Evidence-Based Practice Reports

Allometric Prediction of Energy Expenditure in Infants and Children

Thane Blinman, MD, and Robin Cook, MS, RD

Abstract: *Predicting energy needs in children is complicated by the wide range of patient sizes, confusing traditional estimation equations, nonobjective stress-activity factors, and so on. These complications promote errors in bedside estimates of nutritional needs by rendering the estimation methods functionally unavailable to bedside clinicians. Here, the authors develop a simple heuristic energy prediction equation that requires only body mass (not height, age, or sex) as input. Expert estimation of energy expenditure suggested a power-law relationship between mass and energy. A similar mass-energy expenditure relationship was derived from published pediatric echocardiographic data using a Monte Carlo model of energy expenditure based on oxygen delivery and consumption. A simplified form of the equation was compared with energy required for normal growth in a cohort of historical patients weighing 2 to 70 kg. All 3 methods demonstrate that variation in energy expenditure in children is dominated by mass and can be estimated by the following equation: Power(kcal/kg/d) = 200 × [Mass(kg)$^{(-0.4)}$]. This relationship explains 85% of the variability in energy required to maintain expected growth over a broad range of surgical clinical contexts. A simplified power-law equation predicts real-world energy needs for growth in patients over a wide range of body sizes and clinical contexts, providing a more useful bedside tool than traditional estimators.*

Keywords: energy expenditure; mathematical model; allometric scaling; calories; growth

Introduction

The hallmark of pediatric care is the careful scaling of medical interventions to fit size-dependent physiological needs. Despite its importance, modern medicine lacks a coherent theory of physiological scaling, failing to explain size-dependent variations, even for familiar physiological measures such as heart rate (HR), respiratory rate, or energy expenditure.[1] For example, clinicians are still taught that metabolic power scales with body surface area (BSA), a form of geometric scaling first proposed in 1839[2] but later demonstrated to be theoretically implausible and experimentally untrue.[3] Of all clinical scaling problems, estimation of energy expenditure in sick children seems to cause the most clinical confusion, perhaps because textbook energy prediction equations (Table 1) are confusing and flawed,[4,5] leaving clinicians without a straightforward method for estimating energy needs.

"Although some variables scale geometrically or isometrically (eg, blood volume and gastric volume), most important physiological variables (eg, HR, energy expenditure, and aortic cross section) scale allometrically."

Estimating energy expenditure in children is complicated for the following reasons:

1. Pediatric patients span a broad range of body mass. Patients may weigh from just over 400 to more than 100 kg (or more), a range of nearly 3 orders of magnitude. Physiological parameters are utterly dissimilar over

DOI: 10.1177/1941406411414416. From the Division of General, Thoracic and Fetal Surgery, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania. Address correspondence to Thane Blinman, MD, Division of General, Thoracic and Fetal Surgery, Children's Hospital of Philadelphia, 34th and Civic Center Blvd, Philadelphia, PA 19104; e-mail: blinman@email.chop.edu.

Table 1.

Common Energy Estimation Equations

Equation	Energy Estimate		
Harris-Benedict (kcal/d)	Males	66.4730 + [5.0033 × height (cm)] + [13.7516 × weight (kg)] – [6.7550 × age (years)]	
	Females	655.095 + [1.8496 × height (cm)] + [9.5634 × weight (kg)] – [4.6756 × age (years)]	
Schofield (kcal/d)	Males	<3 years	[0.167 × weight (kg)] + [1517.4 × height (m)] – 617.6
		3-10 years	[19.59 × weight (kg)] + [130.3 × height (m)] + 414.9
		10-18 years	[16.25 × weight (kg)] + [137.2 × height (m)] + 515.5
	Females	<3 years	[16.252 × weight (kg)] + [1023.2 × height (m)] – 413.5
		3-10 years	[16.969 × weight (kg)] + [161.8 × height (m)] + 371.2
		10-18 years	[8.365 × weight (kg)] + [465 × height (m)] + 200.0
WHO (kcal/d)	Males	<3 years	[60.9 × weight (kg)] – 54
		3-10 years	[22.7 × weight (kg)] + 495
		10-18 years	[17.5 × weight (kg)] + 651
	Females	<3 years	[61.0 × weight (kg)] – 51
		3-10 years	[22.5 × weight (kg)] + 499
		10-18 years	[12.2 × weight (kg)] + 746
White (kJ/d)	17 × (age[months]) + (48 × weight[kg]) + (292 × body temperature[°C]) – 9677		

this range and do not vary linearly with mass or age.

2. Current equations are not based on allometric scaling. Extensive theoretical and experimental work from biology describes how physiology scales with body mass (eg, Kleiber,[3] Darveau et al,[6] Packard and Birchard,[7] and Salafia et al[8]). Although some variables scale geometrically or isometrically (eg, blood volume and gastric volume), most important physiological variables (eg, HR, energy expenditure, and aortic cross section) scale allometrically (see below). Allometric principles do not inform current methods for estimating energy expenditure. For example, it is physiologically plausible that baseline metabolic power scales essentially with body mass,[9] but no relationship suggests age, sex, or height as primary variables (except to the extent that these correlate with mass). Nevertheless, these other variables appear in Harris-Benedict, White, World Health Organization (WHO) and Schofield equations solely because linear regression approximations could be found to fit these easy-to-measure clinical data.[10,11] Kleiber[3] points out that statistically derived relationships like the Harris-Benedict equations may be roughly accurate, but "physiologically, the equations are practically meaningless."
3. Common equations (Table 1) are difficult to remember and confusing to apply. Even trained dietitians must resort to "cheat-sheets" or other aids to remember multiple complicated ranges and constants. Even with the equation at hand, clinicians often lack a reliable measure of height, without which the Schofield and Harris-Benedict equations (or any estimate scaled to some estimate of BSA or, worse, body mass index) are useless. In this circumstance, clinicians may resort to satisficing[12] strategies that produce seemingly plausible, yet often dangerously inaccurate, estimates for fluid and energy needs in children. For example, simply ordering enteral feeds at maintenance fluid estimation rates seems plausible to untrained residents, but following this strategy usually delivers too much energy and too little free water, an error that can go unnoticed until serious complications

(uremia, hypercarbia, hypernatremia, constipation, etc) appear.

4. Common equations are precise but not accurate. Common equations return resting energy expenditure (REE). Clinicians need to supply actual energy expenditure. The 3- or 4-decimal precision of commonly used equations (Table 1) is wiped out when the clinician guesses a stress-activity factor (SAF) by which to multiply REE to obtain actual energy needs. The SAF is determined by the clinician's estimate of the degree to which clinical factors (fever, sepsis, injury, and work of breathing) push energy needs up or down. The SAFs may be large, ranging from 0.8 to 2.0 based on an essentially subjective estimate of clinical context and can magnify inaccuracies in the formulas. For example, the WHO equations use mass, age, and sex (but not height) as input. This creates a practical advantage for WHO equations in the inpatient setting, where illness, time pressure, and altered body shape (scoliosis, thoracic insufficiency, etc) make height measures difficult. However, WHO equations underestimate energy needs for patients less than a year old or weighing less than 15 kg, and when combined with the SAF, can produce widely disparate estimates in larger children. Several studies document unacceptable inaccuracy of common energy prediction equations in sick or injured children (eg, De Wit[5] and Suman[13]).

Theoretical Background

Physiological scaling generally follows the allometric scaling equation:

$$Y = A \times M^b, \quad (1)$$

where Y is the parameter of interest (eg, metabolic power, HR, respiratory rate, and oxygen consumption), A is a normalization constant, M is body mass (kg), and b is the allometric scaling exponent. Many physical and metabolic measurements scale simply by a linear relationship with body mass. For example, human blood volume is about 85 mL/kg regardless of age or size. Similarly, normal respiratory tidal volume is around 7 to 8 mL/kg/breath. In cases like these, the b is simply 1. But most important physiological parameters do not scale across body size in such a simple manner. Instead, physiology such as lung surface area, gut absorptive area, HR, cardiac output, aortic cross-sectional radius, and many others vary nonlinearly with body mass. These relationships are well described by power laws like the allometric scaling equation.

A is determined empirically, but b has been thought to follow "Kleiber's Law."[9,14] When measured across species of various sizes (eg, mammals from shrew to whale), b is approximately 3/4 (or −1/4 when indexed to mass). West et al[15,16] provided a theoretical derivation of this so-called 3/4 scaling law, showing that quarter-power (n/4) scaling exponents arise necessarily from fractal-like, self-similar, hierarchical, energy-minimizing distribution networks, such as the branching pattern of the vasculature or bronchi. What is important is that the familiar tree-like structures that are ubiquitous in nature are not random: the fractal-like structure of these networks appears to arise anytime certain energy-minimization constraints are imposed on substrate distribution (eg, sugar or oxygen to all cells within a biological volume).[17]

Recently, it has been shown that the n/4 physiological scaling exponent is valid only in idealized models, rarely conforming to a single quarter-power scaling exponent.[18] This finding implies that the expectation of n/4 power scaling is incorrect. Instead, it is reasonable to assume power-law relationships for physiological scaling but with exponents that are empirically derived for any given species.

Although between-species comparisons are common in biological literature, less work has been done *within* a single species such as humans (eg, Dewey et al,[19] Bide et al,[20] and Livingston and Kohlstadt[21]). Here, the largest variation in body size is not among adults or even between sexes, but with growth from infant to adult. However, variation in capillary number and volume, cell number, mitochondrial density, and age-dependent changes (eg, shift in proportion of lean mass and tissue water content) complicate the picture. Nevertheless, because cell size does not change with overall body mass (ie, adults do not have larger cells than infants) and because efficient, fractal-like substrate distribution networks define organ structure regardless of age or size, allometric principles must apply. In other words, body mass necessarily dominates variation in energy expenditure among individuals within a single species (such as *Homo sapiens*) as it does among multiple species.[9]

This study investigates whether a general allometric scaling equation can be derived that provides a good (or more specifically "good enough") estimate of daily calorie needs in patients over a broad range of body mass. To be useful, such an equation should

- provide an accurate estimate of actual energy expenditure over a large range of human body mass;
- use mass alone as the measured input;
- hedge toward underestimation rather than overestimation;
- be simple to remember;
- be simple to calculate; and
- perform better than traditional methods.

Here, a simplified energy prediction equation is derived by Monte Carlo simulation and then validated in a cohort of pediatric surgical patients.

Methods

Preliminary work confirmed that energy expenditure in real patients was not well described by any quarter-power scaling equation. Nevertheless, simulated estimation of energy expenditure in a small pilot cohort strongly suggested that an inverse power law described energy expenditure well in infants and children over a broad range of body mass. Therefore, scaling constants and exponents were determined empirically.

Monte Carlo Simulation

In a study by Slusymans and Colan,[22] 496 healthy pediatric patients ranging in age from newborn to 20 years underwent echocardiographic measurement of hemodynamic indices. The authors found good fit of the data to different scaling models. Here, because weight alone was desired as the input variable, the authors' weight-based power-law equations were selected for the model.

Energy expenditure was calculated from hemodynamic differential equations using Monte Carlo[23] numerical simulation. Briefly, a cohort of 1000 virtual patients was created by randomly varying mass (M), hemoglobin (Hb), respiratory quotient (RQ), ejection fraction (EF), and oxygen extraction ratio (OER) according to a uniform distribution. These randomized parameters populated standard hemodynamic equations[24] using the power-law relations from Sluysmans and Colan[22] for HR and end-diastolic volume (EDV) as described in detail below.

First, it was assumed that metabolic power (actual energy expenditure) P (kcal/kg/day) is proportional to VO_2:

$$P = V_{O_2} \times J, \quad (2)$$

where J gives oxygen consumed (in kcal/L) and varies from 4.7387 to 4.9087 depending on RQ (here varied between 0.75 and 0.95).

Oxygen consumption was derived from the equation for mixed venous oxygen (SvO_2):

$$V_{O_2} = 1 - (D_{O_2} \times SvO_2), \quad (3)$$

where SvO_2 was varied randomly from 0.67 to 0.73.

Oxygen delivery is well known to be the product of cardiac output Q and arterial oxygen content, CaO_2. Cardiac output was obtained from HR and stroke volume (SV); or because SV is the product of EDV and SV:

$$Q = HR \times EDV \times EF, \quad (4)$$

where EDV was given by

$$EDV = 3.036 \times M^{0.893}. \quad (5)$$

Similarly, HR (bpm) was calculated from

$$HR = 208 \times M^{-0.283}. \quad (6)$$

Both these power laws were taken from Sluysmans and Colan.[22] EF was varied randomly from 60% to 67%.

Arterial oxygen content (CaO2) is

$$CaO_2 = (Hb \times SaO_2 \times 1.34) + (PaO_2 \times 0.0031). \quad (7)$$

Assuming that oxygen saturation SaO_2 is always 100%, we neglected the tiny contribution of dissolved oxygen to the oxygen content and randomized Hb between 8 and 11 mg/dL to give CaO_2.

Using these relationships and normalizing units of volume and time, energy expenditure was calculated for 1000 simulated patients, whose body mass was randomized between 2 and 80 kg. Results are plotted in Figure 1. To confirm a power-law relationship of the form

$$Y = A \times M^b \quad (8)$$

and to derive the scaling constant A and exponent b, $\log(M)$ was plotted against $\log(P)$; see Figure 1 inset. The nonlinear plot becomes the linear relationship $\log(Y) = \log(A) + b\log(M)$ allowing A and b to be found by least-squares fitting of the line. To extrapolate the single daytime echocardiographic measurement to energy expenditure over a 24-hour sleep-wake cycle,[25] the allometric scaling constant A was multiplied by 0.85.

Validation in a Clinical Cohort

As part of quality improvement (QI) monitoring, growth and feeding data were collected for children enrolled in a pediatric surgical clinic. From these, 100 patients were randomly selected after screening for patients meeting growth targets. Specifically, selected patients were said to have stable target growth when they followed (or exceeded) a particular National Center for Health Statistics weight-for-age and length-for-age growth curve for >4 consecutive weeks.

To control for variation in oral caloric intake, all included children were entirely tube fed. To set daily intake (in kcal), an "estimate-intervene-measure-adjust" strategy was used, using frequent weight checks to converge on proportional growth targets. For infants, initial energy needs were estimated from the recommended dietary allowance (RDA) for infants aged 0 to 12 months.[26] The RDAs established by the Food and Nutrition Board and the Institute of Medicine to serve healthy children do not account for cardiopulmonary disease, metabolic disease, or failure to thrive. For these circumstances, 10% was added to the RDA for a first approximation. Similarly, to initially estimate daily calorie needs in older children (aged 1-18 years), REE was estimated (WHO or Schofield equations) and multiplied by a "best guess" SAF to estimate "actual" energy expenditure. If needed, initial calorie estimates were adjusted (±5%-10%) at subsequent visits until stable growth was exhibited. These actual energy requirements were expressed in kcal/kg/d and plotted against body mass (kg). Actual energy requirements were compared with power-law-based prediction equations graphically and by Bland-Altman analysis.

Comparison to Existing Methods

The equation produced from these derivations was compared to the WHO equation, and to the Holliday-Segar fluid estimation rule (which holds the explicit premise that energy and fluid needs are equal [26]). Energy predictions from the new equation and the WHO equations were calculated for 15 male and 15 female patients from the clinical cohort and compared graphically. Comparison to the Holliday-Segar rule is detailed in Figure 2.

Results

Monte Carlo Model

Results of the model are shown in Figure 1. The simulation yields a power law

$$P = 242.1 \times M^{-0.3893}, \quad (9)$$

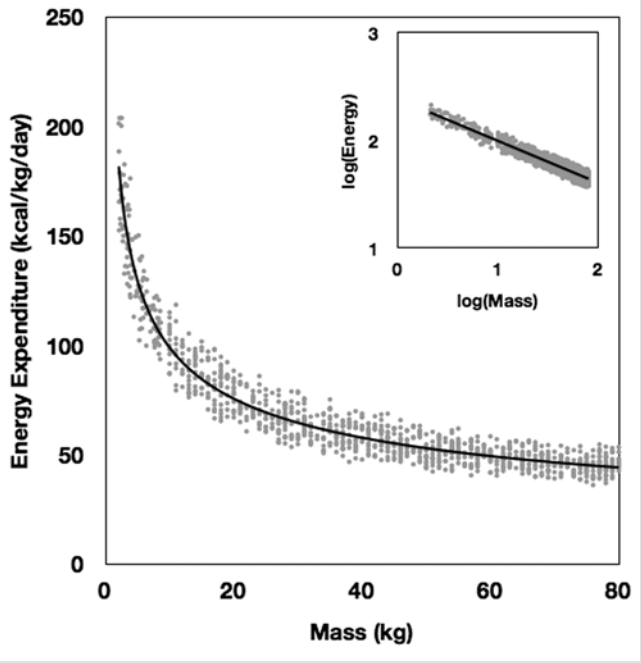
with an R^2 of 0.9226.

Extrapolation of this relation to a typical 24-hour sleep-wake cycle yields

$$P \approx 205.7 \times M^{-0.3893}. \quad (10)$$

Figure 1.

Results from a monte carlo model of energy expenditure based on echocardiographic measurements of hemodynamics in 496 children and adolescents from 2 days to 20 years old. See text for model parameters. Inset: The linear relationship produced by plotting the log of energy expenditure versus the log of body mass allows straightforward calculation of the allometric scaling constants. The nonlinear plot becomes the linear relationship $\log(Y) = \log(A) + b \times \log(M)$.



Clinical Cohort

Actual energy expenditure required for target growth for clinic patients is shown in Figure 3. Patients ranged in age from 2 months to 17.5 years (weight range: 3.6-70 kg) and had a broad range of complex surgical problems (hiatal hernia, chromosomal abnormalities, diaphragmatic hernia, cardiac disease, abdominal wall defects, gastroschisis, trauma, etc). These data fit the relationship $P = 215.72M^{(-0.4328)}$ ($R^2 = 0.8636$).

To meet the requirements of "easy to remember" and "easy to calculate" as well as "hedge toward undersestimation," the similar power-law relationships derived from the 2 methods were simplified by rounding the parameters A and b, giving the simple relationship

$$P = 200M^{-0.4}. \quad (11)$$

This equation, hereafter called the allometric energy estimation (AEE) is plotted in Figure 3 along with actual energy needs ($R^2 > 0.85$). This equation is more likely to slightly underestimate than overestimate energy expenditure (mean difference = −1.2% ± 12.8% kcal/kg/d). See Figure 4.

Comparison With WHO Equations

The AEE gives a better prediction of actual energy needs than the WHO equations (Figure 5). The figure demonstrates that the WHO equations show an irregular falloff in energy estimates for patients who weigh less than 15 kg. Moreover, the plot also illustrates the large variation allowed even by modest SAFs.

Comparison With the Holliday Segar Rule

When Holliday and Segar[27] proposed the well-known 4-2-1 rule for maintenance fluids, they asserted that maintenance fluids in mL/D and energy needs in kcal/D should be the same: "It is generally agreed that the maintenance requirements for water of individuals is determined by their caloric expenditure. By means of the following formula [the 4-2-1 rule], the caloric expenditure of hospitalized patients can be determined from weight alone" (page 831). Examination of the 4-2-1 rule in mL/kg/D shows that the rule also conforms to another simple power law, except for patients <10 kg, where it underestimates fluid needs on a per kilogram basis (Figure 2). The 4-2-1 rule can be approximated by

$$F = 300 \times M^{-0.5}. \quad (12)$$

This equation, Equation (3), and the 4-2-1 rule are plotted in Figure 2. The relationships converge for patients weighing more than 40 kg. Below this weight, the relationships give increasingly divergent estimates. The Holliday-Segar rule underestimates both fluid and energy needs in small children.

Discussion

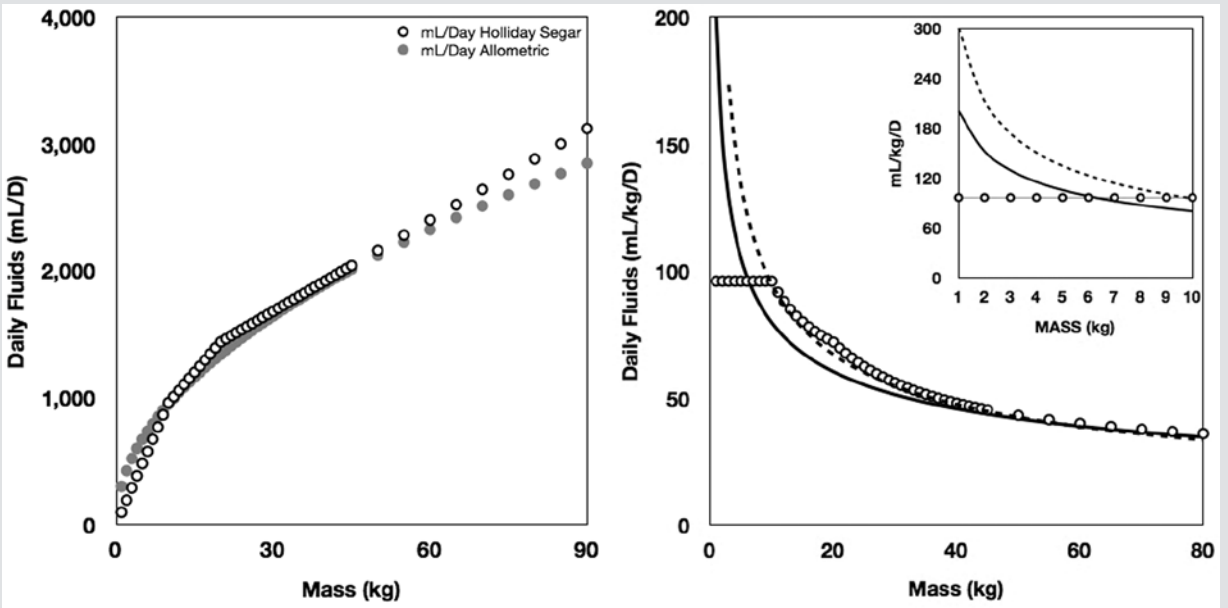
Monte Carlo simulation accurately predicted actual energy expenditure in a mixed real-world clinical cohort of pediatric surgical patients. Both the model and the clinical cohort displayed similar scaling relationships, which can be closely approximated by a simplified equation. This AEE,

$$P = 200M^{-0.4}, \quad (13)$$

satisfies criteria for a useful heuristic prediction equation. First, the nonlinear, power-law-based equation accurately predicts actual energy needs for growing pediatric surgical patients over a broad range of sizes and clinical contexts. Next, because overfeeding is posited to worsen outcomes in critically ill patients,[28-31] the equation intentionally hedges toward a

Figure 2.

A. The well-known holliday-segar or "4-2-1-" rule[27] for daily maintenance fluids was recalculated to give mL/kg/d and plotted against patient weights from 1 to 90 kg (open circles). **B.** For the points greater than 10 kg, a power-law was fitted (solid line), yielding $F = 302.49M^{-0.4928}$, Where ***F*** is fluid needs (mL/kg/d) and *m* is mass (kg). When this equation was simplified to $F = 300M^{-0.5}$, The equation returns values that strongly correlate to the holliday-segar estimates ($R^2 = 0.9946$) for patients greater than 10 kg in weight. In the range from 1 to 10 kg, the holliday-segar equation underestimates fluid needs based on body size (inset). These relationships are superimposed over the allometric energy equation (dotted line). The discrepancy between energy and fluid needs in smaller patients comports with experience: free water needs and calories are routinely calculated separately since, for example, a 3.5-Kg child taking breast milk or formula at 20 kcal/30 mL, would need about 121 kcal/kg/d, or 181 mL/kg/d. At approximately 90% free water, this delivers 163 mL/kg/d of free water, nearly identical to the 160 mL/kg/d predicted by the equation $F = 300M^{-0.5}$. Note that at very small sizes (eg, < 2kg), this equation gives unrealistically high estimates for fluid as the physiological peculiarities (cardiac elastance, renal water handling, etc) of prematurity dominate the effects of mass alone.



slight underestimate of metabolic power. (Figure 4).

Even with this built-in bias, the AEE returns more realistic energy estimates than the WHO equations or the Holliday-Segar rule, especially for small patients (Figures 2 and 5). Both the Holliday-Segar rule and the WHO equation roughly approximate power-law relationships but only for body mass >15 kg approximately. Below this body mass, these methods give inaccurate values, and experienced dietitians are well known to resort to other estimators (eg, the RDA) in routine practice.

The equation was intended to be useful to a harried resident or other pediatric bedside clinician. Calculation of the AEE requires only a single input variable (mass) that is almost always clinically available and accurate. Reliance on mass alone allows the equation to be used in patients for whom height measures are impossible or unreliable (eg, cerebral palsy, severe scoliosis, thoracic insufficiency, etc), a common circumstance in a busy pediatric specialty service. Meanwhile, only 2 simple constants need to be memorized, and any scientific pocket calculator with an exponent key allows fast calculation. In this way, the equation may prevent "availability-"[12] or satisficing-type cognitive errors by giving clinicians a single, unambiguous equation that can be used without looking up tables of equations targeted to sex or arbitrary age ranges.

Although the equation captures the basic relationship between mass and metabolic power, it cannot account for other important sources of variation in metabolic power. Body mass is the most important variable in energy expenditure, and other physiological variables drive actual needs up or down. For example, a child with increased work of breathing from severe reactive airway disease may need 10% to 20% more daily calories than the AEE equation suggests. Similarly, children with single ventricle physiology may need >130% of the estimate. Conversely, a child sustained parenterally, and thereby bypassing the splanchnic "thermogenic effect of food," should need 10% to 15% less.[26] On the other

Figure 3.

Energy expenditure to achieve growth targets (kcal/kg/d) versus body mass (kg) for a cohort of patients followed in a surgical nutrition clinic. The relationship closely follows a power-law relationship (solid line) revealing that body mass determines more than 85% of the variation in energy expenditure over a large range of sizes.

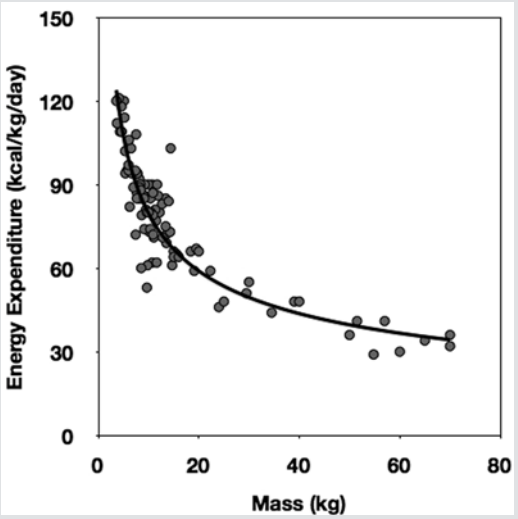
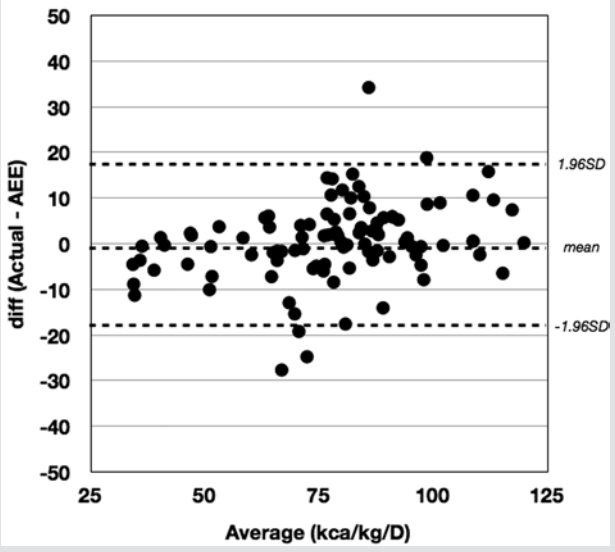


Figure 4.

Bland-altman comparison of measured (actual energy expenditure [aee]) and predicted energy expenditure confirms a slight negative bias in the aee (mean difference –0.48 Kcal/kg/d) but otherwise good agreement between measured and predicted values. Dotted lines show plus and minus 1.96 Standard deviations of the difference.



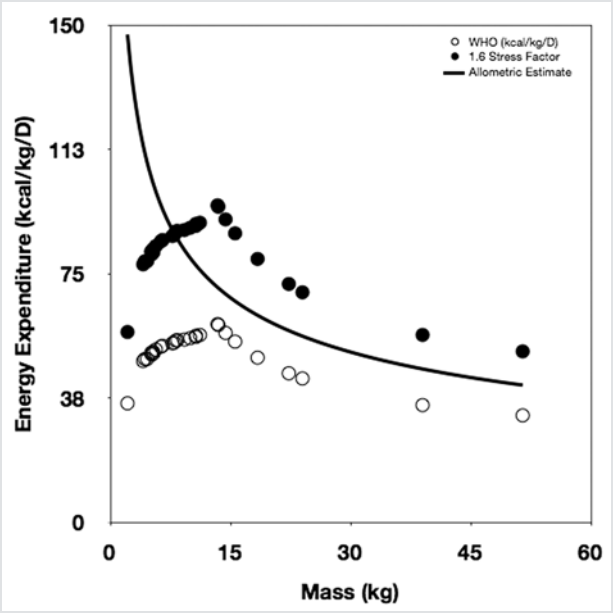
hand, septic or injured children exhibit transiently higher metabolic power (particularly when febrile) but, overall, do not appear to require extra energy.[32] Meanwhile, a malnourished child will need more energy than given by the AEE because the equation only returns an estimate for normal, not catch-up, growth.

Regardless of the context, the AEE gives the clinician a single scale over which to gauge deviation from normal or expected energy requirements. Sharp deviation from this expected energy expenditure can inform the clinician. For example, if a child fails to grow despite delivery of >150% of the AEE, the clinician may suspect zinc deficiency, atopy, worsening cardiopulmonary disease, or other source of calorie resistance. Several instances of formula mixing errors by parents or other caretakers have been discovered in our clinic in this way.

Individual clinical context limits the accuracy of all estimation equations. However, the nonlinear, mass-based AEE is less susceptible to the errors imposed when concatenated linear relationships attempt to approximate nonlinear relationships, as has been done with Schofield, WHO, and others. Similarly, the Holliday-Segar 4-2-1 rule uses a series of linear functions, but this rule can probably be seen as an attempt to approximate (without the benefit of ubiquitous fast computers) a weight-based power-law like the equation presented here (Figure 2). Scaling according to weight avoids BSA for indexing, a physiologically suspect means of scaling that produces wide variation in small patients.[33] For this reason, although no estimation equation can fully escape the use of clinically informed "fudging," adjustments to the AEE are narrower than SAFs used for traditional REE equations, diminishing the subjective error of the estimates. Nevertheless, the estimates returned by the AEE are still only first approximations, and energy delivery to patients must be adjusted over time according to serial measurements of growth and biochemical markers of over- or undersupply.

Figure 5.

Energy expenditure in kcal/kg/d for 15 male and 15 female clinic patients without a stress-activity factor (open circles) and with a stress-activity factor of 1.6 (Solid circles). The solid line shows the equation $P = 200 \times M^{-0.4}$.



Although the equation was designed to be easy to remember and to use, calculation with power laws can be tricky. In particular, the clinician must respect the order of operation and evaluate the exponent on body mass first before multiplication by 200. Spreadsheet programs generally respect this order, but pocket calculators do not. Furthermore, one must remember what the equation returns: kcal/kg/d, not kcal/d. To find the total daily kilocalories for a patient, one must multiply the AEE by the patient's body mass or equivalently use

$$P = 200 \times M^{0.6}, \qquad (14)$$

which returns energy in kcal/d.

The methodology used to derive this equation depends on an unusual means of validation. Typically, energy prediction equations are validated against measurements of REE (indirect calorimetry and doubly labeled water). Generally regarded as a gold standard in both adults and in children, they are expensive, with relatively high start-up costs for hospitals plus ongoing costs for dedicated staff and equipment maintenance. Indirect calorimetry cannot quickly be performed at any bedside in the way in which vital signs can be measured. The tests nearly always are performed on sedated patients, giving a "resting" or basal energy expenditure. Whether measured or estimated by traditional prediction equations, REE must be adjusted according to a best-guess SAF to obtain "actual" energy expenditure. In contrast, for the validation of the AEE, the standard was not resting energy but actual energy expenditure, that is, the calories required to achieve age-specific growth objectives over time.

A potential criticism of this study is that the patient population used to validate the simulated equation is heterogeneous in terms of size and diagnoses. However, although this heterogeneity certainly increases the stochastic variation (and diminished potential predictive power of the equation), it also lends increased validity to the equation as a heuristic. Working clinicians rarely encounter a prescreened, homogeneous set of patients. Therefore, we avoided excluding patients based on diagnosis in order to attempt to maximize general applicability of the equation. Still, the breadth of patient sizes and contexts was limited in both the Monte Carlo model and the actual clinical cohort. Therefore, estimates from this equation are not expected to be accurate for premature infants (<2 kg approximately), elderly patients, the morbidly obese, or in other extreme clinical circumstances. Nevertheless, a study of morbidly obese patients found a remarkably similar power-law relationship for energy expenditure in these patients.[21]

The equation presented here is not intended to supplant energy measurements or textbook methods of energy estimation. Used carefully, the AEE offers busy pediatric specialists a simple but accurate tool for energy estimation over a broad range of body sizes. ■

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