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# Evaluation of a rotary laser body scanner for body volume and fat assessment

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## Abstract

This paper reports the evaluation tests on the reliability and validity of a 3-dimensional (3D) laser body scanner for estimation of body volume and % fat. Repeated measures of body imaging were performed for reproducibility analysis. Validity of the instrument was assessed by comparison of measures of body volume by imaging to hydrodensitometry, and body fat was compared to hydrodensitometry and dual energy X-ray absorptiometry. Reproducibility analysis showed little difference between within-subjects measurements of volume (ICC $\geq 0.99$, $p < 0.01$). Body volume estimations by laser body scanner and hydrodensitometry were strongly related ($r = 0.99$, $p < 0.01$), and agreement was high (ICC = 0.99, $p < 0.01$). Measurements of % body fat also agreed strongly with each other between methods (ICC = 0.86, $p < 0.01$), and mean % fat estimates by body imaging did not differ from criterion methods ($p > 0.05$). These findings indicate that the 3D laser body scanner is a reliable and valid technique for the estimation of body volume. Furthermore, body imaging is an accurate measure of body fat, as compared to dual energy X-ray absorptiometry. This new instrument is promising as a quick, simple to use, and inexpensive method of body composition analysis.

### Keywords

body scanning; hydrodensitometry; body fat; body volume; obesity

## Introduction

Increasing prevalence of overweight and obesity, and their association with type 2 diabetes, hypertension, and dyslipidemia in the United States, poses a mounting public health risk [1]. Common methods to measure overweight/obesity are anthropometrics, densitometry [hydrodensitometry, air-displacement plethysmography (ADP), body imaging], dual energy X-ray absorptiometry (DXA), computed tomography (CT), and magnetic resonance imaging (MRI). Anthropometrics [skinfold, body mass index (BMI), waist and hip circumference] are limited by an inability to estimate body fat. Waist circumference, an indicator of abdominal fat, is a strong predictor of obesity-related diseases [2], but manual measurements exhibit low inter-rater reliability and are awkward [3].

Densitometric methods such as hydrodensitometry and air-displacement plethysmography measure volume and calculate body fat via an equation with weight [4, 5]. However, hydrodensitometry is stressful for participants and inappropriate for some populations, as it requires subjects to be submerged repeatedly in a small enclosure of water while exhaling maximally [6]. ADP and DXA also are common criterion references for body composition [7-9], but their non-portability is restrictive for clinical and field studies. In addition, limits for body weight with DXA preclude its use in morbid obesity [10]. CT scanning and MRI provide measurements of body size, shape, and % fat, but these are limited by large instrument size, high expense (and ionizing radiation for CT). Thus, the need remains for more convenient and precise instruments to assess body size, shape, and obesity.

Over the past decade, body volume has been measured and fat estimated by computerized body imaging via the equations of Siri [5] or Brozek [4]. In 2000, Wells et al. introduced an 8-camera Hamamatsu scanner to assess body composition by near-infrared light emitting diode. The original device required a 12 second scan, but volume estimates were not related strongly to hydrodensitometry [11]. In 2006, an improved version with only four cameras collected 20 times as many data points in 10 seconds; volumes estimated by this scanner were better associated with criterion methods [12]. This same scanner also evaluated severely obese individuals; comparisons to other methods of body fat analysis are unclear [13]. Recently, a portable, 6-camera imager based on structured light by Textile/Clothing Technology Corporation ([$TC^2$]) assessed body size and shape in American and British subjects [14-16]; validation to body volume and % fat is in progress. A system of multiple lasers was used for the Chang Gung scanner developed by Liu et al. to evaluate health based on height, weight, and body area in the Chinese [17]. Measurements via body scanning were related more strongly to metabolic syndrome risk factors (blood pressure, triglycerides, high density lipoprotein cholesterol) than traditional anthropometrics [18, 19].

Recently, we developed a rotary laser scanning system for rapid, noncontact acquisition of 3D whole body images. The system is portable, containing only two small laser depth-sensing units. The individual units rotate in tandem, and the Class II laser line sweeps the body from ground to head via rotation of the step motor [20]. This movement allows optical triangulation and computer identification of over 100,000 data points within 3 seconds. Construction of the compact, smooth, three-dimensional model of the subject was accomplished via surface simplification and fitting techniques [21]. Body volumes were calculated by the proprietary software using automatically located landmarks [20], and body densities were determined using body volumes and scale weights. This 3D body scanner is inexpensive, portable, and more convenient than other available methods.

The purpose of this paper is to determine the validity of this rotary laser body scanner for the assessment of body composition.

## Experiments

### Subjects

Caucasian and Hispanic women were recruited via posters on The University of Texas at Austin campus and in doctors' offices, and by word-of-mouth. The 70 subjects were age 18-65, BMI 18.5-39.9 kg/$m^2$; women who were currently ill, pregnant, or lactating were excluded from the study. Informed consent was obtained and the study was approved by The University of Texas at Austin Institutional Review Board.

Anthropometric measurements, imaging, hydrodensitometry, and DXA scans were performed on one occasion within 3 hours of each other in the same order for all subjects. All subjects refrained from eating at least 3 hours prior to testing. They did not eat or drink during testing, and avoided caffeine, alcohol, and exercise for at least 8 hours before testing.

## Anthropometric measurements

Height (cm) via stadiometer (Perspective Enterprises, Portage, MI) was measured to the nearest 0.1 centimeter. Body mass (kg) was determined by a calibrated electronic scale (Model TBF-300A Body Composition Analyzer/Scale, Tanita Corporation, Arlington Heights, IL) to the nearest 0.1 kg in subjects wearing only plain white undergarments. BMI was calculated as weight in kg divided by height in meters, squared.

## Three-dimensional laser body imaging

Subjects wore fitted, light-colored undergarments with hair concealed by a swim cap and eyes covered via blindfold. Breathing remained normal throughout scanning, and arms and legs were held slightly away from the body to allow scanning of each body segment [20]. In the event of movement, subjects were immediately rescanned. The scanner consisted of two units, each mounted on an aluminum tripod for a total height of 1.2 m, and placed 2 m apart. Units weighed 2.5 kg and contained a class II laser projector, charge-coupled device camera, and step motor that allowed rotation [20]. Data acquisition was completed in less than 3 seconds, and the 3D model of the body was processed in an additional 20 seconds by the proprietary body imaging software, version 3.0 [20]. Resolution of the laser scan yielded 256 three-dimensional pixels per scan line, up to 102,400 total points. The resolution was 3 mm on the horizontal axis and 6 mm along the vertical. This was not adjustable and was set high enough to allow precise volume calculation. Yet it was sufficiently low to impede facial feature identification and improve speed of measurement. Front and side views of the 360° rotatable model are presented in Figure 1.

Body volume (L) was calculated as the average of two scans by our software, and all measurement cites were automatically located. No adjustment was made for lung volume. Eight total scans were conducted in a sub-sample for reproducibility analysis. The volumes of the body segments were defined as follows: upper torso—neck to umbilicus; lower torso—umbilicus to crotch; thigh—crotch to top of knee. Density (g/cm$^3$) was calculated as mass divided by body volume. Percent body fat was assessed from density using an equation developed by Siri: Body Fat (%) = [4.95 / Density (g/cm$^3$) − 4.50] * 100 [5].

## Hydrodensitometry

Body volume (L) was determined via hydrodensitometry from at least ten repeated measures of underwater weight by a load cell [22]. Subjects were instructed to breathe out as much as possible, then submerge themselves and continue blowing until they could not exhale any more air. At maximal exhalation, the underwater weight was determined. The final reported underwater weight was the mean of the three best underwater weights from the ten trials. Underwater weight was adjusted for air remaining in the lungs using the expected residual volume [23]. Measurements were conducted in water at 28 - 30° C at the Fitness Institute of Texas. Percent body fat was calculated by the Siri equation [5].

## Dual-energy X-ray absorptiometry

Subjects wearing clothes with no metal were administered a whole body scan by a trained technician using the GE/Lunar Prodigy densitometer (GE Lunar Medical Systems, Milwaukee, WI) at the Fitness Institute of Texas. The thickness mode was automatically selected by the instrument. Body composition was analyzed with version 12.2 software. Reported mean bias of the Lunar Prodigy densitometer as compared to deuterium dilution was < 2.28 % fat for healthy and obese women [24].

### Statistical Analysis

Descriptive characteristics of healthy weight versus overweight/obese subjects were compared using independent samples t-test to discern statistical variations in the sample. The presence of systematic error by laser imaging was evaluated by regression analysis of testing order, age, or BMI on mean differences between imaging and criterion methods body volume and % fat estimates. Intraclass correlation coefficients (ICC) and coefficients of variation were used to measure reproducibility of the body scanner over eight repeated scans.

Body volume (L) assessments obtained from imaging and hydrodensitometry were compared by paired-samples t-test, ICC of average measures, Pearson's correlation coefficient, and linear regression. ICC demonstrated inter-rater reliability, with the raters designated as methods of body measurement. The value approached 1.0 when the between-subjects differences were very large, as compared to the between-methods differences [25]. ICC for consistency only requires subjects to be ranked similarly; the more rigorous absolute agreement was used to test for similar ranking, as well as similar numerical values [26]. The two-way mixed effect model was chosen because all devices were used on all subjects, making the techniques a constant effect on variance in body measurement [27]. Linear regression also was used to evaluate the relationship between methods, and standard error of the estimate demonstrated the variability in the regression model. The regression equation was compared to the line of identity ($y = 1.0*x + 0.0$) to indicate perfect correlation. Finally, Bland-Altman analysis was conducted to assess measurement bias (mean difference) and 95 % limits of agreement (mean difference ± 1.96 standard deviations) between laser imaging and hydrodensitometry [28].

Imaging and hydrodensitometry volume (L) estimates were used to calculate % body fat by the Siri equation [5]. Mean % fat estimates between methods were evaluated by repeated measures ANOVA, using the Bonferroni adjustment for multiple comparisons [29]. Agreement between % body fat estimates was examined by the absolute agreement model ICC of average measures for all techniques together, and as pair-wise comparisons with body scanning. The relationships between imaging and hydrodensitometry or DXA % fat estimates were assessed using Pearson's correlation coefficients. Linear regression further described the relationships between imaging and criterion methods, specifically the ability of imaging body fat estimations to predict those by hydrodensitometry and DXA. Bland-Altman analysis of body fat estimation by imaging as compared to hydrodensitometry and DXA indicated a mean bias ± 1.96 standard deviations (95 % limits of agreement). Values are given as mean ± standard error and the α level adopted for statistical significance was $p < 0.05$. All analyses were performed using SPSS Statistics version 13.0 (SPSS Inc, Chicago, IL).

## Results

Table 1 shows characteristics of subjects, stratified by healthy and overweight/obese to show variations in the sample. Overweight participants represented 27 % of the sample, and 19 % were obese (BMI 25.0 - 29.9 and ≥ 30 kg/m$^2$, respectively). The overweight/obese subjects were older and had greater fat mass, as well as increased bone mineral content ($p < 0.05$) than those with healthy weights. Healthy weight subjects did not differ from the overweight/obese group in height or lean mass ($p > 0.05$). For all analyses, mean differences between body volume or fat were not related to testing order, age, or BMI by regression analysis ($p > 0.05$). This lack of significant relationship between measurement and order, age, or BMI indicates absence of bias in measurement by the laser imaging device with these factors. In other words, any error in laser imaging analysis of body size and shape is consistent across order, age, and BMI.

Reproducibility of imaging volumes (L) as assessed by eight repeated scans on a subset of 30 subjects, is presented in Table 2. Mean and standard error for total and regional body volumes ranged from 4.87 ± 0.17 L in the thigh to 69.09 ± 3.86 L total body volume. All ICCs were ≥ 0.99, with thigh volume having the lowest ICC (0.997). Coefficients of variation exhibited little difference between within-subjects measurements. Total body volume was the most reliable, with 0.41% variation over eight scans. Thigh volume, the smallest region, was the most variable (coefficient of variation 2.26 %).

The relationship of imaging and hydrodensitometry body volume (L) measurements is found in Figure 2. Body volume by imaging was significantly related to hydrodensitometry ($r = 0.994$, $p < 0.01$). Regression analysis allowed further investigation of the relationship between body volume methods. The regression coefficient of imaging on hydrodensitometry was not significantly different from 1.0 ($p = 0.65$), and the constant was non-significant ($p = 0.84$). This indicates that the relationship was not different from the line of identity ($y = 1.0*x + 0.0$). Standard error of the estimate, an indication of variability, was 1.60 L.

The relationships between estimates of volume and body fat are provided in Table 3. Mean volume measurements were similar (67.84 ± 1.74 and 67.64 ± 1.72 L for imaging and hydrodensitometry, respectively), and were not significantly different by paired-samples t-test (mean difference 0.20 ± 0.19 L, $p = 0.30$). Mean bias when comparing hydrodensitometry to laser imaging volume was 0.20 ± 0.19 L, and limits of agreement were ± 3.12 L. Agreement between body volume measurements was significant and close to 1.0 (ICC = 0.997, $p < 0.01$). Pearson's correlation coefficient showed a strong relationship ($r = 0.994$, $p < 0.01$). As illustrated in Figure 2, regression analysis indicated that the relationship between imaging and hydrodensitometry measurements of body volume was not significantly different from the line of identity.

Percent body fat calculated from imaging demonstrated good agreement with hydrodensitometry and DXA. Repeated measures ANOVA indicated a significant main effect; pairwise comparison revealed the difference between imaging and hydrodensitometry or DXA was not significantly different from zero ($p = 0.81$ and 0.43, respectively). However, hydrodensitometry and DXA were significantly different from each other ($p < 0.01$). Average bias between imaging and hydrodensitometry or DXA measurement of percent body fat were 1.41 ± 1.26 and -1.91 ± 1.29 %, respectively (limits of agreement 20.72 and 21.18 %, respectively). Percent body fat estimates showed good agreement between methods, with an overall ICC relating all methods > 0.86 ($p < 0.01$). Pair-wise ICCs were > 0.74 ($p < 0.01$), and Pearson's correlation coefficients were > 0.67 ($p < 0.01$). Regression analysis demonstrated a significant relationship between body fat measurements by imaging and hydrodensitometry, although the constant also was significant (15.38, $p < 0.01$). Similarly, imaging was significantly related to DXA by linear regression with a significant constant (21.97, $p < 0.01$).

Estimations of % body fat via the imaging technique are shown graphically in comparison to measures from hydrodensitometry and DXA in Figure 3. Mean body fat was 33.95 ± 1.74 % by imaging, 32.54 ± 1.28 % by hydrodensitometry, and 35.86 ± 1.06 % by DXA. There was a significant main effect by repeated measures ANOVA ($p < 0.05$), so pair-wise comparisons were evaluated using the Bonferroni adjustment. Body fat estimates by imaging were not different from hydrodensitometry or DXA (mean differences = 1.41 ± 1.26 % and −1.91 ± 1.29%, $p = 0.81$ and 0.43, respectively). Hydrodensitometry and DXA differed from each other (mean difference = -3.32 ± 0.58 %, $p < 0.01$).

## Discussion

A fully rotatable, computerized body model was produced by the 3D rotary laser scanner for measurement of body volumes. Total body volume, as assessed by the body scanner, had a high level of agreement with hydrodensitometry. A strong relationship was found between imaging and criterion methods, and mean % fat by body imaging did not differ significantly from hydrodensitometry and DXA.

Several photonic scanners have been developed to date, with limitations including variations in ability to accurately measure fat mass. The original Hamamatsu Bodyline Scanner provided a model of the body using eight cameras, which collected up to 102,400 data points in a 12 second scan [11]. When Wells et al. compared this scanner with hydrodensitometry and ADP in 11 adult men and 11 women, body volume had < 3% standard error compared with criterion methods. The laser scanner investigated in this study collected the same number of data points with two cameras in 3 seconds and exhibited a 1.84 % standard error with hydrodensitometry; ADP was not available for comparison. Limits of agreement on body volume were similar between the Hamamatsu Bodyline Scanner and laser imaging when compared to hydrodensitometry (± 2.43 and 3.12 L, respectively), despite the reduced number of cameras in the laser imaging device.

In 2006, a four camera Hamamatsu Bodyline Scanner collected 2,048,000 data points in 10 seconds. The system was validated against hydrodensitometry in 44 women and 48 men, ages 6 to 83 years by Wang et al. [12]. The total body volume by hydrodensitometry and 3D photonic scanning differed significantly ($p < 0.01$). Interestingly, % body fat estimates had no significant differences between methods ($p = 0.48$) [12]. The reasons for this seeming incongruity are unclear. The laser body scanner evaluated in the present study also had volume measurements that did not differ significantly from hydrodensitometry ($p = 0.30$) and % body fat estimates were not different from hydrodensitometry or DXA ($p = 0.81$ and 0.43, respectively), despite the reduced number of cameras and lower resolution.

The [$TC^2$] portable photonic scanner with six cameras measures up to 1 million points in 10 seconds and has focused on circumference measurement exclusively [14-16]. British and American studies utilizing the [$TC^2$] instrument provided valuable information about associations between body size and shape. At present, the $[TC]^2$ device has not been validated for determination of % fat.

In studies utilizing the Chang Gung laser scanner, 7-12 second images of the body in three positions were used to determine 280 measurements [19]. A health index score was calculated via waist, breast, and hip profile areas and BMI, and was strongly related to measures of obesity-related disease and risk of metabolic syndrome [18, 19]. Although it has not been used to assess body fat, this instrument gives important information about the relationship between body size and health. In contrast, the laser scanner in the present study takes only 2 seconds and one position to acquire all measurements.

The current research is limited by the inclusion of only Caucasian and Hispanic women. Thigh volume was the most variable measurement, with a coefficient of variation of 2.25 %. The increased variability of thigh volume could be due to difficulty in locating the top and bottom of this region. Unlike other measures, the thigh does not have a clear anatomical marker for the end point, which may have impacted the measurement variation. Also, advanced spirometry was not available at the time of the study so that predicted residual lung volume, rather than measured, was used in the hydrodensitometry analysis. In the future, imaging could be compared with % fat measures from hydrodensitometry that are adjusted for actual residual lung volume. Subjects undergoing laser imaging did not perform any respiratory maneuver, and no adjustment was made for lung volume. Breath-hold during laser imaging may have improved agreement with criterion methods, and adjustment for lung volume is a topic for future investigation. Additionally, other volumetric methods such as ADP could be used for criterion comparisons. Analysis indicated significant mean differences between hydrodensitometry and DXA in this study. However, these differences were expected, as the Lunar Prodigy system has been shown previously to overestimate as compared to criterion methods [30]. Finally, studies to validate use of this body scanner should incorporate men, as well as a broader range of BMIs, age groups, and ethnicities.

## Conclusions

In summary, several precise and reliable methods are available to analyze percent body fat. However, these instruments are expensive, bulky, and/or require significant training to operate effectively. Three-dimensional laser body imaging appears to be an accurate method to analyze body volume and % fat as compared to criterion methods. Thus, it is ideal for both research and clinical applications due to its ease of use, small size, and improved portability.

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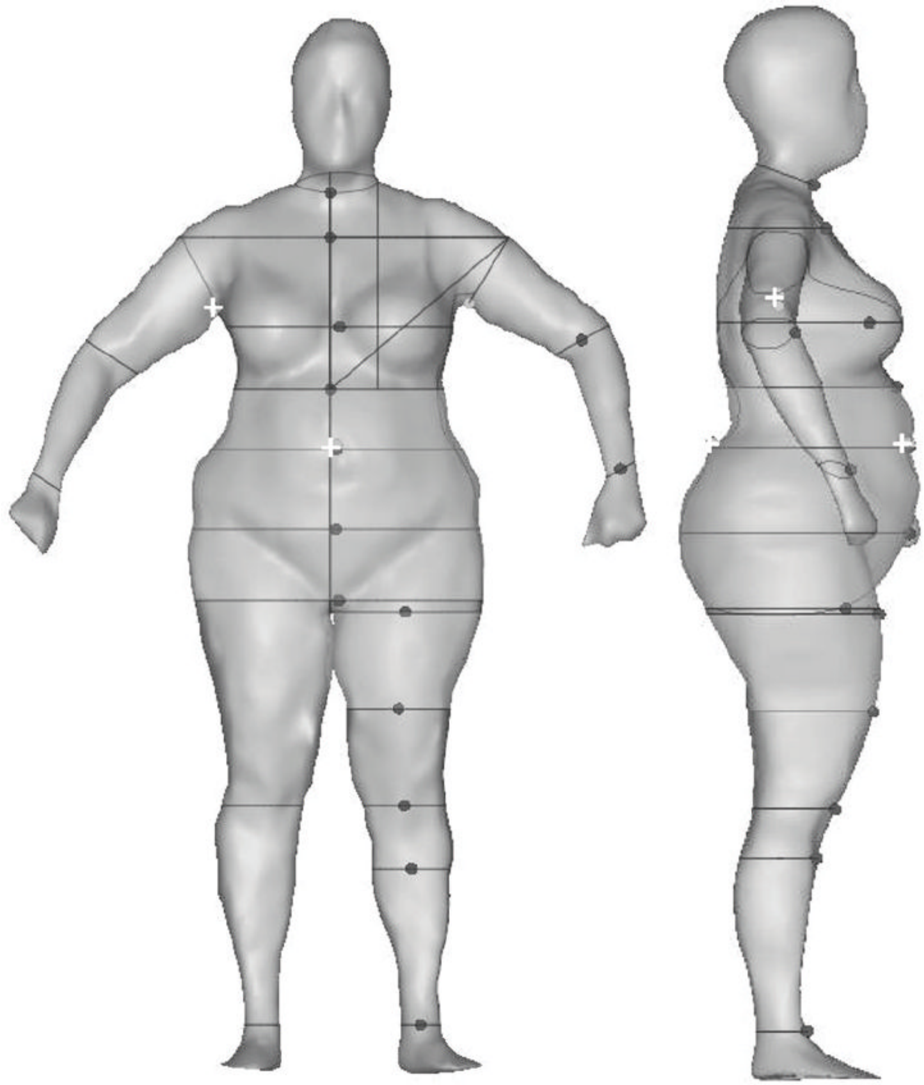

**Figure 1.**
A sample scan produced by three-dimensional laser body imaging. Lines indicate locations of circumference measurements, white crosses show automatically located landmarks, and dots designate adjustable girths. The computer model is 360° rotatable, although only two views are presented. Subject measurements for indication of scale: height 156.21 cm, girth at the umbilicus 111.42 cm, upper thigh circumference 60.39 cm.

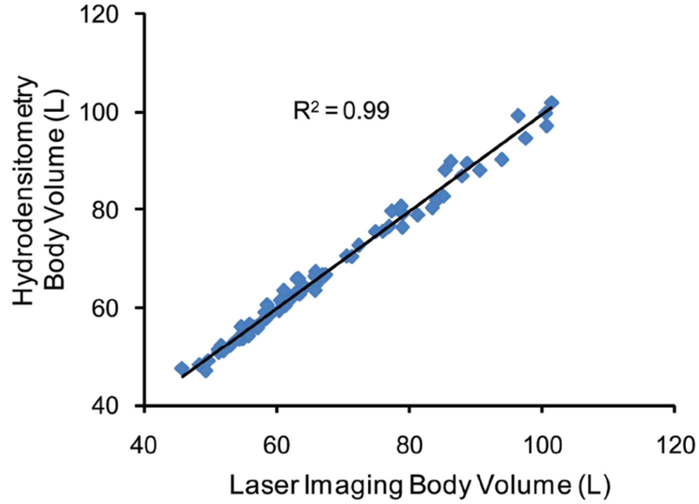


**Figure 2.**
Relationship of body volumes according to three-dimensional laser body imaging and hydrodensitometry in 70 subjects (y = -0.194 + 1.01*Imaging, $R^2$ = 0.99, standard error of the estimate 1.60 L).

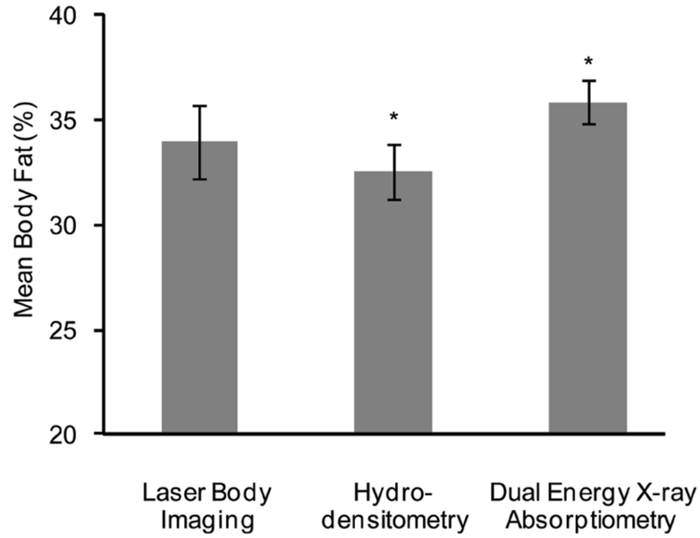


**Figure 3.**
Estimates of percent body fat by multiple methods in 70 subjects.
* $p < 0.05$ pair-wise contrasts by repeated measures ANOVA using the Bonferonni adjustment for multiple comparisons

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## Table 1

Characteristics of subjects[1]

| Characteristic | All Subjects (N = 70) | Healthy Weight (N = 38) | Overweight/Obese (N = 32) |
|---|---|---|---|
| Age(y) | 30.92 ± 1.31 (19.1-64.5) | 26.37 ± 1.21 (19.2-49.8)* | 36.32 ± 2.14 (19.1-64.5)* |
| Weight (kg) | 69.19 ± 1.63 (49.2-101.5) | 59.87 ± 0.98 (49.2-70.5)* | 80.27 ± 2.08 (61.2-101.5)* |
| Height (cm) | 164.46 ± 0.84 (149.9-181.0) | 164.81 ± 0.98 (152.2-176.5) | 164.05 ± 1.42 (149.9-181.0) |
| BMI (kg/m$^2$) | 25.57 ± 0.57 (18.9-36.8) | 22.02 ± 0.27 (18.9-24.6)* | 29.79 ± 0.64 (25.3-36.8)* |
| Fat Mass (kg)[2] | 25.61 ± 1.27 (11.3-51.3) | 17.68 ± 0.65 (11.3-25.5)* | 35.04 ± 1.42 (23.3-51.3)* |
| Lean Mass (kg)[2] | 40.69 ± 0.58 (32.7-54.0) | 39.76 ± 0.66 (32.7-48.7) | 41.79 ± 0.99 (32.7-54.0) |
| Bone Mineral Content (kg)[2] | 2.58 ± 0.05 (1.8-3.8) | 2.41 ± 0.05 (1.8-3.2)* | 2.78 ± 0.08 (2.0-3.8)* |

[1] Values given as mean ± standard error, range in parenthesis

[2] Measured by dual-energy X-ray absorptiometry

* $p < 0.05$ by independent samples t-test

**Table 2**

Reproducibility of 3D body imaging over eight repeated scans (N = 30)

| Imaging Volume Measurement (L) | Mean ± SEM[1] | Intraclass Correlation Coefficient | Coefficient of Variation (%) |
|---|---|---|---|
| Total Body | 69.09 ± 3.86 | 1.000* | 0.41 |
| Upper Torso | 35.49 ± 1.89 | 0.999* | 2.16 |
| Lower Torso | 23.93 ± 1.43 | 1.000* | 1.39 |
| Thigh | 4.87 ± 0.17 | 0.996* | 2.26 |

[1]Standard error of the mean

*$p < 0.05$ by intraclass correlation coefficient

## Table 3

Estimates of volume (L) and fat (%) by laser body imaging as related to hydrodensitometry and dual energy X-ray absorptiometry (N = 70)

| Method | Mean ± SEM[1] | Mean Difference from Imaging | ICC[2] | Pearson's Correlation Coefficient[3] | Regression Analysis[4] | | |
|---|---|---|---|---|---|---|---|
| | | | | | Coefficient | SEE[5] | $R^2$ |
| Laser Imaging | | | | | | | |
| Body Volume (L) | 67.84 ± 1.74 | | | | | | |
| Fat(%) | 33.95 ± 1.74 | | 0.86*[6] | | | | |
| Hydrodensitometry | | | | | | | |
| Body Volume (L) | 67.64 ± 1.72 | 0.20 | 1.00* | 0.99* | 1.01* | 1.60 | 0.99 |
| Fat(%) | 32.54 ± 1.28[a] | 1.41 | 0.79* | 0.69* | 0.51* | 7.81 | 0.47 |
| Dual Energy X-ray Absorptiometry | | | | | | | |
| Fat(%) | 35.86 ± 1.06[a] | -1.91 | 0.74* | 0.67* | 0.41* | 6.61 | 0.45 |

[1] Standard error of the mean

[2] Intraclass correlation coefficient with imaging using an absolute agreement model (25)

[3] Pearson's correlation coefficient with imaging

[4] Coefficient, standard error of the estimate, and $R^2$ by linear regression with imaging

[5] Standard error of the estimate

[6] Intraclass correlation coefficient for all methods using an absolute agreement model

* $p < 0.05$

[a] matching superscripts indicate significantly different means by repeated measures ANOVA using Bonferroni adjustment for pairwise comparisons, $p < 0.05$