical variations may complicate its reliable and expeditious identification, particularly for unexperienced readers. Moreover, unequivocal identification of L3 often requires multiplanar reformation, which may be time-consuming.

As obtainment of opportunistic information should be as simple as possible, the aim of this study was a detailed investigation of the utility of several anatomical landmarks among the entire abdomen for estimation of skeletal muscle mass and abdominal adipose tissue compartments (visceral adipose tissue, VAT; subcutaneous adipose tissue, SAT) from single-slice images. Beyond established landmarks, we investigated the utility of less common, easy-to-identify reference points for simultaneous assessment of skeletal muscle mass and adipose tissue compartment volumes.

Materials and methods

Study population

This study was approved by the institutional review board with waiver of written informed consent due to the retrospective character of the study. A priori statistical power analysis revealed that to demonstrate a correlation coefficient of $r = 0.6$ at a significance level of $P = 0.001$ and a type II error rate of 0.1 a sample size of $N = 47$ would be required. As we aimed to study the correlations between connective tissue compartment volumes and area-based measurements in single-slice images, anatomical distribution patterns of connective tissue compartments in eligible patients needed to be as physiological as possible. Hence, exclusion criteria were history of prior large surgical procedures, presence of metallic implants, and presence of abdominal pathologies such as gastrointestinal malignancies or ascites. For inclusion the complete circumference of the body as well as the whole abdominal cavity in cranio-caudal orientation needed to be captured within the field-of-view of the CT-scan. Medical records were reviewed and baseline clinical characteristics including body height and body weight were accessed. Patients who underwent abdominal multislice-CT for routine diagnostic purposes in our center between April and July 2018 were considered for inclusion. Among those consecutive patients were 5 subjects, whose actual exams have not met the inclusion criteria, but a prior exam from those patients′ history did. These exams were performed between June 2017 and January 2018 and were also included.

Imaging protocol

All patients underwent routine multislice-CT imaging of the abdomen in supine positioning with or without administration of iodinated contrast on a clinical CT-scanner (iCT, Philips Healthcare). Typical imaging parameters were: slice thickness 1 or 2 mm, tube voltage 120 kVp, tube current (exposure time product) 100 mAs.

Image analysis

Image datasets were retrieved from the institutional picture archiving and communication system (IMPAX, Agfa Healthcare, Belgium) and imported as DICOM files into the image analysis tool on a standard workstation. For analysis of skeletal muscle mass and abdominal adipose tissue volumes, a previously developed in-house tool for volumetric assessment of tissue compartments was adapted to the specific task of this study [16]. The software was written in MATLAB (Mathworks, Natick, MA). For volumetric assessment the thinnest available slices were chosen and image datasets were reconstructed to axial, sagittal, and coronal viewing planes. To study the associations between volumetric and single-slice measures, anatomical landmarks for measurement of compartment areas in single-slice images were defined at median sagittal intervertebral disk spaces T12/L1 (1), L1/L2 (2), L2/L3 (3), L3/L4 (4), L4/L5 (5), L5/S1 (6), as well as the radix of the superior mesenteric artery (SMA;

7); and the level of the umbilicus (U; 8). The defined landmarks were determined manually within the image datasets. To ensure inclusion of the complete visceral adipose tissue compartment, the upper and lower boundaries of adipose tissue compartments were defined as follows: The upper boundary was equal to (1), whereas the lower boundary was defined as the cranial margin of the femoral heads. To allow for standardized and comparable volumetric assessment of paraspinal muscles, the cranio-caudal margins were defined as follows: the upper boundary was equal to (1), whereas due to the predominantly tendinous structure of the sacral paraspinal muscles the inferior surface of vertebra S1 was chosen as an appropriate lower boundary based on visual controls. To separate visceral from subcutaneous adipose tissue, contours were manually and carefully drawn around the peritoneal cavity within the corresponding boundary slices as well as in those slices within the imaging volume, in which the extent of the peritoneal cavity varied much from the previously contoured slices. The tool interpolated missing contours linearly in an automated fashion, leading to formation of a three-dimensional region of interest (ROI), which separated the area within the ROI, consisting of the abdominal cavity with visceral adipose tissue, from the area outside of the ROI, containing subcutaneous adipose tissue. Since the contours were drawn within the axial, sagittal, and coronal viewing planes, this approach allowed for exact separation of the two compartments, avoiding incorrect allocation of tissue fractions, e.g., erroneous inclusion of paracardial fat. Based on data provided in the literature and visual controls, adipose tissue was identified by an attenuation threshold ranging from − 190 to − 50 Hounsfield units (HU) [17]. Total amount of adipose tissue for each compartment was calculated by adding up all voxels within the attenuation threshold and multiplication of this sum by the voxel volume.

Next, skeletal muscle mass was obtained bilaterally in a similar fashion, separating the paraspinal muscles from the ambient tissue by tracing the thoracolumbar fascia in the corresponding boundary slices as well as those slices, in which the contour of the muscles differed much from the previously segmented slices. Again, contours were interpolated automatically in between slices of manually defined ROIs. To avoid the potential impact of iodinated contrast agents, a narrow attenuation threshold from − 30 to 100 HU was chosen for identification of skeletal muscle tissue [15]. Skeletal muscle mass was calculated similarly to adipose tissue, adding up corresponding voxels and multiplication by voxel volume (Fig. 1).

To study the association between compartment volumes and tissue areas measured in single-slices, the tool automatically obtained single CT-slices from the axial plane based on the previously defined landmarks (1) to (8). Similar to volumetric measurements, areas of adipose tissue compartments (subcutaneous, visceral) and paraspinal muscles were calculated by counting up pixels within each ROI and multiplying the sum by the pixel surface area (Fig. 2).

As the reference standard, we further obtained areas of adipose tissue compartments as well as the total skeletal muscle area at the level of the third lumbar vertebra, since this is the most common approach to image body composition in literature [9]. The total skeletal muscle area at L3 included the psoas, quadratus lumborum, erector spinae, multifidus, and abdominal wall muscles. Adipose tissue compartments were separated as depicted above (Fig. 3).

Statistical analysis

Statistical analysis was performed in SPSS (version 23; IBM). Linear regression models were illustrated with Python (seaborn package, Python Software Foundation).

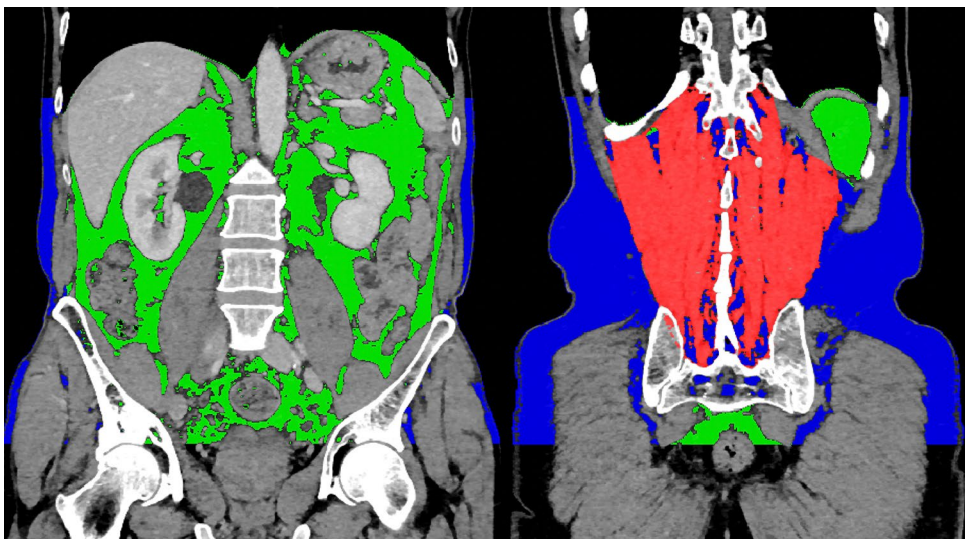

Fig. 1 Volumetric assessment of visceral adipose tissue (green), subcutaneous adipose tissue (blue), and paraspinal skeletal muscle mass (red) from abdominal CT

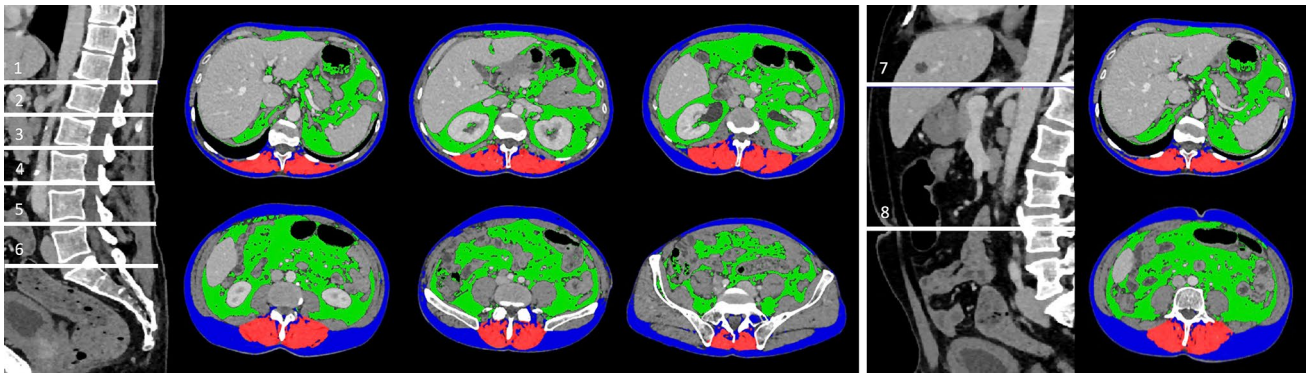

Fig. 2 Anatomical landmarks and corresponding area-based measurements of abdominal connective tissue compartments. Anatomical landmarks were defined as follows: median intervertebral disk spaces T12/L1 (1), L1/L2 (2), L2/L3 (3), L3/L4 (4), L4/L5 (5), L5/S1 (6), offspring of the superior mesenteric artery (7), umbilicus (8). Visceral adipose tissue = green, subcutaneous adipose tissue = blue, paraspinal skeletal muscles = red

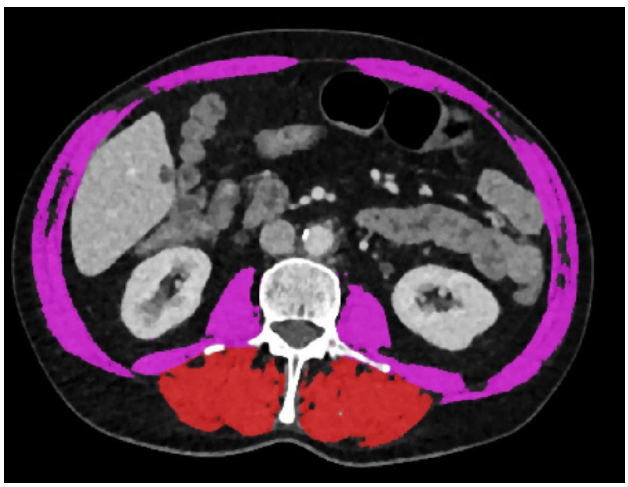

Fig. 3 The total skeletal muscle area obtained at L3 level (reference standard). The paraspinal muscles (*M. erector spinae*, *M. multifidus*) are labeled in red. The abdominal wall muscles (*M. psoas*, *M. quadratus lumborum*, abdominal wall muscles) are labeled in purple

Continuous variables are reported as means with standard deviation. Categorial data are given as frequencies. Mean values of dichotomous data were compared using Mann–Whitney *U* test. The studied compartments (SM, VAT, SAT) were regressed on baseline clinical characteristics (gender, age, BMI) in univariate analyses of variance (ANOVA). Due to the known differences in adipose tissue distribution between men and women, gender-specific correlations between tissue areas measured from single-slice images and volumetric measurements for SM, SAT, VAT were additionally calculated using Pearsons′ correlation coefficients. To study the potential impact of age and nutrition status on distribution of the tissue compartments, the whole study sample was stratified for both age (cut-off, 65 years) and BMI (cut-off, 25 kg/m^2). A P level of < 0.05 was considered as statistically significant.

Results

General characteristics

Fifty patients (26 male, 24 female) with a mean age of 63 ± 15 years were included into the analysis. Patients had a mean BMI of 25 ± 5 kg/m^2 with a mean body weight of 73 ± 15 kg and a mean body height of 172 ± 9 cm. Male patients had significantly higher body weight ($P < 0.001$) and were taller than female patients ($P < 0.001$) but did not differ significantly with regard to BMI ($P = 0.122$) and age ($P = 0.322$).

Mean volumes of visceral adipose tissue (VAT) and subcutaneous adipose tissue (SAT) were 3307 ± 2143 cm^3 and 4792 ± 2648 cm^3, respectively. Mean bilateral paraspinal skeletal muscle mass (SM) was 728 ± 197 cm^3. Statistical analysis revealed no significant differences between men and women with regard to mean volume of SAT ($P = 0.259$), whereas mean volumes of total VAT and bilateral SM were significantly higher in male patients compared to female patients (VAT, $P < 0.001$; SM, $P < 0.001$). Table 1 details patient characteristics.

Associations between clinical characteristics and volumetric measurements

Univariate variance analysis revealed that gender and BMI were significantly associated with both adipose tissue compartment volumes (gender, $P < 0.001$; BMI, $P < 0.001$; for both mean SAT and mean VAT volume). Regarding patient age, no significant associations with adipose tissue compartments were observed (SAT, $P = 0.118$; VAT, $P = 0.190$).

Table 1 General characteristics of the study population ($N=50$)

Variable	Men $N=26$	Women $N=24$	P value
Body weight (kg)	80 ± 13	66 ± 14	< 0.001
Body height (cm)	179 ± 5	165 ± 6	< 0.001
BMI (kg/m^2)	25 ± 4	25 ± 6	0.122
Age (years)	61 ± 15	66 ± 14	0.322
VAT volume (cm^3)	4326 ± 2250	2203 ± 1354	< 0.001
SAT volume (cm^3)	4211 ± 2020	5422 ± 3116	0.259
SM volume (cm^3)	862 ± 166	583 ± 203	< 0.001

BMI body mass index, *VAT* visceral adipose tissue, *SAT* subcutaneous adipose tissue, *SM* paraspinal skeletal muscles

Gender and patient age significantly correlated with mean bilateral SM volume (both $P<0.001$). BMI tended to show an association with bilateral SM volume, although this relation was not significant ($P=0.057$). To investigate the impact of abdominal paraspinal muscle length on these results, we further studied SM values normalized for volume of interest height (VOI), using the fraction SM ÷ VOI (SMVH). Correlation between bilateral SM volume and bilateral SMVH volume was very strong ($r=0.97$, $P<0.001$). Statistical analysis revealed that gender, patient age, and BMI were strongly associated with bilateral SMVH (gender, $P<0.001$; patient age, $P=0.008$; BMI, $P=0.031$).

Correlations between volumetric and single-slice measurements

Compartment volumes (SM, VAT, SAT) were highly correlated with the reference standard obtained at the level of the third lumbar vertebra (SM, $r=0.90$, $P<0.001$; VAT, $r=0.98$, $P<0.001$; SAT, $r=0.97$, $P<0.001$).

Regarding VAT, single-slice measurements from all studied anatomical landmarks were strongly correlated with compartment volumes in both men and women (whole collective, $r>0.89$; $P<0.001$; see Table 2). Overall, the strongest correlation of single-slice measurements of VAT with compartment volumes was found for level L2/3 (whole collective, $r=0.98$; $P<0.001$).

For SAT, a very strong correlation between single-slice measurements from all anatomical landmarks and volume of the corresponding compartment was observed in both genders (whole collective, $r>0.95$; $P<0.001$). Single-slice measurements of SAT performed at level L5/S1 had the strongest correlation with SAT compartment volume (whole collective, $r=0.98$; $P<0.001$).

Single-slice measurements of bilateral SM were strongly correlated with volumetric measurements for both male and female patients (whole collective, $r>0.75$; $P<0.001$) with the exception of level L5/S1 (whole collective, $r=0.61$; $P<0.001$). In general, the best correlations of single-slice and volumetric measurements for bilateral SM were found at the levels L3/4 (whole collective, $r=0.94$, $P<0.001$). Correlations were further improved by normalization to volume of interest height (Table 3).

Figure 4 illustrates correlations between volumetric and single-slice measurements and provides regression coefficients for immediate estimation of compartment volumes from area-based measurements.

Correlations between volumetric and single-slice measurements stratified by age and BMI

Regarding VAT, single-slice measurements at the level L2/3 remained most strongly correlated with total compartment volume for measurements stratified by age ($r\geq 0.97$; $P<0.001$) and BMI ($r\geq 0.96$; $P<0.001$). Similarly, the strongest correlation between single-slice measurements and SAT volume were observed for measurements obtained at level L5/S1 for both age cohorts

Table 2 Correlations between abdominal compartment volumes (VAT, visceral adipose tissue; SAT, subcutaneous adipose tissue; SM, paraspinal skeletal muscles) with single-slice measurements obtained at the levels of median intervertebral disk spaces T12/L1, L1/L2, L2/L3, L3/L4, L5/S1, offspring of the superior mesenteric artery (SMA), and the umbilicus (U) for the whole study population (N = 50)

Variable	Men			Women		
	VAT volume	SAT volume	SM volume	VAT volume	SAT volume	SM volume
T12/L1	0.91	0.96	0.71	0.87	0.95	0.63
L1/L2	0.95	0.97	0.78	0.93	0.96	0.73
L2/L3	0.96	0.97	0.87	0.98	0.98	0.86
L3/L4	0.96	0.96	0.92	0.96	0.98	0.91
L4/L5	0.91	0.97	0.84	0.95	0.98	0.75
L5/S1	0.89	0.97	0.55	0.91	0.99	0.56
SMA	0.94	0.96	0.74	0.91	0.95	0.73
U	0.86	0.97	0.70	0.92	0.98	0.63

All P values were < 0.005

Table 3 Correlations between abdominal compartment volumes (VAT, visceral adipose tissue; SAT, subcutaneous adipose tissue; SM, paraspinal skeletal muscles; SMVH, paraspinal skeletal muscles normalized for height) with single-slice measurements obtained at the levels of median intervertebral disk spaces T12/L1, L1/L2, L2/L3, L3/L4, L5/S1, offspring of the superior mesenteric artery (SMA), and the umbilicus (U) for the whole study population ($N = 50$)

Anatomical landmark	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1	SMA	U
VAT volume	0.93	0.96	0.98	0.97	0.92	0.89	0.94	0.89
SAT volume	0.95	0.96	0.98	0.97	0.98	0.98	0.95	0.98
SM volume	0.85	0.88	0.92	0.94	0.86	0.61	0.87	0.75
SMVH volume	0.88	0.93	0.96	0.98	0.83	0.55	0.92	0.72

All P values were < 0.001

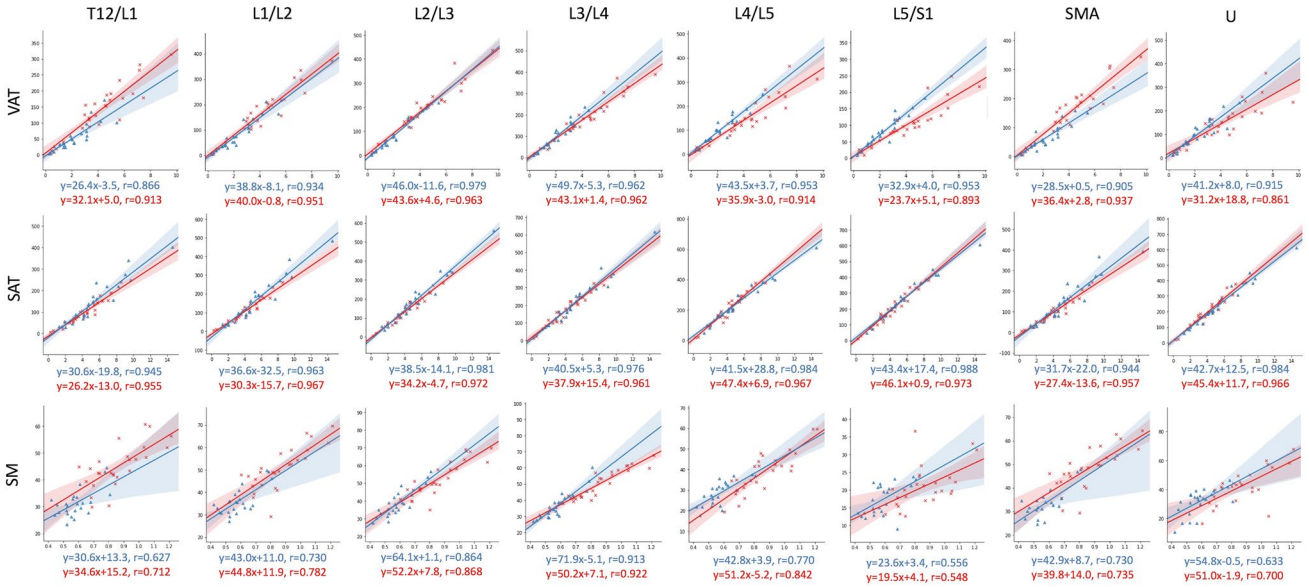

Fig. 4 Correlations between volumetric measures of abdominal compartments of visceral adipose tissue (VAT), subcutaneous adipose tissue (SAT), and paraspinal skeletal muscles (SM) and single-slice measurements obtained at median intervertebral disk spaces T12/L1, L1/L2, L2/L3, L3/L4, L5/S1, offspring of the superior mesenteric artery (SMA), and the umbilicus (U). Volumes are given on the x-axes in 10^{-3} m^3 (liters), and areas are given on the y-axes in cm^2. Inverse functions are given for each level and each compartment to calculate corresponding volumes from area-based measurements

($r \geq 0.98$; $P < 0.001$) as well as for patients with a BMI of more or less than 25 kg/m^2 ($r = 0.97$; $P < 0.001$). In older patients (> 65 years), the strongest correlations between single-slice measurements and bilateral SM and SMVH volumes were recorded at the levels L2/3 (SM, $r = 0.95$; $P < 0.001$) and L3/4 (SMVH, $r = 0.97$; $P < 0.001$), respectively. In younger patients (< 65 years), bilateral SM and SMVH volumes correlated best with single-slice measurements obtained at the level of the offspring of the SMA (SM, $r = 0.94$; SMVH, $r = 0.98$; both $P < 0.001$). Single-slice measurements obtained at the level L3/4 correlated best with bilateral SM and SMVH volumes irrespective of body weight (SM ≥ 0.92; SMVH ≥ 0.97; $P < 0.001$). Further results are detailed in Table 4.

Discussion

In this study, we aimed to explore the correlations between areas of connective tissue compartments measured from single-slice images at several anatomical landmarks and total compartment volumes in abdominal CT-scans. Irrespective of patient age, gender, and BMI, areas of SAT and VAT measured at all studied levels were highly correlated with corresponding compartment volumes. Regarding SM, our results indicate that associations between single-slice estimates and skeletal muscle mass seem to have an age-related component. In general, areas measured at L3/L4 provided the best proxy for estimation of muscle mass irrespective of patient gender and BMI. While in older

Table 4 Correlations between volumetric measures of abdominal compartments (VAT, visceral adipose tissue; SAT, subcutaneous adipose tissue; SM, paraspinal skeletal muscles; SMVH, paraspinal skeletal muscles normalized for height) and single-slice measurements obtained at the levels of median intervertebral disk spaces T12/L1, L1/L2, L2/L3, L3/L4, L4/L5, L5/S1, offspring of the superior mesenteric artery (SMA), and the umbilicus (U) stratified by age and BMI

Anatomical landmark	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1	SMA	U
Age > 65 years ($N=28$)								
VAT volume	0.94 $P<0.001$	0.97 $P<0.001$	0.98 $P<0.001$	0.98 $P<0.001$	0.92 $P<0.001$	0.91 $P<0.001$	0.95 $P<0.001$	0.86 $P<0.001$
SAT volume	0.95 $P<0.001$	0.97 $P<0.001$	0.97 $P<0.001$	0.95 $P<0.001$	0.97 $P<0.001$	0.98 $P<0.001$	0.96 $P<0.001$	0.98 $P<0.001$
SM volume	0.84 $P<0.001$	0.91 $P<0.001$	0.95 $P<0.001$	0.94 $P<0.001$	0.78 $P<0.001$	0.54 $P=0.003$	0.92 $P<0.001$	0.56 $P=0.002$
SMVH volume	0.84 $P<0.001$	0.93 $P<0.001$	0.96 $P<0.001$	0.97 $P<0.001$	0.80 $P<0.001$	0.62 $P<0.001$	0.93 $P<0.001$	0.57 $P=0.002$
Age < 65 years ($N=22$)								
VAT volume	0.91 $P<0.001$	0.96 $P<0.001$	0.97 $P<0.001$	0.96 $P<0.001$	0.94 $P<0.001$	0.88 $P<0.001$	0.96 $P<0.001$	0.93 $P<0.001$
SAT volume	0.95 $P<0.001$	0.96 $P<0.001$	0.99 $P<0.001$	0.99 $P<0.001$	0.98 $P<0.001$	0.99 $P<0.001$	0.95 $P<0.001$	0.98 $P<0.001$
SM volume	0.93 $P<0.001$	0.92 $P<0.001$	0.93 $P<0.001$	0.94 $P<0.001$	0.91 $P<0.001$	0.50 $P=0.018$	0.94 $P<0.001$	0.86 $P<0.001$
SMVH volume	0.96 $P<0.001$	0.97 $P<0.001$	0.98 $P<0.001$	0.98 $P<0.001$	0.88 $P<0.001$	0.40 $P=0.065$	0.98 $P<0.001$	0.84 $P<0.001$
BMI > 25 kg/m^2 ($N=22$)								
VAT volume	0.84 $P<0.001$	0.93 $P<0.001$	0.96 $P<0.001$	0.93 $P<0.001$	0.85 $P<0.001$	0.81 $P<0.001$	0.92 $P<0.001$	0.81 $P<0.001$
SAT volume	0.92 $P<0.001$	0.95 $P<0.001$	0.97 $P<0.001$	0.95 $P<0.001$	0.96 $P<0.001$	0.97 $P<0.001$	0.91 $P<0.001$	0.96 $P<0.001$
SM volume	0.85 $P<0.001$	0.87 $P<0.001$	0.92 $P<0.001$	0.95 $P<0.001$	0.86 $P<0.001$	0.45 $P=0.035$	0.87 $P<0.001$	0.74 $P<0.001$
SMVH volume	0.90 $P<0.001$	0.95 $P<0.001$	0.97 $P<0.001$	0.99 $P<0.001$	0.83 $P<0.001$	0.34 $P=0.121$	0.93 $P<0.001$	0.74 $P<0.001$
BMI < 25 kg/m^2 (N = 28)								
VAT volume	0.96 $P<0.001$	0.97 $P<0.001$	0.98 $P<0.001$	0.97 $P<0.001$	0.94 $P<0.001$	0.90 $P<0.001$	0.94 $P<0.001$	0.89 $P<0.001$
SAT volume	0.89 $P<0.001$	0.90 $P<0.001$	0.95 $P<0.001$	0.96 $P<0.001$	0.96 $P<0.001$	0.97 $P<0.001$	0.91 $P<0.001$	0.97 $P<0.001$
SM volume	0.83 $P<0.001$	0.87 $P<0.001$	0.91 $P<0.001$	0.92 $P<0.001$	0.87 $P<0.001$	0.70 $P<0.001$	0.85 $P<0.001$	0.76 $P<0.001$
SMVH volume	0.85 $P<0.001$	0.91 $P<0.001$	0.96 $P<0.001$	0.97 $P<0.001$	0.81 $P<0.001$	0.66 $P<0.001$	0.90 $P<0.001$	0.71 $P<0.001$

patients (> 65 years) areas measured at L2/3 showed the highest correlation with total compartment volumes, single-slice measurements of paraspinal muscles obtained at the offspring of the SMA, which can easily be identified from the axial plane, appeared to most accurately estimate muscle mass in younger patients (< 65 years).

Abdominal CT-scans are performed for several indications in daily clinical routine and opportunistic body composition analysis is of growing interest [11]. Cross-sectional images allow for measurement of connective tissues [6, 9], were shown to correlate well with certain compartment volumes [12–14, 17], and can provide important prognostic information in several severe and chronic diseases [5, 7, 8, 15]. In accordance with literature we observed a sexual dimorphism with respect to mean VAT and SM volumes [5, 14, 18]. Using a more precise and extensive approach for compartment analysis, our data confirm and extend findings of previous studies. Irlbeck et al. investigated the utility of several single-slice measurements for estimation of adipose tissue compartments (VAT, SAT) using CT. Their study protocol covered 125 mm above S1 and VAT was separated from SAT by tracing the abdominal wall muscles in axial images [14]. As with this approach potentially relevant amounts of perigastric adipose tissue might be missed, we studied only patients in which the entire abdominal cavity was captured within the field-of-view, separated VAT from

SAT using multiplanar reconstruction to ensure precise segmentation of the VAT compartment, and additionally investigated skeletal muscle mass due to its prognostic value in several severe diseases [6–9]. Shen et al. demonstrated in their MRI-based study that single-slice measurements lying 5 cm above and below L4/5 were highly correlated with total body volumes of skeletal muscles and adipose tissue, respectively [12]. Unlike in our study, total body compartment volumes were estimated based on a mathematical equation and abdominal adipose tissue compartments were not discriminated. However, investigating the relations between precisely assessed and separated compartment volumes and single-slice measurements, our data corroborate these previous findings in CT and beyond that proposes several, easy-to-identify anatomical landmarks, which allow for precise estimation of skeletal muscle mass as well as adipose tissue compartments from routine abdominal imaging.

Calculation of the lumbar skeletal muscle index is a frequently applied method for estimation of muscle mass in literature. For this, total skeletal muscle area within one slice at the level of the third lumbar vertebra is assessed and normalized for body height in square meters [6–9, 19]. However, since correct identification of the psoas and abdominal wall muscles in the upper parts of the abdomen may be difficult [13, 20], it appeared impractical to perform volumetric assessment of these muscles in our study. The paraspinal muscles, consisting of the erector spinae and spinotransverse group [20], are of great importance for postural stability and mobility in daily life [21]. Changes in quality and composition of paraspinal muscles seem to have an age-related component [18, 22] and were shown to reveal prognostic and diagnostic information in musculoskeletal [23] and oncologic [24] disorders. Moreover, quality and composition of paraspinal muscles seem to predict outcome in patients undergoing surgical procedures [25]. We observed volumes of the paraspinal muscles to be highly correlated with total skeletal muscle area at L3 level. Therefore, we considered assessment of paraspinal muscles as a reasonable alternative for estimation of skeletal muscle mass. In our study, several anatomical levels were highly correlated with total compartment volume of the abdominal paraspinal muscles. This finding is of particular significance regarding imaging protocols in which not the whole abdomen is captured or identification of the L3 level is hampered since these results indicate that several anatomical landmarks can be considered as alternatives to the more common L3 level. Among several landmarks which were previously investigated primarily regarding adipose tissue compartments [14], we further investigated the value of single-slice measurements obtained at the offspring of the SMA. Interestingly, although currently evidence for this landmark in literature is limited [26], we observed that measurements obtained at the SMA level correlated best with total SM volume in patients with an age of < 65 years. Therefore, having clinical utility in mind, the SMA landmark might be a new interesting level for estimation of muscle mass in younger patients, as it can easily be identified from the axial plane and is always captured within imaging of the upper abdomen.

It was surprising that different anatomical landmarks appeared to correlate most accurately with total skeletal muscle mass in younger versus in older patients. Possibly, this finding can be attributed to age-related changes in body composition. Generally, as individuals get older, the total amount of adipose tissue increases with ongoing shift of fat to the abdominal compartment while the portion of skeletal muscle tissue in total body mass progressively decreases and is accompanied by diminishing muscle quality and strength. Of note, these changes often are not reflected by simultaneous alterations in body weight or BMI [27, 28]. Interestingly, in contrast to our findings regarding skeletal muscles, associations between single-slice measurements and volumes of adipose tissue compartments were not affected by age, gender, and BMI in our study. Perhaps this may be explained by the different sizes of the compartment volumes; mean VAT and SAT were 3307 cm^3 and 4792 cm^3, while mean SM was 728 cm^3. Possibly, the greater adipose tissue compartment volumes are more robust to alterations caused by confounding factors than the smaller paraspinal muscle compartment. However, although we cannot finally solve this issue with our study, the presented results indicate that in future studies the potential impact of patient age on accuracy of body composition measurements should be taken into consideration.

We observed an overall improvement of correlations between single-slice measurements and SM volumes after adjustment for height in our study. That was to be expected, as the size of the skeletal muscle compartment is related to subject's stature [29]. While after normalization in younger patients still the offspring of the SMA appeared to correlate best with total SM volume, in older patients the L3/4 level showed the most accurate association with the compartment volume. We suppose that this observation also might be due to age-related changes in muscle composition [18, 22]. To fully address this question, larger studies with additional assessment of muscle quality would become necessary. However, based on our results we can state that correlations of single-slice measurements of paraspinal muscles with total SM volumes can be improved by normalization to height and therefore in subsequent studies the implementation of height adjustment may contribute to improvement of accuracy of single-slice paraspinal muscle measurements.

We acknowledge that our study has several limitations. First, as with other retrospective studies, generalizability is limited, and reproducibility cannot be ascertained. As mainly white patients were included, the amount of bias when extrapolating the results to other ethnic populations with potentially different body composition patterns

is unclear. However, we studied consecutive patients who received abdominal CT-scans for various indications in daily clinical routine in order to investigate a scenario close to clinical reality and to thereby enhance clinical utility. Larger and particularly prospective cohorts are needed to confirm the presented findings and will eventually substantiate the value of this study for clinical practice. Moreover, these may help to establish reference values for the proposed anatomical landmarks. The small sample size may be regarded as a limitation of the study. However, a priori statistical power estimation demonstrated that sufficient statistical power is provided.

To conclude, in this study we investigated the utility of different anatomical landmarks to estimate the total amount of adipose tissue compartments as well as skeletal muscle mass from single-slice images in abdominal CT. Several landmarks among the entire volume allow for precise and simultaneous assessment of SAT, VAT, and SM and therefore may serve as alternatives in imaging protocols, in which more common landmarks are not captured or their explicit identification is hampered. Moreover, regarding SM, we observed that correlations between single-slice and volumetric measurements seem to have an age-related component. In future studies, this finding may have important implications for an appropriate study design.

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