Total body protein in healthy adolescent girls: validation of estimates derived from simpler measures with neutron activation analysis

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ABSTRACT

Background: Little recent and accurate information about body protein content in healthy adolescent girls is available.

Objective: The objective was to assess the total body nitrogen (TBN) and total body protein (TBPr) contents of fat-free mass (P:FFM) in a group of healthy adolescent girls and to validate previously published TBN prediction equations.

Design: TBN was measured with in vivo neutron activation analysis (TBN_{NAA}). Bone mineral density and FFM were measured with dual-energy X-ray absorptiometry (FFM_{DXA}), total body water and FFM were measured with bioimpedance analysis, and FFM was assessed by measuring skinfold thicknesses in 51 girls with a mean (±SD) age of 14.7 ± 0.7 y. The validity of the TBN prediction equations was assessed with Bland-Altman analysis.

Results: TBN_{NAA} in our adolescent group was higher (1.49 kg) than values reported in earlier studies of women (1.25 and 1.31 kg), and P:FFM was slightly higher (23%) than that documented in adults (19–21%). Previously published TBN equations showed either systematic bias or wide limits of agreement.

Conclusion: A predictive equation derived from the present study population based on FFM_{DXA} improves the prediction of TBN for groups of young girls but may not be helpful for individuals in clinical settings.

KEY WORDS  Body composition, adolescents, total body protein, total body nitrogen, fat-free mass, neutron activation analysis, dual-energy X-ray absorptiometry, anthropometric measures, bioimpedance analysis

INTRODUCTION

Adequate dietary protein intake and protein deposition are essential to achieve normal growth in children and adolescents. However, what constitutes sufficient protein intake and deposition is less than certain. To determine minimal protein requirements for growing populations, the World Health Organization (WHO) developed guidelines in 1985. These guidelines relied on short-term nitrogen balance studies that were carried out in children and adults. Protein requirements for intermediate age groups were obtained by extrapolation after an allowance for growth increment was added (1). These guidelines clearly emphasize the considerable limitations of this method and the need for an accurate indicator of protein nutritional status, the need to identify protein inadequacy before clinically detectable changes occur, and the need to gather information on long-term protein accretion associated with normal growth.

Before NAA measurement, direct assessment of total body protein (TBPr) could only be achieved with chemical carcass analysis. In children, these chemical assessments were limited to very few subjects who died of severe illness or malnutrition (2–4) and thus were not representative of normal body protein content. Current studies often assess fat-free mass (FFM), which is then used as a surrogate for protein nutritional status, assuming that protein is a relatively fixed constituent of FFM (5). However, FFM is a heterogeneous body compartment consisting of water, protein, and bone. Adolescence, in particular, is a period characterized by growth and maturation known to be associated with significant changes in the composition of FFM (6–8). Common methods to measure FFM, such as dual-energy X-ray absorptiometry (DXA), anthropometric measures, and bioimpedance analysis (BIA) are only indirect measures of FFM, based on assumptions, and therefore need to be evaluated against a direct measure in children and adolescents.

TBN measurements with neutron activation analysis (NAA) provide a direct and accurate measure of TBPr. Although most centers with NAA facilities have not examined children because of unacceptably high levels of radiation, the Children’s Hospital at Westmead has developed a low-radiation-dose facility specifically for pediatric use (9). Previously developed TBN prediction equations derived from NAA measurements were developed in adult groups of mixed sex with the use of a 5-compartment model based on NAA and tritiated water analysis (10) or from a regression analysis based on height and age (11). Our previously published pediatric TBN prediction equation was based on a group of

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43 girls and boys aged 4–16 y in whom NAA and anthropometric measures were used (9).

The aim of this study was to accurately assess TBN, and its relation to other body compartments, in an exclusively adolescent female population to provide further reference data on body composition in this age group. Furthermore, we aimed to investigate whether TBN could be estimated with other techniques (DXA, BIA, and anthropometric measures) in adolescent girls. We therefore evaluated previously published TBN prediction equations derived from NAA measurements (9–11) and generated a new prediction equation based on data from our adolescent study population.

SUBJECTS AND METHODS
Study population
A multiethnic group of 51 healthy adolescent girls with a mean age of 14.7 y (range: 13.4–16.0 y) was recruited from a girls school in Westmead, Sydney, Australia. All study participants had been born in Australia, but had family backgrounds from 5 different ethnic groups: white or European Australian (n = 35), at least one parent from the Middle East (n = 8), at least one parent from Asia (n = 6), black African (n = 1), and Latin American (n = 1). Thirty-four girls were tested in the follicular phase (ie, days 1–10) and 17 were tested in the luteal phase (ie, after day 10) of their menstrual cycle. The Ethics Committees at the Children’s Hospital at Westmead and Westmead Hospital approved the study protocol. Before participating, all girls and their parents gave informed written consent.

Anthropometric measurements
All measurements were performed on the same morning after the subjects had fasted overnight. Height (±0.1 cm) was measured with a stadiometer (Holtain Ltd, Crymych, United Kingdom) and body weight (±0.1 kg) was measured with an electronic scale (model FW-150K; AND Tokyo, Japan) while the subjects were wearing light clothing. Body mass index (BMI) was calculated as body weight/height2 (in kg/m2), and SD scores for weight, height, and BMI were estimated from WHO reference equations derived from NAA measurements (9–11; 17). The precision of this method has been shown to be 0.1–0.9% (17).

Dual-energy X-ray absorptiometry
Bone mineral content (BMC) and soft tissue lean mass (STLM) were determined with a Lunar Prodigy whole-body scanner in conjunction with EnCORE software version 8.10 (Lunar Corp, Madison, WI). A whole-body scan takes <10 min, and involves a very low radiation dose of <0.02 mSv. FFMDXA was calculated as LTM + BMC assessed with DXA. The precision for this technique in vivo, as assessed at the hospital, was 0.82% for LTM (18).

Neutron activation analysis
TBN was measured by using a modification of the method of prompt γ NAA with a single californium source as described previously (9). In the modified technique, we now expose subjects bilaterally to neutrons from two 252Cf sources placed above and below the scan table, which halves the scan time. 14N is converted to 15N with the emission of a 10.8-MeV γ-ray, and γ-ray emission is measured with 4 detectors. TBN is calculated as the integral under the nitrogen peak centered at 10.8 MeV on the γ-ray spectrum. The accuracy and precision of these techniques are both 3%, as determined from the measurement of nitrogen mass in child-sized boxes and anthropomorphic phantoms (19). The scan involves a radiation dose of <0.02 mSv and takes <10 min. Nitrogen can be assumed to be a constant constituent of protein (16% by weight), so that TBP is derived from TBN by the equation TBPNAAA = 6.25 × TBNAAA (20).

Estimates of FFM and TBN
FFM was estimated by using skinfold thicknesses (FFMST), BIA (FFMBIA), DXA (FFMDXA), and a modified 4-compartment model (FFM4CBEA) with TBP derived from NAA, bone mineral derived from DXA, and total body water from BIA. We tested 7) the Baur equations used to calculate predicted TBN (TBPNAAA), which were developed earlier in our unit in a pediatric population on a single-source TBN machine and based on height and FFMSF (9);
TABLE 1
General physical characteristics of the study population (n = 51) and body fat estimated with different methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>14.7 ± 0.7 (13.4–16.0)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>163 ± 7 (142–174)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58.3 ± 13.3 (33.9–90.4)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.8 ± 4.1 (15.9–33.2)</td>
</tr>
<tr>
<td>SF (mm)</td>
<td>64 ± 26 (30–139)</td>
</tr>
<tr>
<td>Tanner stage</td>
<td>4 (2–5)</td>
</tr>
<tr>
<td>FM (kg)</td>
<td>9.3 ± 6.3 (19.4–44.7)</td>
</tr>
<tr>
<td>SF (mm)</td>
<td>64 ± 26 (30–139)</td>
</tr>
<tr>
<td>SF (mm)</td>
<td>32.0 ± 9.3 (14.1–51.2)</td>
</tr>
<tr>
<td>SF (mm)</td>
<td>29.4 ± 5.8 (20.0–42.9)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>33.2 ± 6.2 (24.6–54.1)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>41.7 ± 7.6 (22.7–66.1)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>40.4 ± 6.3 (26.1–55.5)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>71.2 ± 1.8 (68.2–76.5)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>23.2 ± 1.7 (17.8–25.6)</td>
</tr>
<tr>
<td>4C (kg)</td>
<td>5.6 ± 0.5 (4.5–6.7)</td>
</tr>
</tbody>
</table>

1 SF: sum of biceps, triceps, subscapular, and suprailiac skinfold thickness; FM: fat mass; SF: skinfold thickness; BIA: bioimpedance analysis; DXA: dual-energy X-ray absorptiometry; 4C: 4-compartment model.

2 Self-estimated by the girls using questionnaires; range in parentheses.

3 Calculated with a prediction equation developed in this study population.

Overweight and obese persons reported in a large survey of young Australians (23).

Body protein, FFM determined according to the different techniques used in this study, and the composition of FFM are shown in Table 2. A 4-compartment model of body composition obtained by combining several measurement techniques is more robust to interindividual variability in the composition of FFM (8). Because our 4-compartment model includes BIA measurements of TBW and not a “gold standard” for TBW assessment, we compared TBW estimates from BIA with deuterium dilution in a subgroup of 14 normal-weight girls from our study group. Mean (±SD) values for TBW predicted with BIA and deuterium dilution were 28.2 ± 3.0 and 28.1 ± 3.6 L, respectively. No significant difference was observed between the means of the 2 methods (P = 0.914), and the r² value was 0.70 when TBW values measured with the 2 methods were regressed against each other. The prediction equation was as follows:

\[ \text{TBW}_{\text{BIA}} = (0.271 \times \text{body weight (kg)}) + (0.321 \times ZI_{50}) + 1.294 \]  

where \( ZI_{50} \) is the impulse index measured at 50 kHz. No significant difference was observed between the mean FFM values measured with different techniques. TBN content itself provides only limited information about nutritional status. It is common to express TBN in relation to weight or height (Figure 1). A strong relation was observed between TBN and both weight and height. The best fitting model to describe TBN in relation to weight was quadratic, whereas the association between TBN and height was linear. Even though the “surplus” weight of the overweight subgroup did not appear to be stored as nitrogen, all overweight subjects had a relatively high TBN content. No significant difference was observed in TBN between the 13 girls with a Tanner stage of ≤3 (1.44 ± 0.22 kg N) and those with a Tanner stage of 4 to 5 (1.52 ± 0.18 kg N).

To determine whether TBN can be estimated with simpler techniques that assess FFM, we examined the relation between TBN and estimates of FFM from DXA (Figure 2) and BIA.
FFMSF was not included because %fat based on SF is part of the TBN calculation to correct for hydrogen background (19), and FFM\textsubscript{4CBIA} was not included because our 4-compartment model was derived with the use of TBN data. On the basis of the methods and equations used in the current study, FFMDXA was more closely associated with TBN than was FFMBIA ($r^2 = 0.81$ compared with $r^2 = 0.64$; Table 3) and was therefore used subsequently to generate TBN prediction equations. Exclusion of the overweight participants improved the associations between TBN and FFMDXA (Table 3).

TBN predicted from height, weight, and FFM

Agreement between TBNNAA and previously developed TBN prediction equations, and the prediction equation developed with regression analysis of our current data, is shown in Table 4. Because techniques to assess body composition have different accuracies in normal-weight and overweight populations, the normal-weight subgroup was also analyzed separately. For both groups, close agreement was provided by the prediction equations derived from FFMDXA that were developed in our unit. For these equations, prediction power improved slightly when overweight subjects were excluded. The Ellis equation performed well in both groups, although it was developed in women. With the Ryde equation, which was developed in a group of adults, including males, TBN was underestimated in both of our adolescent groups. The Bland-Altman plots shown in Figure 3 give more detailed information about the agreement between selected methods.

As expected, TBN predicted according to the equation derived from the normal-weight group in the present study population showed the smallest limits of agreement (134 to 136 g N; data not shown), which, however, is still equivalent to just <10% of the mean TBNNAA. TBN predicted according to Baur on the basis of height showed a negative systematic bias, which suggests that the underestimation of TBN increases as TBN increases. In a regression analysis with weight as an independent variable and this bias as a dependent variable, weight was a significant predictor of the bias ($P = 0.001$). This implies that TBN in the heavier and taller girls will be underestimated when based on height, which is also evident from Figure 1. The mean bias close...
to zero for TBN predicted according to Baur and FFMBIA for all girls could be explained by an underestimation of TBN in the overweight participants that was compensated for by an overestimation of TBN in the overweight participants (Figure 3B). In the normal-weight group, TBN was underestimated when based on FFMBIA (Table 4).

**DISCUSSION**

This study accurately describes total body nitrogen (TBN) content and its relation to other body compartments in a group of adolescent girls. The TBN values of the adolescent girls were higher than those reported previously for women (10, 11), and the protein content of FFM was slightly higher than that expected from early chemical studies of the protein content of children (2–4).

**TABLE 4**

<table>
<thead>
<tr>
<th>Prediction equation</th>
<th>x ± SD</th>
<th>Bias</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>All girls (n = 51)</td>
<td>1493 ± 191</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>TBNNAA</td>
<td>1420 ± 144</td>
<td>——</td>
<td>—77 ± 113 to —107 to —37</td>
</tr>
<tr>
<td>TBNBarn, height</td>
<td>1503 ± 242</td>
<td>——</td>
<td>—7 ± 111 to —25 to 40</td>
</tr>
<tr>
<td>TBNBarn, FFM(DXA)</td>
<td>1487 ± 287</td>
<td>——</td>
<td>—3 ± 177 to —56 to 50</td>
</tr>
<tr>
<td>TBNBarn, FFM(BIA)</td>
<td>1211 ± 163</td>
<td>——</td>
<td>—286 ± 84 to —308 to —257</td>
</tr>
<tr>
<td>TBNRyde, FFM(DXA)</td>
<td>1512 ± 107</td>
<td>——</td>
<td>—16 ± 122 to —16 to 58</td>
</tr>
<tr>
<td>TBNGaskin, height</td>
<td>1497 ± 168</td>
<td>1 ± 84</td>
<td>—22 to 29</td>
</tr>
<tr>
<td>TBNGaskin, FFM(DXA)</td>
<td>1455 ± 188</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>Normal-weight girls (n = 40)</td>
<td>1406 ± 144</td>
<td>——</td>
<td>—51 ± 115 to —88 to —5</td>
</tr>
<tr>
<td>TBNBarn, height</td>
<td>1439 ± 206</td>
<td>——</td>
<td>—18 ± 74 to —38 to 11</td>
</tr>
<tr>
<td>TBNBarn, FFM(DXA)</td>
<td>1379 ± 217</td>
<td>——</td>
<td>—74 ± 145 to —125 to —23</td>
</tr>
<tr>
<td>TBNRyde, FFM(BIA)</td>
<td>1168 ± 139</td>
<td>——</td>
<td>—290 ± 75 to —311 to —259</td>
</tr>
<tr>
<td>TBNRyde, FFM(DXA)</td>
<td>1502 ± 107</td>
<td>——</td>
<td>—45 ± 121 to —5 to 93</td>
</tr>
<tr>
<td>TBNGaskin, height</td>
<td>1458 ± 169</td>
<td>1 ± 69</td>
<td>—17 to 29</td>
</tr>
</tbody>
</table>

1. p, predicted; FFM, fat-free mass; DXA, dual-energy X-ray absorptiometry; BIA, bioimpedance analysis; NAA, neutron activation analysis.
2. The equations of Baur et al (9), Ryde et al (10), Ellis (11), and Gaskin et al (developed in the present study population; see Table 3) were used.
3. Calculated as means ± 1.96 SD.

**TBN in relation to weight, height, and FFM in adolescent girls**

In our group of healthy girls, TBN was closely associated with height (Figure 1B) and also with weight, although not linearly (Figure 1A). Describing nitrogen in relation to weight does not account for the fact that most of the “surplus” weight in overweight subjects normally consists of fat and not protein. Even though this was true for our overweight subjects, we also showed that the body nitrogen content of all overweight girls was relatively high when considering the entire study group. The adolescent group in our study had higher TBN values (1.49 kg) than did adult women in 2 other studies: 1.25 kg (10) and 1.31 kg (11). This difference can be explained by the fact that protein mass is building up during puberty (24) and decreases in adulthood with increasing age. Our data agree with those of Cohn et al (25), which showed that TBN was 1.45 kg in healthy women 20–29 y of age and steadily decreased to 1.15 kg at 70–79 y of age.

**Composition of FFM**

From earlier chemical studies, it is suggested that protein is a relative constant of FFM in specific age groups, rising from 3.7% at birth to ≈17% at 1 y and to between 19% and 21% in adults (2, 4). More recent studies involving NAA have confirmed these numbers in adults (10). To our knowledge, no comparable data are available for adolescents. The P:FFM ratio calculated with the help of a 4-component BIA model in the current study, 23.2%, is slightly greater than the value of 19–21% reported for adults. FFM hydration in our study population (71.2%) was also similar to adult values of between 72% and 73% (26). However, the FFM mineral content of 5.6% in our study was lower than the value of 7% reported for adults and closer to the value of 5% reported previously for children (8). Our analysis of FFM composition also showed that the mineral and protein contents varied more than did the content of water; the CVs for mineral and protein contents were 8.0% and 9.1%, respectively, but the CV for water content was only 2.8%. This finding is consistent with the study by Wells et al (8) in children. Our data confirm earlier findings that the protein chemical maturity of FFM is reached by 14.5 y in girls (27). The higher P:FFM ratio in the 4-compartment BIA model than in earlier chemical studies may be variously
explained. FFM estimates depend on the methodology and their assumptions and could be inaccurate. Unfortunately, our study did not involve a “gold standard” test for FFM, and underestimating FFM will lead to an overestimation of the protein content of FFM. However, there might be more than just a methodologic reason for the observed discrepancy. Studies involving chemical carcass analyses were done in severely malnourished or diseased persons in whom not only absolute protein stores, but also TBPr in proportion to FFM, might have been significantly altered. Evidence exists that P:FFM adapts to nutritional status. The nitrogen content of lean body mass was found to be lower in malnourished cystic fibrosis patients than in well-nourished cystic fibrosis patients (28) and to increase in patients with anorexia nervosa during refeeding (29). Lastly, because of these early chemical studies, people have changed their lifestyle and dietary habits and are most likely better nourished than they were 40 y ago. It is tempting to speculate that the body protein content of FFM is gradually and steadily increasing, both in developing civilizations and in advancing generations.

Validation of TBN prediction equations

When cross-validating previously published TBN formulas with our study population, it became clear that formulas are less suitable when based on height or weight than when based on a DXA-derived measure of FFM and the inclusion of overweight subjects weakens their predictive power. We also conclude that both the sex and age of the study population used to derive the TBN prediction models are important factors that should be taken into account, as has been documented by other authors for different body-composition models. Additionally, we generated a prediction equation from our study population, based on FFM measured with DXA, which is a useful tool when estimating TBN in groups of adolescent girls in research settings where NAA is not available. Specifically, it could be helpful in future studies involving malnourished young girls to detect and quantify changes in body protein. However, clinical application to achieve TBPr assessment without NAA measurements cannot be achieved with our DXA model because of a residual variance of 10% in the TBN group mean. We suggest 2 explanations for this residual variance. First, it might originate from methodologic bias when FFM is measured indirectly with DXA. Studies that have assessed the body composition of animals in vivo and chemically show that DXA can provide accurate measures of FFM (30, 31). However, many authors have cautioned against the use of DXA as a reference method for body composition, other than for bone mineral content, in humans (32, 33). Second, the variance might point to the fact that the nitrogen content per unit FFM is an individual characteristic and is thus subject to biological variation.

**FIGURE 3.** Bland-Altman plots comparing total body nitrogen measured by neutron activation analysis (TBN$_{\text{NAA}}$) with TBN predicted with the Baur equation on the basis of height (A), with TBN predicted with the Baur equation on the basis of fat-free mass measured by bioimpedance analysis (FFM$_{\text{BIA}}$) (B), and with TBN predicted with the Gaskin equation on the basis of FFM measured by dual-energy X-ray absorptiometry (FFM$_{\text{DXA}}$) (C) in 51 normal-weight (●) and overweight (○) adolescent girls. The broken lines represent mean bias, and the unbroken lines represent the upper and lower limits of agreement (x bias ± 1.96 SD).
Study limitations

Because the cohort was relatively small, it did not allow for random division of the participants into 2 groups to test the regression equations developed in the current study. Therefore, and also because of the narrow age range and diverse ethnicity of our study population, caution should be used when extrapolating the data to other populations. In addition, our analysis was complicated by the fact that >20% of our study participants were overweight. Even though our group represented a typical female adolescent Australian population, our overweight group was too small to carry out a separate analysis to better elucidate the effect of overweight on body-composition techniques and the protein content of FFM.

Conclusions

In our adolescent study population, TBN values were higher than those previously described for women, and the protein content of FFM was also higher than values observed in early chemical studies. A prediction model based on DXA measurements of FFM developed in this study can accurately predict the TBN content in a group of young adolescent girls, but not in individuals. This model will be helpful in future studies of the body protein content of malnourished adolescent girls.

We thank Madeleine Thompson for assistance with the body-composition measurements. VKH collected and analyzed the data and wrote the manuscript. JRA, SZ, JNB, and MG collected the data. KIG, MRK, and MMJ: designed the study and provided advice. SDC and SM provided advice. None of the authors had a conflict of interest.

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