Accurate Estimation of Energy Requirements of Young Patients

Andrea Carpenter, Paul Pencharz, and Marialena Mouzaki

ABSTRACT

The provision of optimal nutritional care is based on accurate estimations of patients’ resting energy expenditure. The latter can be calculated with the use of predictive equations or measured with indirect calorimetry (IC). Owing to their ease of use, mathematical equations have largely replaced IC in clinical practice. This article examines the limitations and predictive inaccuracy of commonly used equations in pediatrics, which may contribute to the provision of poor nutritional care and directly affect patient outcomes. In addition, the role of IC is discussed and the physiology of nutrient metabolism, in terms of energy expenditure, is reviewed.

Key Words: energy requirements, FAO/WHO/UNU, indirect calorimetry, Oxford, predictive equations, Schofield

In 1985, the Food and Agriculture Organization/World Health Organization/United Nations University (FAO/WHO/UNU) document “Energy and Protein Requirements” recommended that estimates of daily caloric requirements are based on measurements of energy expenditure (1). The energy expended at rest, while lying awake at a thermoneutral environment after an overnight fast, is called basal metabolic rate (BMR). Indirect calorimetry (IC) is a clinical tool that measures resting energy expenditure (REE), which even though not identical, approximates BMR. The REE can then be used in the estimation of total energy expenditure when an individual’s level of physical activity is known. The ability to measure REE is hence important in assessing an individual’s caloric needs.

IC is not widely available in the clinical setting. It is costly, and its use requires training and expertise. For that reason, although it is believed to be the most accurate clinically available tool for the measurement of REE, its use has been largely replaced by predictive equations that estimate one’s energy expenditure at rest. The first equations developed were based on IC-derived measurements that had been collected from a small number of primarily white subjects. During the 20th century, the predictive inaccuracy of these equations, particularly when applied to subjects with different characteristics (eg, lean vs overweight, healthy vs ill, those living in tropical vs cool climates), became apparent (2). To address this matter, newer equations (FAO/WHO/UNU (1), Schofield (3), and Oxford (2)) were developed.

For the purposes of the 1985 FAO/WHO/UNU report on energy and protein requirements, Schofield reviewed previously published studies reporting on the BMR of healthy children and adults. He synthesized the results of 114 different studies, including the study that had introduced the Harris-Benedict equation at the beginning of the 20th century (1,3). Schofield data included a total of 7173 BMR measurements. These data were subsequently used for the development of the FAO/WHO/UNU equations, as well as the Schofield equations (called Schofield [weight] and Schofield [weight and height]). The generalizability of these equations has since been found to be limited (4–6), particularly because the studies used in their development did not represent all ethnicities (Europeans and North Americans formed the majority, whereas the representation of individuals from the tropics was poor). In addition, 47% of the measurements were made in Italians, who were subsequently found to have a higher BMR per kilogram of body weight than average, leading to overestimations of BMR when the equations were applied to non-Italian individuals (7). In an effort to address some of these limitations, Henry (2) created the Oxford equations in 2005. These equations were based on 10,552 measurements and excluded the Italian cohort used by Schofield. In addition, measurements from 4018 individuals living in the tropics were included. Presently, clinicians primarily use the FAO/WHO/UNU, Schofield, and Oxford equations in their practice. These equations are summarized in Table 1 (1–3).

Considering their aforementioned limitations, as well as the fact that equations are designed to predict the mean REE of a population, rather than that of individuals, we aimed at reviewing the literature addressing the predictive accuracy of these and other disease-specific equations in the pediatric setting. Specifically, the goals of this article were to discuss the performance of predictive equations in various clinical settings, draw attention to the areas of pediatric clinical care wherein the predictive accuracy of these equations has not been elucidated, and review the pathophysiology of energy metabolism as it relates to energy expenditure. Finally, the role of IC in the nutritional monitoring of children with different health issues is discussed.

IC versus Predictive Equations to Estimate REE of Healthy Subjects

The accuracy and generalizability of the FAO/WHO/UNU and Schofield equations have been studied in healthy children of various ages and physical activity levels. Among other equations, Thomson et al (8) studied the predictive accuracy of the FAO/WHO/UNU and Schofield (weight, weight and height) and Harris-Benedict equations in 36 infants. The FAO/WHO/UNU was the most accurate equation studied; however, all of the equations overestimated the REE in this setting: FAO/WHO/UNU overestimated by 104% ± 14%; Schofield [weight] and Schofield [weight and height] overestimated by 107.5% ± 14% and 106% ± 11%, respectively, and

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TABLE 1. Summary of commonly used predictive equations

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAO/WHO/UNU (1)</td>
<td>$BMR = 7.4 \text{[wt (kg)]} + 482 \text{[ht(cm)]} + 217$</td>
</tr>
<tr>
<td>Schofield (weight)</td>
<td>$BMR = 12.1 \text{[wt (kg)]} + 499$</td>
</tr>
<tr>
<td>and height (3)</td>
<td>$BMR = 8.4 \text{[wt (kg)]} + 4.7 \text{[ht (cm)]} + 200$</td>
</tr>
<tr>
<td>Schofield (weight)</td>
<td>$BMR = 13.4 \text{[wt (kg)]} + 693$</td>
</tr>
<tr>
<td>Oxford (2)</td>
<td>$BMR = 0.255wt - 0.141$</td>
</tr>
<tr>
<td></td>
<td>Males, 0–3 years</td>
</tr>
<tr>
<td></td>
<td>$BMR = 0.0937wt + 2.15$</td>
</tr>
<tr>
<td></td>
<td>Males, 3–10 years</td>
</tr>
<tr>
<td></td>
<td>$BMR = 0.0769wt + 2.43$</td>
</tr>
<tr>
<td></td>
<td>Males, 10–18 years</td>
</tr>
<tr>
<td></td>
<td>$BMR = 0.246wt - 0.0965$</td>
</tr>
<tr>
<td></td>
<td>Females, 0–3 years</td>
</tr>
<tr>
<td></td>
<td>$BMR = 0.0842wt + 2.12$</td>
</tr>
<tr>
<td></td>
<td>Females, 3–10 years</td>
</tr>
<tr>
<td></td>
<td>$BMR = 0.0465wt + 3.18$</td>
</tr>
<tr>
<td></td>
<td>Females, 10–18 years</td>
</tr>
</tbody>
</table>

$BMR =$ basal metabolic rate; $ht =$ height; $wt =$ weight; FAO/WHO/UNU = Food and Agriculture Organization/World Health Organization/United Nations University.

Harris-Benedict overestimated by 182% ± 63%. Finan et al (9) performed a similar study in a cohort of 113 prepubertal children. In this study, although the FAO/WHO/UNU equations performed better than the rest, with 99% of the estimates being within 200 kcal/day, none of the equations assessed accurately predicted energy requirements (9). The validity of predictive equations in moderately active adolescents was assessed by De Lorenzo et al (10). In this study, the authors concluded that despite significant variability in the results, the Schofield equations could be used in clinical practice for moderately active 16- to 18-year-olds, because the mean estimated REE was within 1% of that measured. The FAO/WHO/UNU equations were not studied by De Lorenzo et al. Finally, Rodriguez et al (11) assessed the agreement between predictive equations and IC in a cohort of 59 normal weight children, ages 7.8 to 16.6 years. The Schofield [weight] equation performed best in that group, providing results within 300 kcal/day of that measured using IC. Further dividing the cohort based on sex revealed that the Schofield [weight and height] equation was better for boys and the FAO/WHO/UNU for girls. To summarize, the FAO/WHO/UNU equations appear to perform better than others in healthy children; however, they are not consistently accurate across all ages, sexes, and physical activity levels. The Oxford equations remain to be validated in healthy children.

**FAILURE TO THRIVE AND EATING DISORDERS**

Failure to thrive (FTT) indicates poor physical growth and primarily affects children <3 years of age (12,13). FTT may be secondary to suboptimal energy intake, insufficient nutrient absorption, or increased energy expenditure. Regardless of the cause, children with FTT usually have decreased muscle mass, which is associated with a decrease in BMR. The variability in the etiology of FTT may render predictive equations for BMR inaccurate, as discussed below.

Two studies have compared calculated and measured REE in the setting of FTT with similar results. Sentongo et al (14) assessed 45 children ages 0 to 3 years and Kaplan et al (15) studied 77 children ages 0.2 to 20.5 years. Sentongo et al showed that the FAO/WHO/UNU and Schofield equations estimated REE within 10% accuracy in less than half of the subjects studied and overall tended to underestimate the REE. Kaplan et al found that among the FAO/WHO/UNU, Schofield, and Harris-Benedict equations, the Schofield [weight and height] had the best predictive ability, which was, however, suboptimal because it estimated the REE to be within 20% of that measured. Underestimating the energy requirements of patients with FTT can have significant nutritional implications, such as failure to catch up weight gain, suboptimal linear growth, and potential negative future neurodevelopmental outcomes. The use of IC should be considered in the management of these children, particularly when established nutritional plans do not have the expected outcome in terms of weight gain.

Apart from FTT, Cuerda et al have assessed the accuracy of various equations in predicting the caloric requirements of patients with eating disorders in 2 similar studies (16,17). The intraclass correlation between equations studied (including FAO/WHO/UNU and Schofield [weight and height]) and IC results was poor (0.09–0.20), suggesting that the caloric needs of young, hospitalized girls with eating disorders cannot be accurately predicted. The authors concluded that IC is an important clinical tool to assist in the nutritional management of patients with eating disorders.

**OBESITY**

Childhood obesity is a growing epidemic. In 1981, 14% of children ages 15 to 19 years were overweight or obese (18); however, by 2009 to 2011 that number more than doubled, with 32% of Canadian children ages 5 to 17 being overweight or obese (http://www.statcan.gc.ca/pub/82-625-x/2012001/article/11712-eng.pdf). Children who are overweight or obese have different body composition compared with their healthy-weight peers. Apart from the excess adipose tissue, these patients also have increased muscle mass, which increases their REE. For that reason, predictive equations specific for overweight and obese subjects have been developed; their accuracy does not appear to be consistent, however, as discussed below and summarized in Table 2 (15,19–23).

McDuffie et al (19) examined the predictive ability of equations developed for healthy subjects (including FAO/WHO/UNU, Schofield [weight, weight and height]), as well as other equations developed specifically for obese individuals (Molnar-1 and Molnar-2, Tverskaya, and Maffers). In this study, which included 502 subjects between the ages of 6 and 11 years, not a single equation was found to accurately predict the BMR of most individuals. In response to these results, McDuffie et al (19) generated 4 new sexand ethnicity-specific pediatric equations, which allowed for more accurate predictions. In a similar study of 102 subjects 3 to 18 years old, Tverskaya et al (20) showed that, of the equations assessed, the FAO/WHO/UNU was the most accurate predictor of energy requirements, especially in adolescents. Given the inaccuracies of the existing equations, Tverskaya et al (20) created a new equation to include weight, fat-free mass, fat mass, age, and height. It was found to predict requirements within 4% of that measured with IC. The equations derived by McDuffie et al (19) and Tverskaya et al (20) have not yet been validated in subsequent studies.

These results, along with the other studies summarized in Table 2, argue the need for pediatric-specific equations that take variables such as sex, ethnicity, puberty, and body composition into consideration. Until such equations are developed and/or validated, IC will remain the most accurate indicator of REE in these subjects.

**END-STAGE LIVER DISEASE**

Metabolism, energy expenditure, and body composition are altered in patients with end-stage liver disease (ESLD) (24). This is secondary to hepatocellular dysfunction, disease-related complications, and/or malnutrition with associated sarcopenia (25). Shepherd (26) studied 18 infants (mean age 0.44 ± 0.29 years) listed for transplant for ESLD secondary to biliary atresia and showed that the FAO/WHO/UNU and Schofield equations underestimated the BMR by a staggering 30%. Considering the significant prevalence of malnutrition in ESLD (25) and the effects of nutritional status on long-term outcomes (27), IC should be used when available to assist in the nutritional care of these fragile patients. Many studies report...
improved outcomes after liver transplantation, when an optimal nutritional status is maintained before undergoing surgery (28,29). When taking care of patients in ESLD, clinicians should take into consideration complications such as maldigestion because of cholestasis, when estimating their patients’ total caloric requirements.

**INFLAMMATORY BOWEL DISEASE**

Inflammatory bowel disease (IBD) is characterized by intestinal inflammation that waxes and wanes (30). Inflammation and associated fevers increase energy expenditure (31); conversely, malabsorption and anorexia contribute to loss of muscle mass, decreasing energy expenditure. Hill et al (32) studied the accuracy of the FAO/WHO/UNU and Oxford equations in 63 children with IBD at a mean age of 14 years. Neither equation performed well across all subjects because they all underestimated the patients’ REE by 5% to 8%. Cormier et al (33) also assessed the FAO/WHO/UNU equation for children of similar age, who were receiving parenteral nutrition. In this setting the FAO/WHO/UNU equations performed well, with a correlation between measured and calculated energy expenditure of $r^2 = 0.73$.

Finally, a study of 23 patients with inactive IBD (median age

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**TABLE 2. Summary of predictive equations in obesity**

<table>
<thead>
<tr>
<th>Study</th>
<th>n; setting</th>
<th>Age, y</th>
<th>Predictive equations studied</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDuffie et al (19)</td>
<td>502; boys (n = 191) and girls (n = 311) Black and white 37.6% normal weight 10.9% overweight 51.4% obese</td>
<td>6–11</td>
<td>FAO/WHO/UNU Schofield Harris-Benedict Molnar-1 Molnar-2 Tverskaya Maffers</td>
<td>Systematic bias and/or magnitude bias in all equations in obese males and/or females</td>
</tr>
<tr>
<td>Tverskaya et al (20)</td>
<td>110; healthy obese males (n = 50) and females (n = 60)</td>
<td>3–18</td>
<td>FAO/WHO/UNU Harris-Benedict Ravussin Cunningham Schofield</td>
<td>FAO/WHO/UNU was the best predictor of REE (2%)</td>
</tr>
<tr>
<td>Klein et al (21)</td>
<td>58; Hispanic children with obesity</td>
<td>7–15</td>
<td>Harris-Benedict IOM-HW* IOM-OS** Schofield</td>
<td>Harris-Benedict underestimated in males by 9%–11% Remaining underestimated by 17%–22%</td>
</tr>
<tr>
<td>Kaplan et al (15)</td>
<td>102; 55% female, 19% obese</td>
<td>0.2–20.5</td>
<td>FAO/WHO/UNU Schofield (weight)</td>
<td>Harris-Benedict underestimated by 51% Remaining equations underestimated by 22%–23%</td>
</tr>
<tr>
<td>Maffeis et al (22)</td>
<td>130; prepubertal, healthy white children, divided as obese and nonobese</td>
<td>6–10</td>
<td>FAO/WHO/UNU Robertson and Reid Talbot method Fleish</td>
<td>FAO/WHO/UNU overestimated the REE by ~13%</td>
</tr>
<tr>
<td>Henes et al (23)</td>
<td>80 obese subjects</td>
<td>7–8</td>
<td>FAO/WHO/UNU Schofield-HW Harris-Benedict IOM-OY (pEE)** IOM-OS† IOM Molnar Mifflin Lazzer</td>
<td>Proportion of subjects in whom the equations predict the REE within ±10% accuracy: FAO/WHO/UNU 40% Schofield [weight and height] 51% Harris-Benedict 65% Remaining: 47%–61%</td>
</tr>
</tbody>
</table>

FAO/WHO/UNU = Food and Agriculture Organization/World Health Organization/United Nations University; REE = resting energy expenditure.

* Institute of Medicine for Healthy-Weight Children.

** Institute of Medicine for Overweight and Obese Children.

*** Institute of Medicine for Obese Youth.
of Enteral and Parenteral Nutrition recommends the use of IC in the intensive care unit in a number of clinical settings (48). It is useful for patients with a body mass index <5th or >85th percentile, weight loss in excess of 10% while in the intensive care unit, in those with central nervous system trauma with dysautonomia or oncologic diagnoses, patients taking muscle relaxants or on ventilatory support for >7 days, and those who have been in the intensive care unit for >4 weeks (49). IC is also recommended for those “at risk for hypo- or hypermetabolism” and in cases of consistent failure to meet caloric goals (49).

**DISCUSSION**

Of all predictive equations reviewed, none provides consistently accurate results in any population. Despite pooling patients into disease-specific conditions, divided further by age, sex, and, in
some instances, race, generalizations are difficult to make. The common denominator that limits the predictive ability of all equations is the lack of measures of body composition in the calculation. Weight and height are often included; however, neither of those measures reflects body composition. A clinically available tool that allows the determination of muscle mass is the mid-arm muscle circumference. It would be of value to assess the predictive ability of equations that include measures of muscle mass.

In children and adults the major determinant of REE is muscle mass (Fig. 1) (54–56). Conditions associated with changes in muscle mass have been shown to affect REE. An example of such conditions is anorexia nervosa. The REE of children with this eating disorder is significantly decreased and correlates with the degree of sarcopenia (30). Apart from changes in body composition, however, there are other factors associated with chronic illness that have an impact on a patient’s REE. Such factors include inflammation, malignancies, neurological impairment, and medications.

Inflammation has been shown to increase the REE via increased expression of cytokines (57). Inflammation is believed to be the reason why patients with Crohn disease have a “normal”

<table>
<thead>
<tr>
<th>Study</th>
<th>n; setting</th>
<th>Age</th>
<th>Predictive equations studied</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardy et al (41)</td>
<td>52, PICU</td>
<td>Median 4.5 y (range 0–22 y)</td>
<td>FAO/WHO/UNU Schofield equations Harris-Benedict Recommended dietary allowance</td>
<td>Poor predictive ability for all equations; proportion of subjects in whom the equations predict the REE within ±10% accuracy; FAO/WHO/UNU 31% Schofield 36% Harris-Benedict 27%–36% Recommended dietary allowance 4%</td>
</tr>
<tr>
<td>Oosterveld et al (42)</td>
<td>46, PICU Sepsis Postoperative Trauma</td>
<td>0–18 y</td>
<td>Schofield equations</td>
<td>Performed accurately (within 1% of measured REE)</td>
</tr>
<tr>
<td>White et al (43)</td>
<td>100, PICU Trauma Infection Other</td>
<td>54 mo (SD 53 mo)</td>
<td>FAO/WHO/UNU Schofield equations Harris-Benedict Talbot method White equations</td>
<td>Apart from the Talbot and White equations, all others underestimated the REE by 61–86 kcal/day White equations performed better in infants &gt;2 mo</td>
</tr>
<tr>
<td>Framson et al (44)</td>
<td>46, PICU Acute illness Trauma Elective</td>
<td>2 wk–17 y</td>
<td>Schofield equations White equations</td>
<td>Poor predictive ability of all equations Proportion of subjects in whom the equations predict the REE within ±10% accuracy: Schofield 45% White 30%</td>
</tr>
<tr>
<td>De Wit et al (45)</td>
<td>21, CICU Postcardiac operation</td>
<td>Neonate–3 y</td>
<td>FAO/WHO/UNU Schofield equations White equations</td>
<td>Poor performance of all equations The difference between measured and calculated REE was 23% with the FAO/WHO/UNU equations 21% with the Schofield equations 36% with the White equations</td>
</tr>
<tr>
<td>Coss-Bu et al (46)</td>
<td>55, PICU Infection ARDS Postoperative</td>
<td>Mean 5.7 y (SD 5.9)</td>
<td>Harris-Benedict Talbot method</td>
<td>Poor predictive ability of both equations Applying a stress factor of 1.5 to these equations revealed a difference between measured and predicted REE of 24–48 kcal/day, respectively</td>
</tr>
<tr>
<td>Vasquez-Martinez et al (47)</td>
<td>43, PICU Trauma</td>
<td>Mean 4.2 y (SD 3.7)</td>
<td>FAO/WHO/UNU Schofield equations Harris-Benedict Maffeis Fleisch Kleiber Hunter Caldwell-Kennedy</td>
<td>No equation accurately predicts REE Caldwell-Kennedy equation was the most accurate, demonstrating a bias of 38 kcal/day and precision of ±179 kcal/day</td>
</tr>
<tr>
<td>Mehta et al (40)</td>
<td>14, PICU Cardiac</td>
<td>11.2 y (1.6 mo–32 y)</td>
<td>FAO/WHO/UNU Schofield equations Harris-Benedict</td>
<td>Risk of under- or overfeeding with all predictive equations studied</td>
</tr>
</tbody>
</table>

ARDS = acute respiratory distress syndrome; CICU = cardiac intensive care unit; FAO/WHO/UNU = Food and Agriculture Organization/World Health Organization/United Nations University; PICU = pediatric intensive care unit; REE = resting energy expenditure.
FIGURE 1. Determinants of resting energy expenditure. ATP = adenosine triphosphate.

measured REE, despite measurable decreases in muscle mass (58). Also, inflammation plays a role in patients with CF, whose energy expenditure is higher than what would be considered normal, despite a poor nutritional status (59). The fact that the REE is higher in this group than those with Crohn disease suggests that the inflammatory response is more pronounced in CF or the energy cost of breathing contributes to this increase (60). The latter has been shown in patients with CF, who on average have an increased oxygen uptake per kilogram of lean body mass compared with healthy controls (61). Certain malignancies are also associated with changes in REE. Children with acute lymphoblastic leukemia have an increased REE, which correlates closely with the degree of tumor burden and promptly returns to normal with treatment (62). In contrast, patients with CP have a disproportionately low REE for their degree of sarcomenia (63). It has been postulated that central nervous system impairment may be contributing to this phenomenon (63). Sym pathetic nerve activity has been shown to correlate with energy expenditure, and apart from its role in patients with neurological impairment it is also believed to contribute to ethnic variations in REE (63). Finally, medications can have a direct effect on energy expenditure, as shown with nifedipine, which increases the REE and paralytic agents, which are associated with decreases in REE (64,65).

To summarize, REE is reflective of muscle mass but, in the clinical setting, is also determined by disease states and medical interventions. General predictive equations (eg, the FAO/WHO/UNU and Harris equations) are inefficient in predicting REE in most cases because they are not disease specific and they are based on the assumption that weight is reflective of body composition, which does not always hold true.

Of the available equations, the Oxford equations may prove to be the most accurate and generalizable considering the number of BMR measurements used to design them and the wide spectrum of populations and geographical origins they represent. Their validity has not yet been assessed in different settings, and hence their accuracy remains to be determined. Other disease-specific equations will also need to be validated further to determine their predictive ability. Presently, the FAO/WHO/UNU equations perform better than the rest; however, they should be interpreted with caution in certain patient populations. IC should be used, when available, to determine the energy needs of populations at risk (especially those who are extremely young, frail, already malnourished and critically ill).

REFERENCES


