Toward a Routine Assessment of Visceral Adipose Tissue Volume from Computed Tomographic Data

Alexander Schaudinn1*, Andrea Hudak1*, Nicolas Linder1,2, Martin Reinhardt1, Gertraud Stocker1, Florian Lordick3, Timm Denecke1, and Harald Busse

Objective: The study’s aim was to determine to what extent total visceral adipose tissue (VAT) volume (V_{VAT-T}) measured from segmented VAT areas (A_{VAT}) on all axial computed tomography (CT) sections (thickness of 5 mm) between the diaphragm and pelvic floor can be predicted by the A_{VAT} of commonly selected landmark sections in patients with overweight or obesity.

Methods: A total of 113 patients (31 females, 82 males) with images of full abdominopelvic coverage and proper image quality were included (BMI = 25.0-64.1 kg/m², 29.5 ± 4.9 kg/m²). Linear regression between A_{VAT} and V_{VAT-T} (reference) was used to determine approximate equations for VAT volume for all parameters (single sex, different anatomical landmarks or lumbar intervertebral disc spaces, one or five axial sections). Agreement was evaluated by the multivariate coefficient of determination and by the SD of the percentage difference (s_d%) between the estimated VAT volume on one or five sections and V_{VAT-T}.

Results: The V_{VAT-T} was 0.9 to 8.4 (3.8 ± 2.2) L for females and 2.7 to 11.7 (5.6 ± 2.1) L for males. Best agreement was found at L2-3 (s_d% = 14.3%-15.5%) for females and at L1-2 or L2-3 (11.7%-12.4%) for males. Agreement at the umbilicus or the femoral heads was poor (20.2%-57.9%). Segmentation of one or five sections was substantially faster (11/70 seconds) than whole-abdomen processing (15 minutes).

Conclusions: V_{VAT-T} can be rapidly estimated by VAT segmentation of axial CT sections at sex-specific lumbar intervertebral disc spaces.

Introduction

Obesity is a worldwide public health problem, and its prevalence has nearly doubled over the past 35 years (1,2). Abdominal obesity and the endocrinologically active visceral adipose tissue (VAT) are strongly linked to a higher overall mortality, often caused by cardiac, vascular, or metabolic diseases (3-7). Therefore, VAT quantification plays an important role in the evaluation of such patients but it may also be useful for a periprocedural assessment in the surgical disciplines (8-14). Anthropometric measures like BMI or waist to hip ratio usually correlate poorly with VAT only, whereas dual-energy x-ray absorptiometry has shown both VAT under- and overestimation in comparison with magnetic resonance imaging (MRI). Cross-sectional imaging is, therefore, often regarded as the reference standard for VAT quantification (15,16).

Study importance

What is already known?
- Visceral adipose tissue (VAT) amounts are increasingly quantified from imaging data for an advanced assessment of obesity-related risks and diseases.
- Prior computed tomographic (CT) analyses have suggested that segmented VAT areas (A_{VAT}) on landmark axial sections are a time-efficient measure but are not always referenced properly (one sex or partial VAT volume only).

What does this study add?
- This work provides linear equations for the approximation of the fully segmented VAT volumes (V_{VAT-T}) for each sex and various landmarks.
- A_{VAT} at intervertebral spaces L2-3 (females) and L1-2 or L2-3 (males) correlated best with V_{VAT-T}.

How might these results change the direction of research or the focus of clinical practice?
- Tissue areas segmented on a single predetermined axial CT section provide a means to estimate body composition parameters like V_{VAT-T} within the time constraints of clinical practice.
- A reliable VAT estimation might contribute to an improved understanding and clinical assessment of cardiometabolic or oncological diseases.
Manual analysis of dozens of computed tomography (CT) or MRI images, however, is very time consuming (17). This dilemma has been addressed by developing software and algorithms for fully automatic or semiautomatic segmentation, which still require some user interaction (18-23). Another step toward further clinical application relies on the identification of accurate predictors of total VAT volume (\(V_{\text{VAT}}\)) measured from segmented VAT areas (\(A_{\text{VAT}}\)) on all axial CT sections (thickness of 5 mm) between the diaphragm and pelvic floor, for example, by restricting segmentation to only a single section or a few sections.

The majority of such quantification studies have relied on MRI data (15,17,24-27). CT studies are generally rare and often incomplete (28-31), with results applying to a single sex only (29-31) or not using the entire abdominopelvic cavity as the reference volume (28-29,31). In one of the largest studies, for example, the axial dimension of the reference volume covered only 12.5 cm above the vertebral body S1 and thus excluded substantial upper and lower abdominal VAT amounts (28).

The aim of this work was to determine for each sex to what extent whole-abdomen VAT volume of patients (single sex) with overweight or obesity can be estimated from \(A_{\text{VAT}}\) segmented on a few axial CT sections at common anatomical landmarks. We hypothesized that our simplified CT quantification is still accurate enough for whole-abdomen VAT assessment and is not independent of the patient’s sex. The compilation of regression coefficients computed here will enable VAT volume prediction from segmented VAT areas for different experimental conditions and may also be useful for independent clinical studies.

### Methods

#### Patients

The initial study cohort consisted of 1,043 patients with CT data sets of the abdominopelvic cavity. Five individual criteria resulted in the exclusion of 930 subjects in total (Figure 1). Retrospective analysis was then performed on 113 patients with overweight and obesity, 82 males and 31 females. The majority of patients (about 61%, 69 of 113) had been part of an oncological multicenter trial on the benefit of chemotherapy for advanced gastric cancer between June 2008 and December 2010 (32). Data from the other 44 subjects came from radiological routine or emergency examinations at Leipzig University Hospital, Germany, between September 2015 and November 2016. Analysis of anthropometric and imaging data were approved by the institutional review board, and informed consent was obtained from all patients.

#### CT imaging

Trial subjects were examined in supine position using several CT systems (10 models, four major vendors) at the involved research sites. More than 70% of the subjects (80 of 113) underwent CT imaging with either a 256-slice system (iCT 256; Philips Healthcare, Best, the Netherlands; 57 of 113 patients [about 50%], single site) or a 64-slice system (Somatom Sensation; Siemens Healthcare, Erlangen, Germany; 23 of 113 patients [about 20%], single site).

Data were acquired across the whole abdomen and reconstructed as 5-mm–thick axial sections. Other imaging parameters were as follows: x-ray tube voltage of 120 kVp (kilovolts [peak]), Dose Right Index of 16 (219-270 mA), autocollimation of 128 × 0.625 mm, liver area Dose Right Index of +3, pitch of 0.758, revolution time of 0.75 seconds, data collection diameter of 500 mm, and average scan time of 6 seconds.

#### Postprocessing

CT data were analyzed on a standard personal computer (Dell Optiplex 7010 [Dell, Round Rock, Texas], Intel-Core i7-3770 central processing unit, 3.4 GHz, 16 GB of random-access memory [Intel, Santa Clara, California]). A custom-made analysis tool (from MATLAB; MathWorks, Natick, Massachusetts), originally developed for MRI data (18), was used for semiautomatic VAT segmentation (Figure 2). VAT amounts of 20 data sets segmented with the MRI tool had previously been found to correlate well (Pearson \(r = 0.989, R^2 = 0.978\)) with those using an established commercial software (sliceOmatic, version 5.0; TomoVision, Magog, Quebec, Canada).

For a given axial section, the segmentation software automatically computes best estimates of outer and inner subcutaneous adipose tissue boundaries (which were not further analyzed here) and computes only a crude VAT boundary, typically along the inner boundaries of the abdominal wall and paraspinal muscles (Figure 2). VAT is then quantified by adjustable thresholds, typically between −190 and −30 Hounsfield units (HU), in the corresponding histogram of CT densities (33). One reader (3 years’ experience in abdominal imaging) then reviewed the resulting VAT overlays and adjusted the thresholds if needed. Adipose tissue volumes were simply calculated from the number and geometry of the segmented pixels.

\(V_{\text{VAT}}\) (reference) was determined by simply segmenting all axial sections between the visually identified abdominal limits (diaphragm and pelvic floor). Processing involved an average of 83 contiguous, 5-mm–thick sections (34). Estimated VAT volumes (\(V_{\text{VAT}}\)) were then computed from \(A_{\text{VAT}}\) on a limited number of sections (\(A_{\text{VAT}}\) on one section \([A_{\text{VAT,1}}]\) or \(A_{\text{VAT}}\) on five sections \([A_{\text{VAT,5}}]\) at selected landmarks (Figure 2D); at five lumbar intervertebral disc spaces (L1-L2 to L5-S1), at the umbilicus (UM), and at the femoral heads (FH). Stacks of five sections were built by adding two upper and two lower sections (except for FH with four upper sections). Conversion coefficients (slope \(m_{1/5}\) and intercept...
between VAT and VAT-T were computed by linear regression for all landmarks, where the subscript indicates the number of sections and not a particular section position. $V_{\text{VAT,T}}$ was calculated as $m_{\text{VAT,T}} = V_{\text{VAT,1}} + V_{\text{VAT,2}} + V_{\text{VAT,3}} + V_{\text{VAT,4}} + V_{\text{VAT,5}}$. Automatic-segmentation, manual-correction, and overall processing times were recorded for a subgroup of 10 patients.

**Statistical analysis**

Statistical measures of agreement were the coefficient of determination $R^2$ for a linear fit as well as for the SD of the percentage difference ($s_{\%}$) between $V_{\text{VAT,T}}$ and $V_{\text{VAT,T}}$ ($s_{\%} = \frac{s_{\text{VAT,T}}}{V_{\text{VAT,T}}} \times 100$) or the $s_{\%}$ between $V_{\text{VAT,T}}$ and $V_{\text{VAT,T}}$ ($s_{\%} = \frac{s_{\text{VAT,T}}}{V_{\text{VAT,T}}} \times 100$). All statistical analyses were performed using SPSS Statistics.
24 (IBM Corp., Armonk, New York). Statistical P values less than 0.05 were considered to be significant.

Results

The study cohort consisted of 113 patients (31 females and 82 males). Patient characteristics and BMI distribution are shown in Table 1 and Figure 3 for both sexes. There were no statistical differences between sexes in age or BMI, but differences were present in height and weight. VAT and section-based $A_{VAT}$ ($A_{VAT-1}$ or $A_{VAT-5}$) could be determined for all patients. Males had significantly higher $V_{VAT-T}$ values than females (mean of 5.65 L vs. 3.88 L).

Parameters for the regression between $A_{VAT-1}$ or $A_{VAT-5}$ and $V_{VAT-T}$ are given in Table 2. Coefficients of correlation ($R^2$) varied between 0.34 and 0.91 for males and between 0.61 and 0.95 for females. Quantitative agreement at the level of the UM or FH was generally poor (low $R^2$ and high SD of the differences for both sexes).

For males, the highest $R^2$ (0.89-0.91) and lowest $s_d$% values (11.7%-12.4%) were found at L1-2 and L2-3 for both $A_{VAT-1}$ and $A_{VAT-5}$. The minimum $s_d$% value was observed at L1-2, but the second best at L2-3 was only marginally larger (Figure 4). For females, the highest $R^2$ (0.92-0.95) and lowest $s_d$% values (14.3%-19.4%) were found for disc spaces L1-2 through L4-5, again for both planimetric VAT measures. The minimum $s_d$% value was observed at L2-3.

Differences between one-section and five-section measures were generally small; for example, the $s_d$% was only 1.2% in females and 0.2% in males at the respective optimal landmark positions. Sample linear fits through the origin are shown in Figure 5, and sample Bland-Altman plots are shown in Figure 6.

Processing of all sections (mean of 83 sections per patient) took an average of about 15 minutes (range of 10.5 to 18.3 minutes). Average processing times for $A_{VAT-1}$ and $A_{VAT-5}$ were 11 seconds (range of 8.3 to 15.1 seconds) and 70 seconds (range of 47.0 to 77.0 seconds), respectively.

Discussion

This work determined to what extent the fully segmented VAT volume in patients with overweight or obesity may be predicted by using $A_{VAT-1}$ and $A_{VAT-5}$ at common anatomical landmarks. Most of the previous analyses have relied on MRI data (15,17,24-27), although CT data have been used as well (28-31). Variations between study designs are generally considerable, most notably for the anatomical reference positions. In accordance with Noumura et al. (30), we have used the umbilicus (UM) as a reference landmark. VAT, visceral adipose tissue; $V_{VAT-T}$, total volume of VAT measured from segmented VAT areas on all axial CT sections (thickness of 5 mm) between diaphragm and pelvic floor.

### Table 2 Parameters for linear regression (slope $m_{1/5}$, intercept $b_{1/5}$) between $A_{VAT-1}$ and $A_{VAT-5}$ and fully segmented $V_{VAT-T}$

|         | Females ($n = 33$) |         | Males ($n = 81$) |
|---------|--------------------|---------|------------------|
|         | $R^2$  | $m_1$ (cm) | $b_1$ (cm$^3$) | $s_d$% | $R^2$  | $m_1$ (cm) | $b_1$ (cm$^3$) | $s_d$% |
| $A_{VAT-1}$ (L1-L2) | 0.92  | 47.72  | 454  | 19.2 | 0.91  | 50.91  | 168  | 11.9 |
| $A_{VAT-1}$ (L2-L3) | 0.94  | 44.17  | 358  | 15.5 | 0.89  | 43.78  | 609  | 12.4 |
| $A_{VAT-1}$ (L3-L4) | 0.95  | 44.36  | 78   | 18.0 | 0.84  | 42.36  | 903  | 15.2 |
| $A_{VAT-1}$ (L4-L5) | 0.93  | 51.51  | 106  | 16.5 | 0.71  | 41.58  | 1,963 | 17.7 |
| $A_{VAT-1}$ (L5-S1) | 0.82  | 60.45  | 499  | 25.0 | 0.68  | 61.30  | 1,812 | 18.9 |
| $A_{VAT-1}$ (UM)    | 0.73  | 53.27  | 322  | 26.9 | 0.62  | 47.42  | 1,217 | 20.6 |
| $A_{VAT-1}$ (FH)    | 0.61  | 115.4  | 256  | 57.9 | 0.34  | 100.99 | 1,907 | 32.4 |
| $A_{VAT-5}$ (L1-L2) | 0.92  | 9.66   | 438  | 19.4 | 0.91  | 10.20  | 148  | 11.7 |
| $A_{VAT-5}$ (L2-L3) | 0.94  | 8.88   | 338  | 14.3 | 0.89  | 8.76   | 611  | 12.1 |
| $A_{VAT-5}$ (L3-L4) | 0.95  | 8.93   | 90   | 16.3 | 0.85  | 8.48   | 901  | 14.6 |
| $A_{VAT-5}$ (L4-L5) | 0.93  | 10.4   | 74   | 16.1 | 0.72  | 8.45   | 1,890 | 17.6 |
| $A_{VAT-5}$ (L5-S1) | 0.82  | 12.3   | 453  | 24.4 | 0.69  | 12.27  | 1,771 | 18.7 |
| $A_{VAT-5}$ (UM)    | 0.74  | 10.7   | 285  | 25.6 | 0.64  | 9.64   | 1,129 | 20.2 |
| $A_{VAT-5}$ (FH)    | 0.62  | 23.2   | 417  | 51.8 | 0.37  | 22.27  | 1,607 | 31.7 |

Quantitative agreement can be assessed from $R^2$ or $s_d$%.

$A_{VAT-1}$, segmented VAT area on 1 section; $A_{VAT-5}$, segmented VAT area on 5 sections; $m$, intercept; FH, femoral heads; L1-L2 to L5-S1, lumbar intervertebral spaces; $b$, slope; $s_d$, SD of the percentage difference between the estimated VAT volumes on one or five slices ($V_{VAT-1/5}$) and $V_{VAT-T}$, total volume of VAT measured from segmented VAT areas on all axial CT sections (thickness of 5 mm) between diaphragm and pelvic floor.
for practical reasons), sex differences can be seen in the details, as, for example, in the work by Demerath et al. (27). The BMI range of our cohort (mean of 29.5 kg/m²) is comparable to that of other studies of obesity, but a few other analyses of section-based estimates have investigated subjects with normal weight (25,35) or BMI values above of obesity, but a few direct comparisons with (lumbar) vertebral landmarks, including this work, have shown that estimation using the FH, without any apparent validation. In patients with overweight or obesity, a few direct comparisons with (lumbar) vertebral landmarks, in which the respective CT and MRI data were acquired on the same day (36). Other studies were partially limited by a small sample size or respective acquisitions being weeks apart. From a technical standpoint, however, differences in findings obtained using these modalities should be minimal because fat is easily identifiable with both (absolute CT numbers and high contrast on T1-weighted MRI).

It seems reasonable that the best correlation with VAT volume is observed at anatomical positions with the highest VAT area. Given the difference in overall body shape and fat distribution between sexes, the peak VAT amount for males might then be distributed more cranially than that of females. This effect is seen in different studies (17,24,27,28,35) and also for higher BMI, but a generalization remains difficult. A detailed account of the study design (sex, BMI, age, observer, imaging parameters) is therefore important to improve the relevance of specific findings.

Agreement of VAT volumes between MRI and CT studies has generally been found to be good (36-39), with an emphasis on a study of 27 females in which the respective CT and MRI data were acquired on the same day (36). Other studies were partially limited by a small sample size or respective acquisitions being weeks apart. From a technical standpoint, however, differences in findings obtained using these modalities should be minimal because fat is easily identifiable with both (absolute CT numbers and high contrast on T1-weighted MRI).

In three previous MRI studies (17,24,25), the best VAT volume prediction was observed at L3-4 for females and at L1-2 or L2-3 (slightly more cranial) for males, in very good agreement with the results here. The two largest MRI studies of subjects with overweight found L2-3 to be most accurate for both sexes (26,27), which is also in line with our findings.

$V_{VAT,T}$ is often estimated by (axial) sections located at the UM or FH, without any apparent validation. In patients with overweight or obesity, a few direct comparisons with (lumbar) vertebral landmarks, including this work, have shown that estimation using the UM is inferior (17,24) and should, therefore, not be used for such subjects. A recent comparison in 50 patients with a mean BMI of 25 kg/m², however, showed the UM to be as accurate as lumbar-spine landmarks (40), which might be explained by the lower positional (craniocaudal) variation of the UM in patients with (presumably) less subcutaneous fat. The FH have also been evaluated in abdominal studies, however, five-section blocks repeatedly outperformed single-section analyses (17,24). This apparent discrepancy can be attributed to the axial coverage scaling with the underlying section thickness. A four-section CT approach at 5-mm thickness, for example, samples the same anatomy as a two-section MRI approach at

The differences between one or five sections were generally small in this work. This is supported by Tong et al., who found the correlation of three-section blocks around L4- with $V_{VAT,T}$ to be only minimally better than that of single sections (31). In two MRI-based VAT studies, however, five-section blocks repeatedly outperformed single-section analyses (17,24). This apparent discrepancy can be attributed to the axial coverage scaling with the underlying section thickness. A four-section CT approach at 5-mm thickness, for example, samples the same anatomy as a two-section MRI approach at
The covered partial volume is then more relevant for comparisons than the mere number of sections.

For large-scale clinical application of VAT volumetry, efficiency is essential. In comparison with an earlier analysis of the whole abdomen (83 sections), the section-based approaches (one or five) save a considerable amount of time (average of 14 minutes) and effort (17). The analysis of just one section (instead of five) may be preferable here because processing ease and speed seem to outweigh the minimal loss of accuracy. Other segmentation tools may be used as well but typically do not feature an automatic preselection of the VAT boundaries. Although this retrospective VAT analysis did not require any additional radiation exposure, a prospective CT assessment would also have to factor in the higher radiation dose of a full abdominopelvic CT examination.

Our study is limited by a retrospective design and moderate cohort size, especially for females, suggesting that the findings for females should be interpreted with some care. The moderate size also explains the omission of further subgroup analyses, for example, with respect to age. Our analysis does not account for different ethnicities because patients were selected without that information. The use of data from different CT models is likely to have introduced some variability and has been partially addressed by selecting data sets with a fixed section thickness (5 mm).

Another limitation is the missing comparison of our CT segmentation results with an independent reference. We may assume, however, that the quantitative agreement of such a comparison would be similar to that of a previous validation of an MRI tool (18), from which our CT tool practically evolved. In addition, segmentation of standardized CT intensities should be more reliable than that of MRI intensities, which typically have arbitrary units. A limitation of other studies is the use of correlation coefficients only, which do not provide a magnitude of agreement like the $\varsigma^2$ added here. Landmarks with the highest correlation might then differ from those with the smallest error, as observed for females here. Future comparisons would, therefore, benefit from following relevant standards.
Conclusion

Our CT-based VAT analysis in patients with overweight and obesity suggests that single-section data should be preferred for practical volume estimation. $A_{VAT}$ should generally be measured at axial levels above L4-5, and landmarks like the UM or the FH should not be used. Our data indicate L1-2 or L2-3 for males and L2-3 for females as suitable levels. The respective $s_d$ values (roughly 12%-15%) are considered to be accurate enough for whole-abdomen VAT assessment, which also confirms our working hypothesis. The postprocessing of single sections is considerably faster than that of complete abdominal data sets. We believe that our findings have a practical value and that they may also encourage more clinical studies on the relevance of VAT in patients with chronic metabolic or oncological diseases as well as on periprocedural stratification of surgical patients.

Acknowledgments

We would like to thank Roland Stange and Nikita Garnov for their extensive technical assistance with the software.

Disclosure: FL reports personal fees from Amgen, Astellas, Astra Zeneca, Biontech, Eli Lilly, Elsevier, Excerpta Medica, Imelex, Intumedica, Medscape, MedUpdate, Merck Serono, Merck Sharp Dohme, Oncovis, Promedicis, Springer Nature, StreamedUp!, Zymeworks, Bayer, and Roche, as well as grants and personal fees from Iomedico and Bristol-Myers Squibb, all outside the submitted work. The other authors declared no conflict of interest.

References

1. Arroyo-Johnson C, Mincey KD. Obesity epidemiology worldwide. *Gastroenterol Clin North Am* 2016;45:571-579.
2. Williams EP, Mesider M, Winters K, Dubbert PM, Wyatt SB. Overweight and obesity: prevalence, consequences, and causes of a growing public health problem. *Curr Obes Rep* 2015;4:363-370.
3. Després J-P, Lemieux I. Abdominal obesity and metabolic syndrome. *Nature* 2006;444:881-887.
4. Bergman RN, Kim SP, Catalano KJ, et al. Why visceral fat is bad: mechanisms of the metabolic syndrome. *Obesity (Silver Spring)* 2006;14(suppl 1):168-198.
5. Fox CS, Massaro JM, Hoffmann U, et al. Abdominal visceral and subcutaneous adipose tissue compartments: association with metabolic risk factors in the Framingham Heart Study. *Circulation* 2007;116:39-48.
6. Abraham TM, Pedley A, Massaro JM, Hoffmann U, Fox CS. Association between visceral and subcutaneous adipose depots and incident cardiovascular disease risk factors. *Circulation* 2015;132:1639-1647.
7. Wagenknecht LE, Langefeld CD, Scherzinger AL, et al. Insulin sensitivity, insulin secretion, and abdominal fat: the Insulin Resistance Atherosclerosis Study (IRAS) Family Study. *Diabetes* 2003;52:2490-2496.
8. Bian X, Dai H, Feng J, et al. Prognostic values of abdominal body compositions on survival in advanced pancreatic cancer. *Medicine (Baltimore)* 2018;97:e10988. doi:10.1097/MD.0000000000010988.
9. Zhai T, Zhang B, Qu Z, Chen C. Elevated visceral obesity quantified by CT is associated with adverse postoperative outcome of laparoscopic radical nephrectomy for renal clear cell carcinoma patients. *Int Urol Nephrol* 2018;50:845-850.
10. Tranchart H, Gaujoux S, Rebours V, et al. Preoperative CT scan helps to predict the occurrence of severe pancreatic fistula after pancreaticoduodenectomy. *Ann Surg* 2012;256:139-145.
11. Pausch T, Hartwig W, Hinze U, et al. Cachexia but not obesity worsens the postoperative outcome after pancreatectoduodenectomy in pancreatic cancer. *Surgery* 2012;152:581-588.

12. Iwase T, Sangai T, Fujimoto H, et al. Quality and quantity of visceral fat tissue are associated with insulin resistance and survival outcomes after chemotherapy in patients with breast cancer. *Breast Cancer Res Treat* 2019;179:435-443.

13. Nattrass Miller J, Böhm J, Bagdassarian A, et al. CT quantified adipose tissue distribution: risk or protective factor for complications after rectal cancer surgery? *Obes Facts* 2019;12:259-271.

14. Lee JW, Ban MJ, Park JH, et al. Visceral adipose tissue volume and CT attenuation as prognostic factors in patients with head and neck cancer. *Head Neck* 2019;41:1605-1614.

15. Schwenzer NF, Machann J, Schraml C, et al. Quantitative analysis of adipose tissue in single transverse slices for estimation of volumes of relevant fat tissue compartments: a study in a large cohort of subjects at risk for type 2 diabetes by MRI with comparison to anthropometric data. *Invest Radiol* 2010;45:788-794.

16. Reinhardt M, Paggi P, DeMers B, Trinidad C, Krakoff J. Cross calibration of two dual-energy X-ray densitometers and comparison of visceral adipose tissue measurements by iDXA and MRI. *Obesity (Silver Spring)* 2016;25:332-337.

17. Schaudinn A, Linder N, Garnov N, et al. Predictive accuracy of single- and multi-slice MRI for the estimation of total visceral adipose tissue in overweight to severely obese patients. *NMR Biomed* 2015;28:583-590.

18. Thörner G, Bertram HH, Garnov N, et al. Software for automated MRI-based quantification of abdominal fat and preliminary evaluation in morbidly obese patients. *J Magn Reson Imaging* 2013;37:1144-1150. doi:10.1002/jmri.23890

19. Nemoto M, Yeurner T, Masutani Y, et al. Development of automatic visceral fat volume calculation software for CT volume data. *J Obes* 2014;2014:495084. doi:10.1155/2014/495084

20. Hau SCN, Zhang T, Shi L, Wang D, Ip C-B, Chu WCW. Automated segmentation of abdominal subcutaneous adipose tissue and visceral adipose tissue in obese adolescent in MRI. *Magn Reson Imaging* 2018;45:97-104.

21. Ozola-Zālīte I, Mark EB, Gudauskas T, et al. Reliability and validity of the new VikingSlice software for computed tomography body composition analysis. *Eur J Clin Nutr* 2019;73:54-61.

22. Kim YJ, Park JW, Kim JW, et al. Computerized automated quantification of subcutaneous and visceral adipose tissue from computed tomography scans: development and validation study. *JMRI Med Inform* 2016;4:62. doi:10.2196/medinform.4923

23. Addeman BT, Kanny S, Perkins TG, et al. Validation of volumetric and single-slice MRI adipose analysis using a novel fully automated segmentation method. *J Magn Reson Imaging* 2015;41:233-241.

24. Linder N, Schaudinn A, Garnov N, et al. Age and gender specific estimation of visceral adipose tissue amounts from radiological images in morbidly obese patients. *Sci Rep* 2016;6:22261. doi:10.1038/rep22261

25. Schweitzer L, Geisler C, Pourhassan M, et al. What is the best reference site for a single MRI slice to assess whole-body skeletal muscle and adipose tissue volumes in healthy adults? *Am J Clin Nutr* 2015;102:58-65.

26. Maislin G, Ahmed MM, Goonereene N, et al. Single slice vs. volumetric MR assessment of visceral adipose tissue: reliability and validity among the overweight and obese. *Obesity (Silver Spring)* 2012;20:2124-2132.

27. Demerath EW, Shen W, Lee M, et al. Approximation of total visceral adipose tissue with a single magnetic resonance image. *Am J Clin Nutr* 2007;85:362-368.

28. Iftekhar T, Massaro JM, Bamberg F, O’Donnell CJ, Hoffmann U, Fox CS. Association between single-slice measurements of visceral and abdominal subcutaneous adipose tissue with volumetric measurements: the Framingham Heart Study. *Int J Obes (Lond)* 2010;34:781-787.

29. Kuk JL, Church TS, Blair SN, Ross R. Measurement site and the association between visceral and abdominal subcutaneous adipose tissue with metabolic risk in women. *Obesity (Silver Spring)* 2010;18:1336-1340.

30. Noumura Y, Kamishima T, Sutherland K, Nishimura H. Visceral adipose tissue area measurement at a single level: can it represent visceral adipose tissue volume? *Br J Radiol* 2017;90:20170253. doi:10.1259/bjr.20170253

31. Tong Y, Udupa JK, Torigian DA. Optimization of abdominal fat quantification on CT imaging through use of standardized anatomic space: a novel approach. *Med Phys* 2014;41:63501. doi:10.1118/1.4876275

32. Lordick F, Kang YK, Chung HC, et al. Cetuximab and cisplatin with or without cetuximab for patients with previously untreated advanced gastric cancer (EXPAND): a randomised, open-label phase 3 trial. *Lancet Oncol.* 2013;14:490-499. doi:10.1016/s1470-2045(13)70102-5

33. Yoshizumi T, Nakamura T, Yamane M, et al. Abdominal fat: standardized technique for measurement at CT. *Radiology* 1999;211:283-286.

34. Shen W, Wang Z, Punyanita M, et al. Adipose tissue quantification by imaging methods: a proposed classification. *Obes Res* 2003;11:5-16.

35. Shen W, Punyanita M, Wang Z, et al. Visceral adipose tissue: relations between single-slice areas and total volume. *Am J Clin Nutr* 2004;80:271-278.

36. Klopfenstein BJ, Kim MS, Krisky CM, Szumowski J, Rooney WD, Purnell JQ. Comparison of 3 T MRI and CT for the measurement of visceral and subcutaneous adipose tissue in humans. *Br J Radiol* 2012;85:e26-e30.

37. Pescatori LC, Savarino E, Mauri G, et al. Quantification of visceral adipose tissue by computed tomography and magnetic resonance imaging: reproducibility and accuracy. *Radiol Bras* 2019;52:1-6.

38. Yoon DY, Moon HJ, Kim HK, et al. Comparison of low-dose CT and MR for measurement of intra-abdominal adipose tissue: a phantom and human study. *Acad Radiol* 2008;15:62-70.

39. Mitsiopoulos N, Baumgartner RN, Heymsfield SB, Lyons W, Gallagher D, Ross R. Cadaver validation of skeletal muscle measurement by magnetic resonance imaging and computerized tomography. *J Appl Physiol* 1998;85:115-122.

40. Faron A, Luetkens JA, Schmeel FC, Kuetting DLR, Thomas D, Sprinkart AM. Quantification of fat and skeletal muscle tissue at abdominal computed tomography: associations between single-slice measurements and total compartment volumes. *Abdom Radiol (NY)* 2019;44:1907-1916.