Cross Calibration of Two Dual-Energy X-Ray Densitometers and Comparison of Visceral Adipose Tissue Measurements by iDXA and MRI

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Objective: Compare total percentage body fat (pfat) measurements between two densitometers and visceral adipose tissue (VAT) estimates between iDXA and magnetic resonance imaging (MRI) from the same defined abdominal region.

Methods: Participants \[N = 93\] (50 men, 43 women), BMI: 19.1–57.6 kg/m² underwent dual-energy X-ray absorptiometry (DXA) scans on two DXA systems (GE Healthcare Lunar iDXA and Lunar Prodigy), and a subgroup underwent abdominal MRI imaging for quantification of VAT.

Results: Pfat correlated strongly between both machines \((r^2 = 0.98, P < 1.0E-14)\). Bland-Altman plots showed a bias with higher measured pfat on iDXA versus Prodigy in leaner subjects and the opposite in more overweight subjects. The \(R^2\) for regression of MRI on iDXA VAT values was 0.948. Bland-Altman bias was \(+104.1 \text{ cm}^3\) with 95% limits of agreement of \(-681.9\) to \(890.0 \text{ cm}^3\). For both DXA methods, and iDXA versus MRI determined VAT, comparison using rank regression demonstrated no order bias.

Conclusions: The total pfat measured by both machines was strongly and linearly associated, allowing for conversion (equations are provided) of iDXA for assessment of longitudinal body fat changes. Despite a bias of abdominal VAT measures of iDXA versus MRI, the high rank correlation makes iDXA a good alternative to the more complicated and time-consuming MRI for use in larger cross-sectional and longitudinal studies.

Introduction

Dual-energy X-ray absorptiometry (DXA) provides accurate measurement of body composition, which is essential for the quantification of adipose and lean tissue and their distribution during and after interventions in energy balance studies. DXA systems have replaced underwater weighing as a method to determine body composition in nearly all clinical and research facilities. Technical innovations led to a transition from the early pencil-beam to modern fan-beam densitometers, which utilize multiple detectors in favor of faster scan times and near-radiographic image quality (1). Longitudinal studies with repeated body composition measurements require comparable assessments of the percentage body fat (pfat), fat mass (FM), and fat-free mass (FFM). When baseline and follow-up body composition measurements are not performed with the same DXA machine, e.g., due to system upgrades, cross-calibration studies are necessary to compare results from different DXA systems. Recent cross-calibration studies comparing precision of body composition measurements between different fan-beam systems have reported excellent (2) or good agreement (3) and have proposed the use of translational equations to ensure comparability of body composition measurements (3).

The recently introduced fan-beam Lunar iDXA (GE Healthcare) densitometer allows, for the first time, fully automated, dedicated measurement of visceral adipose tissue (VAT), separately from subcutaneous adipose tissue. Adipose tissue distribution (in particular VAT vs. subcutaneous adipose tissue) rather than total adiposity has been associated with adverse health events (4-7). Previous reports on the precision of VAT measurements done by iDXA in...
comparison with the time- and resource-intensive gold standard methods computed tomography (CT) and magnetic resonance imaging (MRI) have reported a strong correlation of VAT measured with the respective imaging modalities throughout a wide range of body sizes and different ethnicities (8-10). However, to our knowledge, previous reports have compared a fixed region of interest (ROI) from CT or MRI scans, defined as 150 mm of the abdomen, beginning at the top of S1 and moving toward the head (8-10), while the CoreScan software (iDXA) individually defines a ROI whose caudal limit is the top of the iliac crest and in which the height is set to 20% of the distance from the top of the iliac crest to the base of the mandible to account for interindividual differences in body size.

The aim of this study was to precisely compare total pfat measurements between two fan-beam densitometers (GE Healthcare Lunar Prodigy and Lunar iDXA) and VAT estimates between iDXA and MRI from the same defined abdominal region.

**Methods**

**Subjects**

We recruited 100 subjects without reported health problems (50 women and 50 men, aged 18.6–64.7 years) from the greater Phoenix, AZ, area with a broad range of body mass index (BMI) (19.1–57.6 kg/m²), who underwent DXA scans on both machines (Prodigy and iDXA), in random order. The only exclusion criteria were age <18 years, pregnancy or breastfeeding, or weight >159 kg (weight limit for Prodigy). By design, we recruited approximately equal numbers of women and men in the following BMI groups <25 kg/m² (normal weight; 16 women, 16 men), ≥25 to <30 kg/m² (overweight; 16 women, 18 men), and ≥30 kg/m² (obesity; 16 women, 16 men). Seven participants (all with BMI >30 kg/m²) were excluded from the analyses. These seven scans were performed as half scans of the right side of the body, previously validated for calculation of total-body fat on the same scanner (11). A limitation of available DXA systems is the size of the scanning area (~190 × 60 cm), meaning the body dimensions can exceed the scanning area. These seven participants had been improperly positioned on the table during one of the scans. Thus, in the Results section we report results of 93 participants (Table 1) whose demographic and anthropometric characteristics did not differ significantly from the initially recruited 100 subjects.

From the initial 100 individuals, 40 (20 women and 20 men) underwent additional abdominal MRI [<25 kg/m² (six women, six men), ≥25 to <30 kg/m² (seven women, seven men), and ≥30 kg/m² (seven women, seven men)]. Female participants underwent a urine pregnancy test within 1 hour of the DXA scans. Volunteers were fully informed of the nature and purpose of the study they participated in, and written informed consent was obtained before admission. DXA measurements were done at the clinical research unit of the Obesity and Diabetes Clinical Research Section of the National Institute of Diabetes and Digestive and Kidney Diseases, Phoenix, AZ. MRIs were performed at St. Joseph’s Hospital and Medical Center at the Kelly Center for Imaging Innovation, Phoenix, AZ. The protocol was approved by the Institutional Review Board of the National Institute of Diabetes and Digestive and Kidney Diseases and by the St. Joseph’s Hospital and Medical Center at the Kelly Center for Imaging Innovation’s Institutional Review Board.

**Dual-energy X-ray absorptiometry**

All total-body DXA scans were performed in the morning after an overnight fast (no caloric intake after 8 p.m. the night before the

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**TABLE 1** Demographic and anthropometric characteristics of the study population

|                      | Total study cohort with both DXA scans | Subgroup with both DXA scans and abdominal MRI scan |
|----------------------|---------------------------------------|-----------------------------------------------------|
|                      | Total (N = 93)                      | Women (N = 43)                                     | Men (N = 50)                                      |
|                      |                                      | Total (N = 40)                                     | Women (N = 20)                                    | Men (N = 20)                                      |
| **Race**             | B = 1, H = 2                        | A = 1, B = 5                                      | B = 1, H = 1                                      | A = 3, H = 4                                      |
|                      | NA = 4                              | NA = 15                                          | NA = 3                                           | NA = 5                                           |
| **Age (y)**          | 38.6 ± 11.6                         | 36.6 ± 10.7                                      | 37.4 ± 11.5                                      | 35.8 ± 9.9                                      |
|                      | 168.6 ± 9.6                         | 168.3 ± 9.1                                      | 161.9 ± 7.3                                      | 174.7 ± 5.3***                                   |
| **Height (cm)**      | 79.1 ± 17.7                         | 8.2 ± 20.6                                       | 7.6 ± 21.7                                       | 87.3 ± 18.6                                      |
| **BMI (kg/m²)**      | 27.8 ± 5.7                          | 29.1 ± 7.5                                       | 29.5 ± 8.8                                       | 28.6 ± 6.1                                      |
| **pfat DXA (%)**     | 34.2 ± 11.0                         | 35.1 ± 12.0                                      | 42.9 ± 8.8                                       | 27.3 ± 9.5***                                   |
|                      | 34.1 ± 10.0                         | 35.1 ± 11.3                                      | 41.7 ± 9.3                                       | 28.5 ± 9.1***                                   |
| **FM DXA (kg)**      | 27.8 ± 12.5                         | 29.8 ± 15.2                                      | 34.3 ± 16.0                                      | 25.2 ± 13.2                                      |
| **FM iDXA (kg)**     | 27.7 ± 12.5                         | 30.0 ± 15.9                                      | 33.6 ± 17.3                                      | 26.3 ± 13.7                                      |
| **FFM DXA (kg)**     | 51.3 ± 11.4                         | 52.4 ± 12.4                                      | 42.6 ± 7.1                                       | 62.1 ± 8.0***                                   |
| **FFM iDXA (kg)**    | 51.4 ± 10.8                         | 52.2 ± 11.1                                      | 43.3 ± 6.0                                       | 61.1 ± 7.1***                                   |
| **VAT iDXA (cm³)**   | 1,210 ± 1,245                       | 997 ± 948                                        | 1,423 ± 1,480                                    | 1,318 ± 1,157                                    |
| **VAT MRI (cm³)**    | 1,106 ± 930                         | 893 ± 584                                        | 1,423 ± 1,480                                    | 1,318 ± 1,157                                    |

Shown is the total study population N = 93 and N = 40 with both DXA scans and abdominal MRI scan. Values are presented as mean ± SD. Differences between men and women were assessed by two-sample Student’s t-test (*P < 0.05; **P < 0.01; ***P < 0.0001). A, Asian; B, Black; BMI, Body mass index; FM, fat mass; FFM, fat-free mass; H, Hispanic; NA, Native American; pfat, percentage body fat; W, White.
scans). Consecutive whole-body composition measurements were performed in random order on two fan-beam DXA machines—one being the Prodigy (enCORE 2003 software version 7.53.002, GE, Madison, WI) and the second being the iDXA (enCORE version 15, GE Healthcare). Subjects were scanned using standard imaging and positioning protocols. With both DXA systems, the operator remained in the room with the subject during the scan. For measuring VAT, a ROI was automatically defined by the iDXA software algorithm, with the caudal limit at the top of the iliac crest and the height set to 20% of the distance from the top of the iliac crest to the base of the mandible. FM data (gram) from iDXA were transformed into MRI adipose tissue volume using a constant correction factor (0.94 g/cm³), assuming a constant density for adipose tissue (12).

Magnetic resonance imaging
Abdominal imaging was done with a Philips Ingenia 3.0T scanner (Philips, Amsterdam, Netherlands). Volunteers were examined in a supine position, using 2 dS anterior coils and a dS posterior coil. Images were obtained in transverse slice orientation (two-point Dixon sequence; eight stacks containing 8–12 slices each; thickness 10 mm; and 0.1 mm inter-slice gap; TR shortest (3.7 ms); TE 1.4 ms; flip angle 10°). VAT volume as measured by MRI was determined according to an individually sized ROI based on the respective VAT ROI estimates from the automated iDXA software algorithm (see Methods/Dual-energy X-ray absorptiometry) and were quantified using OsirIX image processing software (version 6.5.2). All MRI–VAT volumes were quantified twice in random order by a single radiologist blinded to participant data [CV 2.8% ± 3.1 (SD)].

Sample size calculation
Based on previous studies (3,13) comparing the Prodigy and iDXA, using total FM of 23,027 ± 10,167 g for Prodigy and 24,351 ± 9,543 g for iDXA with a correlation coefficient of 0.97 between the measurements at a two-sided α of 0.05, we calculated that 50 participants would give us a power of 0.94 to detect a difference in pfat. An additional 50 subjects were recruited to validate the prediction equation calculated in the first 50 subjects (see below).

Previous studies of VAT comparisons using CT scans and iDXA demonstrated an \( r^2 \) for the univariate model of DXA visceral fat regressed on CT visceral fat equal to 0.96. For our power calculation, we used a more conservative \( r^2 \) of 0.80 for the univariate model of MRI visceral fat with iDXA visceral fat. Thus, 40 participants would give us power of >0.9 to detect a significant association between these two measurements.

Statistical analysis
To compare body composition measurements between the Prodigy DXA and iDXA systems on the same individuals, linear regression models and paired Student’s \( t \)-test were used for each of the main variables of interest (pfat, FM, and FFM). An equation was used to convert the pfat values, measured by iDXA on the first \( n = 50 \) (\( n = 47 \), please see Methods/Subjects for clarification) individuals, to values measured by Prodigy in the same individuals. The results of this prediction were then validated against the measurements of the second \( n = 50 \) (\( n = 46 \)) individuals. To compare the measured pfat values of the second 46 subjects (iDXA) with the predicted Prodigy values obtained by using the regression equation calculated from the first 47 subjects’ values, we calculated the difference between measured minus predicted pfat values for each subject and then tested these differences against 0, using one-sample Student’s \( t \)-tests.

We used linear regression models to assess the association between pfat values acquired with the Prodigy versus iDXA, as well as between visceral fat measured by iDXA and MRI. For both comparisons, we assessed the agreement between different imaging techniques and evaluated any systematic (intercept) or proportional (slope) bias by two methods using: Bland-Altman diagrams and the 95% limits of agreement procedure (14) and the nonparametric Passing-Bablok regression (11) which is more robust to the presence of outliers. The CUSUM test was used to evaluate the linearity of the relationship. Lastly, the coefficient of variation (CV), the intra-class correlation (ICC), and the Spearman’s rank-order correlation (\( \rho \)) between the measures of body fat on each machine were also calculated.

Results
Comparison analysis: Prodigy DXA versus iDXA
Demographic characteristics of the study population are presented in Table 1.

In the first 47 subjects, over a wide range of adiposity we found a strong correlation between the pfat values measured on both machines (\( r^2 = 0.98, P < 1.0E-14; \) Figure 1a). We found an equally strong correlation when we used the regression equation obtained from the first 47 subjects (Prodigy DXA pfat = -3.417 + 1.099 \( \times \) iDXA pfat) to calculate the predicted Prodigy DXA pfat values in the second cohort and compare them with measured values (\( r^2 = 0.98, P < 1.0E-14; \) Figure 1b). Furthermore, there was an equally strong correlation between the measured values of the second 46 subjects (\( r^2 = 0.98, P < 1.0E-14; \) Figure 1c). The mean difference between the predicted Prodigy versus measured (iDXA) pfat values was not significantly different from 0 [mean pfat difference = 0.27%, 95% confidence interval (CI): -0.15 to 0.70, \( P = 0.21 \)]. The mean absolute error of the pfat prediction was 1.7%, ranging from 0.1% to 9.8%. The ICC for all 93 pfat measurements performed on both machines was 0.986 (95% CI: 0.979 to 0.991), and the CV was 3.6%. In the entire group (\( n = 93 \)), pfat, FM, and FFM measurements were not significantly different between the two systems (paired \( t \)-test: \( P = 0.59, P = 0.58, P = 0.58 \), respectively).

The Bland-Altman plots (Figure 2a, b) demonstrated a bias with higher measured pfat on iDXA versus Prodigy DXA in leaner subjects and the opposite in more overweight subjects. As mentioned above, seven participants with improperly positioned half-right body scans were excluded from all analyses. To assess the impact of excluding those half scans, we performed a sensitivity analysis with and without these seven scans included and then without all half scans. Compared with the correlation between the two scans calculated in the whole cohort (\( N = 100, r^2 = 0.95, P < 1.0E-14 \)), excluding these scans did produce a marginal improvement in the correlation between the two DXA systems (\( N = 93, r^2 = 0.98, P < 1.0E-14; N = 77, r^2 = 0.98, P < 1.0E-14 \)). For the half scans only (\( n = 7 \),...
23), the ICC was 0.89 (95% CI: 0.76 to 0.95), and the CV was 6.5%. After removal of all 23 half-right scans, the Bland-Altman bias was more pronounced (Figure 2a, b). Linearity of relationships between methods was confirmed by the CUSUM test for all $N = 100$, $N = 93$, and $N = 77$ ($P = 0.70$, $P = 0.64$, $P = 0.71$, Figure 3a, b, respectively). Preservation of individual ranks was also confirmed by the Spearman’s correlation ($n = 100$: $\rho = 0.98$; $n = 77$: $\rho = 0.99$, both $P < 0.0001$). Nonparametric Passing-Bablok regression confirmed the bias seen in the Bland-Altman analyses with a significant proportional difference (slope $= 3.0$, 95% CI: 2.24 to 3.85, $N = 93$) and systematic difference (intercept $= 0.90$, 95% CI: 0.88 to 0.93, $N = 93$) between the two methods.

VAT measured with MRI versus iDXA

Demographic characteristics of the 20 men and 20 women who also underwent a MRI scan are presented in Table 1.

The coefficient of determination ($r^2$) for regression of MRI on iDXA values was 0.958 for women, 0.959 for men, and 0.948 combined (Figure 4a). Bland-Altman bias was $+103.6$ cm$^3$ for women and $+104.6$ cm$^3$ for men. The 95% limits of agreement were...
266.9 to +877.0 cm³ for women and −713.7 to +923.0 cm³ for men. Combined Bland-Altman bias was +104.1 cm³ with 95% limits of agreement of −681.9 to 890.0 cm³ (Figure 4b). Linearity of relationships between MRI and iDXA measurements of VAT was confirmed by the CUSUM test ($P = 0.97$). A significant proportional bias (slope = 1.40, 95% CI: 1.28 to 1.57, $n = 40$) between the two methods was confirmed by the Passing-Bablok nonparametric test (Figure 4c). A systematic difference over the total range of values (intercept) was estimated as 287 cm³ (95% CI: −442 to −159). The ICC of the VAT measurements performed by both methods was 0.93 (95% CI: 0.87 to 0.96), and the CV was 25.0%.

Discussion
This study compared body composition from two fan-beam DXA systems and VAT volume of iDXA versus MRI. While the overall correlation between pfat values measured on the two different machines was very high in the 93 subjects over a wide BMI range, we did find a trend toward an overestimation of pfat measured with iDXA compared with Prodigy in leaner individuals and a slight underestimation of pfat in those at the higher ranges of adiposity.

We also found that VAT measured by iDXA showed a strong overall correlation with MRI but was slightly underestimated for lower VAT volumes and overestimated for higher volumes, compared with MRI. For both methods, comparison using rank regression did not
demonstrate a bias in terms of order, indicated by the given linearity of the respective relationships.

Given the reported differences in pFat values measured by the two systems and in agreement with previous works (3,12,16), we recommend the employment of conversion equations derived from cross-calibration studies like ours. This procedure becomes crucial when upgrading DXA units during ongoing longitudinal data collection, e.g., in order to observe and quantify body composition changes during long-term weight gain or weight loss trials. However, albeit statistically significant, the small discrepancy between the two methods (pFat error <1%) is not clinically relevant. The main component of the metabolic syndrome—VAT—seems to be strongly associated with cardiometabolic risk factors, due to its metabolic activity (15). Furthermore, VAT has been shown to be predictive of all-cause mortality (17). Hence, precise estimation of VAT volume in both cross-sectional and longitudinal settings might be one of the important parameters in monitoring obesity.

With a population based overall rank correlation of $r^2 = 0.948$, iDXA’s fully automated VAT estimation and MRI-derived values are in strong agreement and consistent with previous studies (8,10). However, we found an underestimation in leaner subjects and overestimation of VAT in subjects with greater adiposity in measuring VAT using iDXA versus MRI. This differs from prior studies that found no significant BMI dependent variability (8) or the opposite directionality in the bias for measuring VAT (10). However, these studies compared body size-adjusted iDXA-VAT estimates with an arbitrarily standardized CT or MRI ROI that was defined as 150 mm of the abdomen, starting at the top of S1 and moving toward the head. As noted in our methods, we were able to compare the same ROI designated by the iDXA software to the MRI. Thus, the strength of our study is that we compared that same estimated abdominal VAT from the same ROI for both the iDXA and MRI. Given the demonstrated, clinically significant, systematic difference over the total range of VAT values between iDXA and the gold standard method MRI, we propose that iDXA-VAT measurements might be useful for relative VAT assessment in longitudinal studies, rather than for accurate absolute measurements.

This study did not include subjects under the age of 18 and over the age of 65, which limits the interpretation of our findings for these age groups. The conversion equations provided are tailored to our specific (though ethnically diverse and representative of a wide BMI range) study population and might, however, not be perfectly suitable for any other study population. In addition, the half-body DXA scans used for some of the subjects with more severe obesity resulted in a greater difference between the measurements. The half scan has been validated on the same machine but not between machines. Given the automated algorithm for calculation of pFat, a slight difference in alignment on the table might account for these errors. We performed several sensitivity analyses to assess the impact of these scans and still found an excellent agreement between the measurements.

In conclusion, the total pFat measured by iDXA and Prodigy is strongly and linearly associated and allows for conversion of iDXA for assessment of longitudinal body fat changes. Despite the under- and overestimation of pFat in subjects with very low and very high BMIs, the high rank correlation of abdominal VAT measures of iDXA with MRI, which is considered the gold standard for this measurement, makes iDXA a reliable, cost- and time-effective alternative to MRI for use in cross-sectional and longitudinal studies.

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