Relation of BMI to a dual-energy X-ray absorptiometry measure of fatness

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Dual-energy X-ray absorptiometry (DXA) is a valid technique for measuring the fat, bone and lean (muscle, organs and water) masses of the body. We evaluated relationships of BMI (kg/m2) with independent measurements of fat and lean masses using DXA in 226 adult volunteers. The evaluation was an application of a general approach to compositional data which has not previously been used for describing body composition. Using traditional regression analyses, when lean mass was held constant, BMI varied with fat mass (men r 0.75, P < 0.05; women r 0.85, P < 0.05); when fat mass was held constant, BMI varied with lean mass (men r 0.63, P < 0.05; women r 0.47, P < 0.05). In contrast, a regression model for compositional data revealed that BMI was: (a) strongly associated with log fat mass in both sexes (b1 4.86, P < 0.001 for all women and b1 5.96, P < 0.01 for all men); (b) not associated with bone mass, except in older men; (c) related to lean mass in women but not in men (b1 −4.04, P < 0.001 for all women and b1 −2.59, P < 0.01 5 for all men). Women with higher BMI tended to have more fat mass and more lean mass than women with lower BMI. Men with higher BMI had more fat mass but similar lean mass to men with lower BMI. Investigators need to be alert to the inaccuracy of BMI to assign a fatness risk factor to individuals, especially among women.

Body composition: BMI: Dual-energy X-ray absorptiometry

Weight-for-height ratios (e.g. weight/height2 = BMI) are often used in clinical and epidemiological studies as surrogate measures of fatness (Keys et al. 1972; Garrow & Webster, 1985; Wellens et al. 1996), either because only weight and height are measured or because the study design requires recalled information of past weight and height. Bioelectrical impedance analysis (BIA) is now being used increasingly in epidemiological and clinical studies to determine the respective contributions of fat and lean tissues to overall body mass. BIA measures electrical characteristics of the human body and then extrapolates to the fat and lean masses using formulas that assume a constant hydration level (73%) of the lean mass (Chumlea et al. 1996; Hendel et al. 1996; Kushner et al. 1996; De Lorenzo et al. 1997; Jensen et al. 1997). The accuracy of BIA formulas has been questioned (Pichard et al. 1997) and they are thought to underestimate obesity (Piccoli et al. 1998).

The advantage of methods such as dual-photon absorptiometry (DPA) and dual-energy X-ray absorptiometry (DXA) over BIA is that they yield direct measurements of lean mass (including soft tissues) and bone mass in each pixel of body surface (Slosman et al. 1992). Fat mass can then be derived from these two measures. Therefore, these methods offer a new opportunity to evaluate the validity of BMI as a proxy measure of fatness. Previous studies that have compared BMI with fat mass or percentage fat measured using DXA or DPA have all found strong statistical correlations between these variables (Wang et al. 1994; Hannan et al. 1995; Gallagher et al. 1996; Goran et al. 1996; Goulding et al. 1996; Gutin et al. 1996; Daniels et al. 1997; Abbasi et al. 1998; Pietrobelli et al. 1998). However, these analyses have not taken into consideration the information on lean and bone masses even though these measures were also provided by DXA or DPA. Because the human body is composed mostly of fat and lean tissues (muscle, organs, connective tissues and water), a strong correlation of BMI with fat mass does not rule out an equally strong correlation with lean mass. For instance, an athlete with a very large muscle mass and an obese person can both have high BMI values.

The aim of the present study was to evaluate the validity of BMI in terms of a measure of fatness obtained by DXA, adjusted for lean mass and bone mass. The evaluation was an application of a general approach to compositional data which has not previously been used for describing body composition.

Abbreviations: BIA, bioelectrical impedance analysis; DPA, dual-photon absorptiometry; DXA, dual-energy X-ray absorptiometry.

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Materials and methods

From September 1990 to July 1991, we enrolled 153 female and seventy-three male Caucasians, aged 15–86 years, in Geneva, Switzerland. These were either healthy volunteers without risk factors for osteoporosis or chronic diseases recruited among the hospital employees, or patients admitted for acquired immunodeficiency syndrome, osteoporosis or other conditions which may lead to DXA examination. Thus, subjects represented a wide range of body mass compositions and ages (Table 1). Height (m; ± 5 mm) and weight (kg; ± 100 g) were measured, using a medical gauge and scales, on subjects without shoes or outer clothing.

Bone, fat and lean masses were determined by DXA. All DXA measurements were conducted by two trained operators. Inter-observer agreement was not checked. The technique combined a total body scanner (model QDR-1000/W; Hologic Inc., Waltham, MA, USA) using software version v.5.35, an X-ray source, an internal wheel to calibrate the bone mineral component and an external lucite–aluminium phantom to calibrate the fat compartment. Subjects lay in dorsal decubitus on the scan table for 12–18 min, a longer time being needed for larger subjects. According to the manufacturer, the radiation dose was small, that is, 0–1 mSv. DXA determines body composition by measuring the attenuation of an X-ray beam for every pixel of the entire body surface scanned from head to toe.

Technical aspects of DXA have been described in detail elsewhere (Heymsfield et al. 1989; Mazess & Barden, 1989; Slosman et al. 1992; Svendsen et al. 1993). In short, an X-ray generator emits a beam with a lower and a higher intensity (70 and 140 kVp). This beam is attenuated as it passes through the body, the degree of attenuation being relative to the body components absorbing the beam. Attenuated beams are detected for every pixel of the entire scan. DXA systems solve for two components in each pixel, fat+lean or soft tissue+bone minerals. This is the truism that weight (or total body mass) is the sum of fat, bone and lean masses:

\[
\text{fat mass} + \text{bone mass} + \text{lean mass} = \text{weight}.
\]

Dividing this expression by weight gives the unit-sum constraint on the proportions (denoted by capital letters) of fat, bone and lean:

\[
\text{FAT} + \text{BONE} + \text{LEAN} = 1.0.
\]

Warnings about difficult analyses and spurious correlations of variables subject to the unit-sum constraint date from an 1897 paper by Karl Pearson (Pearson, 1897). According to Aitchison (1986): ‘... right up to the present day, there has been no other form of data analysis where more confusion has reigned and where more improper and inadequate statistical methods have been applied’.

One consequence of the unit-sum constraint is a negative bias afflicting the covariance-correlation structure of body composition estimates. The sum of bone, fat and lean masses equals total body mass (Slosman et al. 1992).

Bone mass is calcium hydroxyapatite, that is, largely Ca and P. Fat mass is triacylglycerol. Lean mass comprises what is neither bone mineral nor triacylglycerol, that is, total body water, organs, muscle, connective tissues, fat cell walls, osteoid water and organic components of the skeleton (Haarbo et al. 1991). Lean mass assessed with DXA is highly correlated with lean mass derived from total body K (Slosman et al. 1992). DXA measurements of bone, lean and fat masses are reproducible: CV range from 1–1 to 2% according to body compartment (Slosman et al. 1992).

Measures of precision of the various DXA body composition estimates were similar to those given in a previous report (Slosman et al. 1992).

Scales weight, which was used for BMI, was recorded to 0–1 kg. It varied slightly from total mass given by DXA: the standard error of the estimate of the DXA weight by scales weight was 0.760 kg. The study received the approval of the Ethical Committee of the Department of Medicine.

Statistical analysis

Compositional data analysis. Problems of analysis and interpretation of body composition data stem from the truism that weight (or total body mass) is the sum of fat, bone and lean masses:

\[
\text{fat mass} + \text{bone mass} + \text{lean mass} = \text{weight}.
\]

Dividing this expression by weight gives the unit-sum constraint on the proportions (denoted by capital letters) of fat, bone and lean:

\[
\text{FAT} + \text{BONE} + \text{LEAN} = 1.0.
\]

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Table 1. Description of the study population

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
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<tbody>
<tr>
<td></td>
<td>16–49 years</td>
<td>50–84 years</td>
<td></td>
<td>15–49 years</td>
<td>50–86 years</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Mean (n = 119)</td>
<td>Mean (n = 34)</td>
<td></td>
<td>Mean (n = 48)</td>
<td>Mean (n = 25)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Weight (kg)</td>
<td>60.1 ± 12.3</td>
<td>57.1 ± 9.4</td>
<td></td>
<td>62.1 ± 12.9</td>
<td>68.6 ± 14.3</td>
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<tr>
<td>Height (m)</td>
<td>1.68 ± 0.09</td>
<td>1.59 ± 0.07</td>
<td></td>
<td>1.73 ± 0.11</td>
<td>1.70 ± 0.08</td>
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</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.3 ± 3.3</td>
<td>22.6 ± 3.6</td>
<td></td>
<td>20.7 ± 3.7</td>
<td>23.6 ± 4.0</td>
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<tr>
<td>Fat (%)</td>
<td>24.8 ± 8.1</td>
<td>29.1 ± 7.7</td>
<td></td>
<td>16.0 ± 5.0</td>
<td>21.1 ± 6.4</td>
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<tr>
<td>Lean (%)</td>
<td>71.8 ± 7.9</td>
<td>68.4 ± 8.1</td>
<td></td>
<td>80.9 ± 5.2</td>
<td>76.1 ± 6.0</td>
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<tr>
<td>Bone (%)</td>
<td>3.6 ± 0.4</td>
<td>3.0 ± 0.6</td>
<td></td>
<td>3.6 ± 0.4</td>
<td>3.3 ± 0.4</td>
<td></td>
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</tr>
<tr>
<td>Fat:lean</td>
<td>0.36 ± 0.17</td>
<td>0.44 ± 0.17</td>
<td></td>
<td>0.20 ± 0.08</td>
<td>0.29 ± 0.11</td>
<td></td>
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</tr>
<tr>
<td>Log(fat:lean)</td>
<td>−1.11 ± 0.46</td>
<td>−0.88 ± 0.39</td>
<td></td>
<td>−1.67 ± 0.39</td>
<td>−1.33 ± 0.42</td>
<td></td>
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</tr>
</tbody>
</table>

* Two-way ANOVA.

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Correlations of the proportions FAT with LEAN, FAT with BONE or LEAN with BONE are not free to realize all values in the interval (−1.0, +1.0): at least two of the correlations must be negative. This is an artifact of the unit-sum constraint; it is not a reflection of the biology of body composition. The bias may cause usual regression and correlation analyses involving FAT, BONE and LEAN to give ‘inadequate or irrelevant analysis with a doubtful or distorted inference’ (Aitchison, 1986).

A general solution to this problem has been proposed by Aitchison (1986) in which a key element is, in this example, the transformation of the three component masses (lean, fat and bone) to the two log ratios:

\[ f = \log(\text{fat} : \text{lean}), \]

and

\[ b = \log(\text{bone} : \text{lean}). \]

Aitchison’s (1986) approach enables valid analyses of compositions. Expressing the three body composition masses (or proportions) in terms of two log ratios preserves all of the information in the composition, and it reduces three constrained variables to two that are not compelled structurally to be dependent.

The regression model is:

\[ \text{BMI} = \alpha + \beta_1 \log \text{fat} : \text{lean} + \beta_2 \log \text{bone} : \text{lean} + \gamma \text{age}. \]

Equation (1) can be re-expressed as:

\[ \text{BMI} = \alpha + \beta_1 \log \text{fat} + \beta_2 \log \text{bone} - (\beta_1 + \beta_2) \log \text{lean} + \gamma \text{age}. \]

Thus, the coefficient for log lean mass is \((-\beta_1 + \beta_2)\) and the variance (var) of the sum of the coefficient \((\beta_1 + \beta_2)\) is: var \(\beta_1 + \var \beta_2 + 2 \times \text{covariance}(\beta_1, \beta_2).

Our choice of lean as a divisor, rather than using, say, log(fat : bone) and log(lean : bone), does not influence conclusions drawn from the analyses presented here (Aitchison, 1986) since an equation equivalent to (1) would also be obtained. The choice was made because the ratio fat : lean, and its natural logarithm (f), directly express the notion of fatness. Body composition is then represented by the two unconstrained log ratios, f and b, rather than by the three structurally dependent proportions, FAT, BONE and LEAN.

**Variable definition.** The three body mass compartments (fat mass, bone mass, lean mass) were transformed to the two log ratios \(f = \log(\text{fat mass} : \text{lean mass})\) and \(b = \log(\text{bone mass} : \text{lean mass})\) (Aitchison, 1986). Analyses were stratified by sex and age category: 15–49 years, and 50–86 years. The cut-off of 50 years was chosen because it is the age at which the distribution of BMI increases by about 1 kg/m² in the female population of Geneva (Morabia et al. 1997). In contrast, at a population level, male BMI varies only modestly between the ages of 35 and 75 years (Morabia et al. 1997).

The results are given as means, standard deviations, and a box plot diagram. To describe the relationship of BMI to body composition and to fatness in particular, we employed ANOVA, multiple regression and partial correlation methods. Within age category, age was adjusted for as a continuous variable.

**Results**

The 226 subjects were not ‘representative’ of any particular broader population. Table 1 displays mean values and standard deviations of variables measured in this study. BMI increased with age \((P = 0.001)\) but was, on average, not different between males and females \((P = 0.68)\). Women had a greater percentage fat mass and smaller percentage lean mass than males, but the increases in percentage fat mass and decreases in percentage lean mass with age were similar for both sexes \((P < 0.05)\) for % fat and % lean. Percentage bone mass decreased with age in both sexes \((P = 0.001)\), more so in females than in males \((P = 0.001)\). The fat:lean ratio was larger in men \((P = 0.001)\), and similarly increased with age \((P = 0.001)\) in both sexes \((P = 0.001)\). The distributions of the log(fat : lean) ratios in Fig. 1 are consistent with what one would expect in a general population: older persons and females tend to have more body fat than younger persons and males.

Table 2 shows the correlation structure of BMI with fat mass and lean mass when other variables were held constant. All partial correlation coefficients \((r)\) were statistically significant. As desired if BMI is used as a proxy for fatness, BMI and fat mass were highly correlated for constant lean mass \((r = 0.85)\) for all females; \(r = 0.77\) for all males). However, BMI and lean mass were also positively correlated for constant fat mass, but to a lesser degree \((r = 0.47)\) for all females; \(r = 0.63\) for all males). As expected, BMI was strongly correlated with total mass, that is, with weight, for constant age \((P = 0.001)\) but was, on average, not different between males and females \((P = 0.001)\) for % fat and % lean. Percentage bone mass decreased with age in both sexes \((P < 0.05)\), more so in females than in males \((P = 0.001)\). The fat:lean ratio was larger in men \((P = 0.001)\), and similarly increased with age \((r = 0.47)\) for all females; \(r = 0.63\) for all males). As expected, BMI was strongly correlated with total mass, that is, with weight, for constant age \((P = 0.001)\) but was, on average, not different between males and females \((P = 0.001)\) for % fat and % lean. Percentage bone mass decreased with age in both sexes \((P < 0.05)\), more so in females than in males \((P = 0.001)\). The fat:lean ratio was larger in men \((P = 0.001)\), and similarly increased with age \((P = 0.001)\) in both sexes \((P = 0.001)\). The distributions of the log(fat : lean) ratios in Fig. 1 are consistent with what one would expect in a general population: older persons and females tend to have more body fat than younger persons and males.

Table 3 presents the correlation structure of BMI with the two log ratios \(f = \log(\text{fat mass} : \text{lean mass})\) and \(b = \log(\text{bone mass} : \text{lean mass})\). BMI was positively correlated with f, the fatness aspect of body composition, in all age and sex categories. The relationship of BMI and f was systematically stronger in women than men \((r = 0.59)\) for all females; \(r = 0.54\) for all males). Except for older men, BMI was essentially uncorrelated with the bone component of body composition \((r = 0.07)\) for all women; \(r = 0.03\) for all men). Among men \(< 50\) years, BMI depended in part on age for body composition held constant \((r = 0.36)\). At best, body composition and age explained (in the sense of multiple regression) between one-third and two-thirds of the variation in BMI \((R^2\) varied between 0.35 and 0.67).

Table 4 presents the regression coefficients for the three body compartments. BMI was strongly associated with log fat mass in both sexes \((b_1 = 4.86, P < 0.001)\) for all women and \(b_1 = 5.96, P < 0.001\) for all men). BMI was not associated with bone mass, except in older men for whom there was a strong negative association \((P = 0.013)\). However, this age- and sex category had a small sample size. Finally, BMI was related to lean mass in women but not in men \((b_1 = 4.04, P < 0.001)\) for all women and \(b_1 = 2.59, P < 0.15\) for all men).

**Discussion**

In the present study, separate correlations of BMI with either percentage fat mass or percentage lean mass showed that BMI was strongly related to fat mass but also
Fig. 1. Box-plot of log(fat mass : lean mass) by sex and age. The upper and lower edges of the box are at the 25th and the 75th percentiles of the number of points in the data respectively. The middle line is the median. The whiskers extend to data values outside the box and within 1.5 times the spread between the top and the bottom of the box. Data (—) beyond box edges ± 1.5 spread are outliers.

Table 2. Partial correlations (r) of BMI with fat, lean and total masses determined by dual-energy X-ray absorptiometry in male and female subjects of different ages

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (years)</th>
<th>n</th>
<th>Fat mass†</th>
<th>Lean mass‡</th>
<th>Total mass§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>16–49</td>
<td>119</td>
<td>0.81*</td>
<td>0.44*</td>
<td>0.81*</td>
</tr>
<tr>
<td></td>
<td>50–84</td>
<td>34</td>
<td>0.93*</td>
<td>0.43*</td>
<td>0.85*</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>153</td>
<td>0.85*</td>
<td>0.47*</td>
<td>0.81*</td>
</tr>
<tr>
<td>Male</td>
<td>15–49</td>
<td>48</td>
<td>0.76*</td>
<td>0.63*</td>
<td>0.78*</td>
</tr>
<tr>
<td></td>
<td>50–86</td>
<td>25</td>
<td>0.83*</td>
<td>0.75*</td>
<td>0.90*</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>73</td>
<td>0.77*</td>
<td>0.63*</td>
<td>0.84*</td>
</tr>
</tbody>
</table>

* P < 0.05 for hypothesis that r = 0.
† Holding lean mass, bone mass and age constant.
‡ Holding fat mass, bone mass and age constant.
§ Holding age constant.

Table 3. Partial correlations (r) and multiple correlation (R^2) of BMI with relative fatness (f†), relative boniness (b‡) (both determined from dual-energy X-ray absorptiometry analysis) and age

| Sex  | Age group (years) | n   | r_{BMI, f} § | r_{BMI, b} ||| | r_{BMI, age} ¶ | R^2 †† |
|------|-------------------|-----|--------------|--------------|
| Female | 16–49             | 119 | 0.54*        | −0.13        | −0.01       | 0.35*     |
|       | 50–84             | 34  | 0.78*        | −0.06        | 0.04        | 0.67*     |
|       | All               | 153 | 0.59*        | −0.07        | 0.01        | 0.41*     |
| Male  | 15–49             | 48  | 0.50*        | −0.12        | 0.36*       | 0.40*     |
|       | 50–86             | 25  | 0.65*        | −0.10        | −0.03       | 0.45*     |
|       | All               | 73  | 0.54*        | −0.03        | 0.19        | 0.44*     |

* P < 0.05 for hypothesis that r = 0 or R^2 = 0.
† f = log(fat mass : lean mass).
‡ b = log(bone mass : lean mass).
§ Holding b and age constant.
¶ Holding f and age constant.
†† From the model BMI = α + β_1 f + β_2 b + γ age.
to lean mass in both sexes. These findings are consistent with those from studies that have compared BMI with a DXA measure of body fat (Wang et al. 1994; Hannan et al. 1995; Goran et al. 1996; Goulding et al. 1996; Gutin et al. 1996; Pietrobelli et al. 1996b, 1998; Abbasi et al. 1998; Taylor et al. 1998). For example, Abbasi et al. (1998) reported Pearson correlation coefficients ($r$) of 0.87 and 0.83 respectively, in a sample of 118 women and 144 men aged 60–80 years. However, it is well known that a correlation coefficient is not necessarily a measure of agreement between two methods: two variables can be highly correlated but this does not mean that the intercept is constant and the slope is equal to 1. This is illustrated by the report of Daniels et al. (1997) who found that for an equivalent BMI, DXA-measured percentage body fat was greater in girls than in boys, in whites than in blacks, and among those with central obesity than among those with peripheral obesity. Gallagher et al. (1996) also observed a dependence on age and sex (but not on ethnicity) when BMI was used as an indicator of total body fat calculated from DPA and tritium dilution.

Studies that have gone beyond simple correlation analysis have reached contrasting conclusions with respect to the validity of BMI as a proxy for body fat (Wang et al. 1994; Hannan et al. 1995). Goran et al. (1996) evaluated the accuracy of BMI for the assessment of body fat in forty-nine adolescents and 13–32% in adults. In attempting to assess the validity of BMI, Taylor et al. (1998) found that the 75th percentile for BMI had a sensitivity of 83% and a specificity of 94% compared with the 75th percentile of either total body fat in kg or percentage fat measured by DXA. However, the relationship of BMI to fat measured by DXA may vary according to the leanness of the subjects (Curtin et al. 1997). In the paper by Wang et al. (1994), the correlations between percentage fat and BMI varied by sex and race, but their discordance was stronger in leaner subjects.

Compared with previous validation studies of BMI, the present study went further in assessing the relationship of BMI to fat mass while controlling for the importance of the two other compartments, bone mass and lean mass. We expressed fatness as the ratio fat mass : lean mass. This ratio can be measured exactly using DXA. This DXA-based definition of fatness satisfies necessary conditions for a standard to evaluate obesity in adults: (1) the ratio is a natural expression of fatness: obese persons are those who have an excess of fat mass relative to their lean mass; (2) its distributions on the log scale are roughly symmetrical with comparable spread in four sex–age groups and reveal clearly the associations of fatness that one would expect (Fig. 1); (3) it allows a statistically sound analysis of the relationship of BMI with fatness controlling for lean and bone masses.

The regression analysis revealed very different associations of BMI with fat, bone and lean masses in men and women (see Table 4). BMI appears to be a more specific indicator of total body fat calculated from DPA and tritium dilution.

### Table 4. Regression coefficients for BMI v. log fat mass, log bone mass and log lean mass (from dual-energy X-ray absorptiometry analysis) using compositional data analysis

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age group (years)</th>
<th>n</th>
<th>b_1*</th>
<th>SE(b_1)</th>
<th>P</th>
<th>b_2*</th>
<th>SE(b_2)</th>
<th>P</th>
<th>b_3*</th>
<th>SE(b_3)</th>
<th>P</th>
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<tr>
<td>Female</td>
<td>16–49</td>
<td>119</td>
<td>4.76</td>
<td>0.7</td>
<td>&lt;0.0001</td>
<td>-3.45</td>
<td>2.5</td>
<td>0.17</td>
<td>-1.31</td>
<td>2.13</td>
<td>0.02</td>
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<tr>
<td></td>
<td>50–84</td>
<td>34</td>
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<td>1.09</td>
<td>&lt;0.0001</td>
<td>-0.05</td>
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<td>-0.82</td>
<td>1.52</td>
<td>0.59</td>
<td>-4.04</td>
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<tr>
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<td>15–49</td>
<td>48</td>
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<td>2.81</td>
<td>0.23</td>
<td>-2.59</td>
<td>2.55</td>
<td>0.15</td>
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</table>

*b_1* and *b_2* are derived from the equation: \( \text{BMI} = a + b_1 \times \log \text{fat} + b_2 \times \log \text{bone} + b_3 \times \log \text{lean} \), where \( a \) is the intercept and \( b_3 = -(b_1 + b_2) \).
when past measures of fatness are needed, since subjects are examined for the first time after diagnosis and their fatness may have changed as a consequence of the pathological process.

As BMI will remain an index widely used in epidemiological studies, investigators need to be alert to the inaccuracy of BMI in assigning a fatness risk factor to individuals, especially women.

References


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