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Energy Expenditure in Humans and Other Primates: A New Synthesis*

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Keywords

doubly labeled water, flex-heart rate, factorial method, life history, total energy expenditure, basal metabolic rate

Abstract

This review examines the proximate, ecological, and evolutionary determinants of energy expenditure in humans and primates, with an emphasis on empirical measurements of total energy expenditure (TEE). Body size is the main proximate determinant of TEE, both within and between species; physical activity, genetic variation, and endocrine regulation explain substantially less of the variation in TEE. Basal metabolism is the single largest component of TEE, far exceeding the cost of physical activity, digestion, growth and reproduction, and thermoregulation in most instances. Notably, differences in physical activity do not generally result in corresponding differences in TEE, undermining the utility of activity-based factorial estimates of TEE. Instead, empirical measurements of energy expenditure in humans and other primates suggest that the body adapts dynamically to long-term changes in physical activity, maintaining TEE within an evolved, and relatively narrow, physiological range.

INTRODUCTION

At its biological core, life is a game of turning energy into offspring. Morphological, physiological, and behavioral strategies that improve an individual's ability to acquire energy and convert it to successful offspring proliferate over evolutionary time through the process of natural selection. The ecological and evolutionary importance of energy expenditure has long been recognized; several examples in Darwin's (1859) *Origin of Species* articulate the central role of energy gain and expenditure in evolutionary biology. Not surprisingly, the strategies by which individuals gain and expend energy (e.g., feeding, foraging, locomotion, growth, reproduction) have remained a recurring and important element in evolutionary reconstructions of the primate radiation and our hominin lineage (e.g., Darwin 1871; Keith 1891; Dart 1949; Leakey et al. 1964; Lee & Devore 1968; Cartmill 1974; Lovejoy 1981; Carrier 1984; Shipman & Walker 1989; Sussman 1991; Aiello & Wheeler 1995; Leonard & Robertson 1997; Key & Ross 1999; Aiello & Key 2002; Aiello & Wells 2002; Antón et al. 2002; Leonard & Ulijaszek 2002; Pontzer & Wrangham 2004; Steudel-Numbers 2006; Snodgrass et al. 2007; Snodgrass & Leonard 2009; Pontzer et al. 2010, 2012, 2014; Orkin & Pontzer 2011; Pontzer 2012).

Much of the early technology used to measure energy expenditure required captive subjects, confined to a laboratory. These efforts led to many seminal insights that remain salient today despite the artificial nature of the laboratory setting (e.g., Kleiber 1947). The development of accurate, noninvasive methods for measuring or estimating energy expenditure in free-living subjects has greatly improved our understanding of activity and energy expenditure in humans and other primates. Although much of this work was motivated by and directed toward estimating nutritional requirements and energy stress among living human populations (e.g., Panter-Brick 1992, 1993; FAO et al. 2001; Dufour & Piperata 2008), anthropologists have applied these methods to reconstructions of energy budgets in nonhuman primates and fossil hominins (e.g., Coelho et al. 1977, Leonard & Robertson 1997, Knott 1998, Key & Ross 1999, Aiello & Key 2002, Steudel-Numbers 2006, Froehle & Churchill 2009, Snodgrass & Leonard 2009). This work highlighted the importance of local ecology and activity levels on daily energy requirements and, in turn, on reproductive and somatic investment.

More recently, anthropologists and those in public health have been employing the doubly labeled water (DLW) method (Speakman 1997, Int. At. Energy Agency 2009, Westerterp 2010) in measurements of energy expenditure in human and primate populations (e.g., Nagy & Milton 1979; Stein et al. 1988; Singh et al. 1989; Heini et al. 1991, 1996; Kashiwazaki et al. 1995, 2009; Drack et al. 1999; Esparza et al. 2000; Schmid & Speakman 2000; Snodgrass et al. 2006; Pontzer et al. 2010, 2012, 2014; Simmen et al. 2010, 2015; Rosetta et al. 2011). DLW is considered the gold standard for measuring daily energy expenditure in free-living populations because it tracks the body's rate of carbon dioxide production (and hence caloric expenditure) without encumbering the subject with equipment, confining them to a calorimetry chamber, or extrapolating from activity budgets (Int. At. Energy Agency 2009) (see sidebar Methods for Determining Total Energy Expenditure). Results from DLW studies have often complemented and confirmed results from other approaches, but they have also challenged long-held ideas about the flexibility and plasticity of daily energy expenditure (Westerterp & Speakman 2008, Dugas et al. 2011, Pontzer et al. 2012), suggesting that energy budgets may be more constrained and less responsive to variation in activity levels than is generally thought. These results hold implications for models of energy stress and metabolic syndrome in humans and for variation in metabolic ecology and life history across primates more broadly.

In this article I review studies of total energy expenditure (TEE) (kcal/day) in humans and other primates. After briefly discussing the classic laboratory work on metabolic energy expenditure,

METHODS FOR DETERMINING TOTAL ENERGY EXPENDITURE

Doubly labeled water method: Considered the gold standard for measurements of TEE in free-living subjects, the DLW method calculates TEE by measuring the body's rate of carbon dioxide production (Speakman 1997, Int. At. Energy Agency 2009). Subjects drink a dose of water enriched with ^2H and ^{18}O , and the concentrations of these stable isotopes are tracked over time (usually 10–14 days) through a series of urine samples. Both isotopes are lost through water: urine, sweat, and expired water vapor. ^{18}O is also lost via carbon dioxide; thus, the rate of carbon dioxide production can be calculated by subtracting the rate of ^2H depletion from the rate of ^{18}O depletion. The rate of carbon dioxide production (moles/day) is converted to TEE (kcal/day) using the food quotient or respiratory quotient, which can be estimated from dietary information or measured via a respirometry trial.

Flex-heart rate method: Recorded using a heart rate monitor and data logger, calibrated heart rate data are used to estimate TEE (Leonard 2003). Prior to the measurement period, a calibration trial in which heart rate and energy expenditure are measured simultaneously, over a range of exercise intensities, is performed for each subject. Energy expenditure is typically measured via mask-based respirometry in these trials. DLW validation studies have shown that flex-heart rate measurements are generally reliable and accurate (e.g., Heini et al. 1991, 1996; Leonard 2003).

Respirometry: The body's consumption of oxygen and production of carbon dioxide are measured by monitoring expired air. Mask-based systems are commonly used to measure the cost of specific activities (e.g., walking or running). For TEE measurements using respirometry, subjects are confined to a calorimetry chamber, a small, sealed room equipped to monitor the movement and concentration of room air (Ravussin et al. 1982). Respirometry studies provide highly accurate measures of energy expenditure, minute by minute, throughout the study period, but they require subjects to be confined to a calorimetry chamber.

Factorial method: TEE estimates are based on an individual's height, weight, age, and activity budget (FAO et al. 2001). BMR is estimated using available anthropometric data. Time-allocation studies are then used to estimate the mean time per day in various activities (e.g., light work, sleep, walking). Activity data are then converted to energy expenditures using an individual's estimated BMR and established PAL values for each activity. Factorial estimates of TEE are relatively easy and inexpensive to conduct but have relatively low accuracy; thus, they should be treated as estimates, not measurements, of energy expenditure.

I focus on more recent studies of energy expenditure in free-living populations. This review is organized around four broad questions, beginning with proximate determinants of energy expenditure in humans and working toward an integrated ecological and evolutionary perspective on human and primate energy expenditure:

1. **Anthropometry of TEE:** How much energy do humans and other primates expend each day, and how does this vary with body size, age, and sex?
2. **Components of TEE:** How do basal metabolic rate (BMR), physical activity, reproduction, maintenance, thermoregulation, and other functions contribute to TEE?
3. **Ecological determinants of TEE:** How does variation in activity budgets or lifestyle affect TEE, and to what extent is TEE a constrained physiological trait shaped by evolution?
4. **TEE and metabolic ecology in humans and other primates:** How does TEE shape the life-history strategies and foraging ecology of humans and other primates?

ANTHROPOMETRY OF TOTAL ENERGY EXPENDITURE

It seems obvious from our daily experience that larger individuals require more energy each day than do smaller individuals, other factors being equal. A positive relationship between energy

expenditure and body size follows intuitively from first principles: Larger organisms have more cells, each involved in myriad homeostatic processes, and they also carry more weight and thus must perform more physical work as they move. The question, then, is not whether larger size will tend to increase TEE, but to what extent.

Kleiber (1947), in his seminal work on energy expenditure across a range of animals, showed that the relationship between size and energy expenditure was nonlinear. Kleiber focused on measurements of BMR, the rate of energy expended when the organism is at rest. Although BMR is only one component of TEE (often accounting for less than half of daily expenditure among mammals) (see Westerterp & Speakman 2008), it is relatively easy to measure in laboratory settings (usually via respirometry) (see sidebar, Methods for Determining Total Energy Expenditure) and is repeatable and reliable. Kleiber found that BMR increased allometrically, with $\text{Mass}^{0.75}$, a relationship now commonly referred to as Kleiber's Law. The physiological mechanism underlying the scaling exponent of 0.75 has been debated by comparative biologists ever since. One hypothesis, by West and colleagues (West et al. 1997, Gillooly et al. 2001), proposes that the 0.75 exponent stems from the fractal branching patterns of the energy supply systems (blood vessels) common among animals. More recently, White and colleagues (2009), using phylogenetically informed analyses of a large, quality-controlled data set of mammalian BMR, reported considerable variation in the scaling exponent among clades, with exponents for the majority of orders falling between 0.67 and 0.75. For the purposes of this review, it is sufficient to note that BMR does not increase linearly with mass and that larger animals use less energy per gram of body mass than do smaller animals.

Measurements of TEE using the DLW method (see sidebar, Methods for Determining Total Energy Expenditure), in both wild and captive populations, indicate a similar scaling exponent for mammals. Nagy and colleagues (1999) reported a scaling exponent of 0.77 for eutherian (placental) mammals, with some variation among taxonomic groups. Primate TEE scales with a similar exponent of 0.73 ± 0.03 , but the intercept is significantly lower, such that TEE for primates (including humans) is 50% lower than expected for a eutherian mammal of the same body mass (Pontzer et al. 2014). As discussed below, this substantial reduction in TEE appears to be related to the remarkably slow life histories evident in humans and other primates. This grade shift in TEE notwithstanding, the scaling exponent (i.e., the allometric slope) does not differ between primates and other eutherian mammals (Pontzer et al. 2014).

A similar allometry of energy expenditure is evident within human populations, both in BMR and in TEE. Predictive equations for BMR (Henry 2005, FAO et al. 2001), developed from large diverse human samples, indicate that smaller individuals have, on average, higher mass-specific BMR. Black and colleagues (1996) analyzed DLW measurements from 564 adults living in developed countries (mostly Western Europe and the United States) and developed predictive equations for TEE. The exponent for mass is substantially lower than 1.0, indicating that larger individuals generally expend less energy per gram of body mass than do smaller individuals. For this reason, correcting for body size in analyses of TEE and BMR should be done via multiple regression or ANCOVA, with log-transformed data, rather than simply dividing by mass or fat-free mass (Tschöp et al. 2011).

The effects of height and sex likely reflect effects of body composition on metabolic rate. Adipose tissue is much less active metabolically than other tissues, and both calorimetry chamber studies and DLW studies have shown that the strongest size-related predictor of TEE is lean mass, also called fat-free mass, which often accounts for 65–75% of the variation in TEE between subjects (e.g., Ravussin et al. 1982, Pontzer et al. 2012). Subjects who are taller for a given mass are generally leaner, and men tend to carry less body fat for a given mass than do women. Thus height is positively correlated with TEE, and women tend to have lower TEE for a given body mass.

Large studies of TEE across a broad age range have noted a small but detectable decline with age, on the order of ~ 15 kcal/year for adults older than ~ 30 years (Black et al. 1996, Vinken et al. 1999, Elia et al. 2000). Speakman & Westerterp (2010), in the largest analysis of age and TEE to date, argue that this decline does not begin until ~ 50 years of age. At least half of the age-related decline in TEE can be ascribed to age-related decline in BMR, suggesting that the decline in TEE is due to age-related changes in body composition (i.e., less lean mass) as well as senescence in cellular activity (Elia et al. 2000, Speakman & Westerterp 2010). Indeed, predictive equations for BMR (e.g., Henry 2005) developed in large, diverse samples indicate similar effects of age, sex, and height as reported for TEE. Reduced physical activity with age, particularly among elderly subjects, appears to contribute to the decline in TEE as well (Elia et al. 2000, Speakman & Westerterp 2010).

Variation In and Limits to Total Energy Expenditure

Representative TEE values for human populations, measured using the DLW method, are shown in **Table 1**. Repeated measures of TEE using DLW indicate that average TEE (i.e., mean TEE averaged over a two-week period) (see sidebar, Methods for Determining Total Energy Expenditure) is a relatively stable trait, with a coefficient of variation within subjects of $\sim 6\%$ (Schoeller & Hnilicka 1996). The coefficient of variation between subjects is considerably greater, approximately 15% (see **Table 1**) (Pontzer et al. 2012). In fact, variation in TEE between subjects within a population is considerably greater than the variation between populations, as evident in **Table 1**.

Only 50–75% of the variation in TEE between subjects is explained by anthropometric variables, particularly fat-free mass (Black et al. 1996, Dugas et al. 2011, Pontzer et al. 2012). Measurements of physical activity can explain some of the remaining variation in TEE, but this is dependent on the methods used to measure activity and the population being examined. For example, GPS-based measurements of daily walking distance were not correlated with TEE in an adult sample ($n = 30$) of Hadza hunter-gatherers, after accounting for fat-free mass (Pontzer et al. 2012, 2015). Accelerometer measurements of activity account for some of the variation in TEE (Butte et al. 2012, Plasqui et al. 2013), but the amount of variation explained is generally modest, ranging from 4% to 23% (Plasqui et al. 2013). Indeed, accelerometry-based estimates often deviate substantially from measured TEE (Leenders et al. 2006). Genetic variation likely accounts for some of the variation in TEE as well. In a study of 294 elderly subjects, Tranah and colleagues (2011) found that subjects with mitochondrial DNA haplotypes of African origin had $\sim 10\%$ lower TEE than those with mitochondrial DNA haplotypes of European origin, after correcting for body size and activity.

Variation in hormone profiles undoubtedly affects energy expenditure, but endocrine regulation of BMR and TEE is complex and understudied. Several hormones, including thyroid hormones (thyroxine and triiodothyronine), estrogen, testosterone, and growth hormone, promote metabolism and tissue growth (Widmaier et al. 2004) and can be expected to increase energy expenditure. In particular, thyroid hormone is a primary regulator of metabolic rate and of heat production in response to cold exposure. However, although extreme levels of thyroid hormone affect BMR and TEE, normal variation in thyroid hormone levels in healthy adults is not necessarily correlated with variation in BMR or TEE (Tagliaferri et al. 2001, Klieverik et al. 2009, Leonard et al. 2014, Spadafranca et al. 2015). Similarly, growth hormone has positive effects on BMR and TEE (Gregory et al. 1991, 1993; Chong et al. 1994), but variation in growth hormone levels among adults, even those with clinically low levels, does not necessarily predict variation in TEE (Chong et al. 1994). Santosa and colleagues (2010) manipulated testosterone and estrogen levels in older men and found no difference in BMR when these hormones were completely



Table 1 Mean TEE (measured using the doubly labeled water method) and PAL (\pm standard deviation) in human populations

Population	N	Sex	Mass (kg)	BMI	Age (years)	TEE (kcal/day)	PAL	Reference(s)
Combined populations^a								
Developing countries	10	M	66.1 \pm 2.7	22.7 \pm 1.0	32.0 \pm 3.3	2,940 \pm 96	1.88 \pm 0.06	Dugas et al. 2011
Developed countries ^b	42	M	81.3 \pm 2.0	26.0 \pm 0.6	34.5 \pm 1.7	3,226 \pm 72	1.81 \pm 0.03	Dugas et al. 2011
Developing countries	13	F	59.1 \pm 2.0	24.3 \pm 0.7	33.2 \pm 2.7	2,223 \pm 48	1.70 \pm 0.03	Dugas et al. 2011
Developed countries ^b	102	F	72.6 \pm 3.2	26.6 \pm 0.4	35.1 \pm 1.3	2,462 \pm 24	1.72 \pm 0.02	Dugas et al. 2011
Extremely low physical activity^c								
Enforced bed-rest, healthy subjects	8	F	52.6 \pm 1.4	19.8 \pm 0.4	33.9 \pm 0.8	1,702 \pm 186	1.37 \pm 0.06	Bergouignan et al. 2010, 2013
Demented elderly	7	F	–	–	–	1,242 \pm 167	1.27 \pm 0.14	Black et al. 1996
Nonambulatory adolescents	11	M, F	–	–	–	1,458 \pm 239	1.22 \pm 0.18	Black et al. 1996
Extremely high physical activity^{c,d}								
Tour de France cyclists	4	M	67.8	–	–	8,054 \pm 143	4.69 \pm 0.20	Black et al. 1996, Cooper et al. 2011
Arctic explorers	2	M	62	–	42.5	7,910 \pm 358	4.47 \pm 0.06	Black et al. 1996, Cooper et al. 2011
Swedish national nordic skiers	4	F	54.2 \pm 5.4	–	25 \pm 2	4,374 \pm 550	2.81 \pm 0.09	Black et al. 1996, Cooper et al. 2011
Runners in training	9	F	51.9 \pm 3.7	–	26 \pm 3	2,820 \pm 311	2.03 \pm 0.16	Black et al. 1996, Cooper et al. 2011
Foragers and farmers^c								
Hadza hunter-gatherers	13	M	50.9 \pm 5.4	20.2 \pm 1.3	33.1 \pm 14.4	2,649 \pm 395	2.04 \pm 0.28 ^e	Pontzer et al. 2015
Hadza hunter-gatherers	17	F	43.4 \pm 6.4	20.1 \pm 1.7	40.0 \pm 19.4	1,877 \pm 364	1.76 \pm 0.28 ^e	Pontzer et al. 2015
Bolivian farmers ^e	11	M	54.7 \pm 2.9	21.2 \pm 1.6	49.1 \pm 20.9	2,866 \pm 435	2.08 \pm 0.26	Pontzer et al. 2012
Bolivian farmers ^e	14	F	48.1 \pm 6.9	20.7 \pm 3.2	43.9 \pm 21.8	2,469 \pm 315	2.11 \pm 0.30	Pontzer et al. 2012
Gambian farmers ^f	8	M	61.2 \pm 3.6	21.2 \pm 0.9	25.0 \pm 1.4	3,879 \pm 351	2.40 \pm 0.14	Heini et al. 1996
Gambian farmers ^f	10	F	49.4 \pm 1.7	–	30.0 \pm 2.2	2,407 \pm 196	1.98 \pm 0.13	Singh et al. 1989

Abbreviations: BMI, basal metabolic index; PAL, physical activity level; TEE, total energy expenditure.

^aN represents the number of populations included.

^bRestricted to cohorts with a mean age <65 years (see Dugas et al. 2011).

^cN represents the number of individuals measured.

^dSubjects lost weight during these periods (0.2–1.3 kg/week) (see Cooper et al. 2011).

^ePAL is calculated using estimated basal metabolic rate.

^fCombines periods of high and low farming activity. PAL was 11% greater during high versus low activity (Kashiwazaki et al. 2009).

^gMeasured during periods of high farming activity.

suppressed versus maintained at normal levels. More work is needed to disentangle the actions and interactions of individual hormones in the regulation of BMR and TEE in free-living, healthy humans.

Several studies have examined subjects at the extremes of physical activity to investigate the limits to sustained TEE in humans. To compare across subjects and populations of different body mass and age, daily energy expenditure in these studies is often expressed as physical activity level (PAL), calculated as the ratio of TEE/BMR. At the low end of the range, patients who are confined to bed rest have a PAL of 1.2–1.3, whereas athletes and military personnel achieve a maximum PAL of ~5 during competition (Black et al. 1996, Hammond & Diamond 1997, Cooper et al. 2011). In addition to documenting the limits of human physiology, these studies point to two important aspects of our metabolism. First, even inactive subjects exhibit a PAL of 1.2–1.3, rather than the theoretically lowest value of 1.0. Second, even in well-provisioned athletes with unlimited food supply, there is a limit to the rate at which the body can take in and expend energy.

COMPONENTS OF TOTAL ENERGY EXPENDITURE

Basal Metabolic Rate

BMR is the body's lowest rate of energy expenditure, reflecting summed energy requirements of the body's organ systems at rest. Organs and tissues differ in their resting energy requirements, and expensive tissues such as the brain, gut, kidneys, heart, and liver account for a correspondingly large portion (Elia 1992, Aiello & Wheeler 1995, Wang et al. 2011). Accordingly, fat-free mass is a strong predictor of BMR (e.g., Ravussin et al. 1982). By definition, BMR is measured after a period of rest (usually after a full night's sleep) and 10–12 h of fasting, with the subject awake, lying down, and at rest in a thermoneutral (22–26°C) room; the subject must also be free from psychological or other stress and accustomed to the apparatus (Henry 2005). Measurements taken outside of these conditions (e.g., at midday or while standing or seated) are sometimes called resting metabolic rate (RMR) and will be elevated relative to BMR.

Mean PAL for healthy adult populations in developed countries generally ranges from 1.6 to 1.9 for men and from 1.6 to 1.7 for women (Black et al. 1996, Dugas et al. 2011) (**Table 1**), meaning that BMR accounts for more than half of TEE for most subjects. Moreover, as noted above, subjects restricted to bed rest generally exhibit PAL values of 1.2–1.4 owing to the marked diurnal increase in RMR (**Table 1**). As a result, PAL is somewhat of a misnomer, because a substantial portion derives not from physical activity but from other generally unseen physiological processes. Similarly, activity energy expenditure (AEE), calculated as the difference between TEE and BMR (Black et al. 1996) includes energy expenditure on physiological activity other than movement and muscle activity.

Physical Activity

Muscles at rest use relatively little energy (Elia 1992, Wang et al. 2011), but during physical activity they can raise the body's rate of energy expenditure by more than an order of magnitude above BMR. A compendium of energy costs for a broad range of activities is regularly updated by Ainsworth et al. (2000). Still, calculating the proportion of TEE expended in physical activity is difficult, because recording all muscle activity is challenging and estimating its cost introduces error. Further, as noted above, common measures of physical activity, such as PAL and AEE, overestimate the true contribution of physical activity to TEE by ignoring diurnal fluctuation in RMR.



One approach to estimating the contribution of physical activity to TEE is to subtract the PAL of subjects restricted to bed rest from the PAL of healthy, active adults. Given that a completely inactive adult has a PAL of ~ 1.3 (Black et al. 1996) (**Table 1**), physical activity in healthy adults (PAL = 1.6–1.9) must contribute an additional 0.3–0.6 PAL, equivalent to 19–32% of TEE. Note that this figure includes the cost of walking, climbing stairs, and other gross motor activities as well as that of less-noticeable activities (e.g., sitting, typing, fidgeting). Levine (2004) has argued that the daily energetic cost of these minor activities constitutes an important component of TEE, which he terms nonexercise activity thermogenesis.

Growth

Butte (2000) provides a thorough overview of the energy costs of growth for humans, synthesizing a large body of DLW measurements. Growth costs are generally estimated at 20 kJ/g of new tissue deposited (Butte 2000). By combining TEE measured via DLW (which does not capture the energy invested in new tissue) with weight velocities for growing children from Tanner and colleagues (1996), Butte calculated the proportion of daily energy requirements allocated to growth in healthy human children. For both boys and girls, growth accounted for 28–39% of daily energy requirements during the first 3 months of infancy, falling to 4–5% of daily energy throughput at 1 year and then to $\sim 2\%$ or less by age 2. These estimates are for well-nourished children in developed countries and may be somewhat lower for children with slower growth rates.

These rough estimates of growth cost are useful but may obscure many important costs of development. For example, Kuzawa and colleagues (2014), using data from positron emission tomography studies of brain glucose uptake, found that the energy requirements of the developing human brain peak in early childhood, around age 5, accounting for more than 40% of TEE. This peak in brain energy use is associated with synapse development and learning, rather than with the deposition of new brain tissue (brain growth is nearly complete by age 5). Notably, this period of high metabolic activity in the brain corresponds to a period of slow growth in the body overall, strongly suggesting that the high metabolic demands of the developing human brain lead to a slowing of growth and an extension childhood (Kuzawa et al. 2014). Similar studies of developmental cost in other organ systems are needed to provide an integrated perspective of growth and metabolism in humans and other primates.

Reproduction

The energetic costs and consequences of pregnancy and reproduction in both humans and non-human primates have received a great deal of attention (see Ellison 2001, 2003; Dufour & Sauter 2002; Butte & King 2005; Martin 2007; Dunsworth et al. 2012; Emery Thompson 2013). Reproduction is incredibly expensive for humans, with an estimated total metabolic cost of pregnancy of $\sim 78,000$ kcal, and peak lactation costs of ~ 630 kcal/day (Butte & King 2005). The cost of lactation is offset by the mobilization of fat reserves, such that daily energy requirements during lactation peak at ~ 450 kcal/day, similar to the daily energy cost of pregnancy during the third trimester (Butte & King 2005). These costs bring human mothers to the brink of unsustainable TEE, with a PAL of ~ 2.1 (Hammond & Diamond 1997). Dunsworth and colleagues (2012) have argued that gestation length in humans is limited by the mother's capacity for energy throughput, with birth occurring just as the fetus threatens the mother's metabolic ceiling (and see Ellison 2001). Under this scenario, the relatively underdeveloped, altricial nature of human newborns is a consequence of the mother's metabolic limits; longer gestations and greater development in utero simply cannot be sustained.

With reproduction so energetically expensive, humans and other primates have evolved a suite of physiological strategies for limiting its costs and reducing the likelihood of failure. Ellison (1990, 2001, 2003) and others have shown that human ovarian function is remarkably sensitive to energy availability and stress, reducing the likelihood of conception during unfavorable conditions. Energy investment during gestation and lactation are relatively buffered against maternal energetic stress, but gestation length, birth weight, and the duration of lactational amenorrhea all respond to some degree to energy availability (Ellison 2003). Milk content and volume also appear to be relatively buffered, but more studies of milk composition across the lactation period are needed (Hinde & Milligan 2011). This buffering requires decreased metabolic throughput in other organ systems. Mothers in traditional farming populations, with physically demanding lifestyles, may reduce BMR during pregnancy and lactation to keep total daily energy requirements in check (Heini et al. 1991, Dufour & Sauter 2002).

Immune Function

Mounting an immune response to infection requires energy, but although the physiological responses to disease have been intensively studied, their energy costs are not well characterized (Muehlenbein 2010, Muehlenbein et al. 2010). Work in nonhuman mammals suggests metabolic rate increases of 10–50% are common in response to infection (see Muehlenbein et al. 2010). Muehlenbein and colleagues (2010), in one of the few human studies of immune function energetics, report an 8% increase in RMR among nonfebrile men with relatively minor respiratory tract infections. Torine and colleagues (2007) compared premature infants with sepsis to age-matched healthy controls and found 43% greater TEE among those fighting infection.

Digestion

The energy costs of digestion, termed the thermic effect of food (TEF) (Kinabo & Durnin 1990), are typically estimated at 10% of the caloric value of the meal consumed (Black et al. 1996). Kinabo & Durnin (1990) reported TEF values ranging from 7% to 9% of the energy consumed for a range of diets, with no effect of nutrient composition on TEF. The majority of TEF reflects the work done in digestion and transport of nutrients, but approximately 20% of TEF derives from the activation of the sympathetic nervous system (Welle 1995). Calculations of AEE sometimes account for TEF by reducing TEE by 10% prior to subtracting BMR, such that $AEE = 0.9 TEE - BMR$.

Thermoregulation

In conditions outside of the thermoneutral zone (22–26°C for lightly clothed human subjects) metabolic rate increases to either heat or cool the body and defend a core temperature of 37°C. The metabolic responses to acute cold and heat exposure have been relatively well studied in laboratory settings, but in normal daily life, clothing, housing, and other cultural innovations greatly reduce thermoregulatory demands. Nonetheless, Leonard and colleagues (2002) showed that circumpolar populations, living in exceptionally cold environments, exhibit elevated BMR. Indigenous subjects showed a greater elevation in BMR (women: 17%, men: 19%) than nonindigenous subjects (women: 5%, men: 14%) after controlling for fat-free mass, suggesting a genetic component to cold adaptation in native populations. More recently, in a study of the Yakut population in Siberia, Leonard and colleagues (2014) reported a 6% increase in BMR during winter months among adults 19–49 years, but no difference in older adults. The elevation in BMR in response to cold is likely due in part to the activity of brown adipose tissue (Saito 2013, Muzik



et al. 2013). It remains unclear whether these increases in BMR result in corresponding increases in TEE. In a study of Dutch adults, Plasqui & Westerterp (2004) found similar TEE in summer and winter despite increased winter BMR.

ECOLOGICAL DETERMINANTS OF TOTAL ENERGY EXPENDITURE

It is often assumed that TEE reflects variation in ecology, particularly the level of physical activity, among individuals and populations. Indeed, this is the foundational assumption underlying factorial models of TEE (FAO et al. 2001) (see sidebar, Methods for Determining Total Energy Expenditure), which have been widely adopted in human and nonhuman primate ecology and paleoanthropology. However, factorial estimates are generally no more reliable for predicting TEE among individuals than are estimates from body mass (r^2 values of 0.2–0.3 within populations) (see Leonard et al. 1997, Walsh et al. 2004) and tend to underestimate mean TEE, particularly in physically active populations (Leonard et al. 1997, Kashiwazaki et al. 2009). Similarly, as noted above, accelerometry-based measures of physical activity add little to TEE estimates based on fat-free mass (Plasqui et al. 2013), and accelerometry-based estimates of TEE often deviate substantially from observed values (Leenders et al. 2006). Empirical measurements of TEE in a broad range of populations and species indicate that the relationship between ecology and TEE is much more complex than factorial models and accelerometry-based estimates of TEE allow.

Intervention studies regularly show a short-term increase in TEE among sedentary individuals enrolled into exercise programs (Ross & Janssen 2001). But over the long term, this effect is diminished as the body adapts to the increased workload. For example, Westerterp and colleagues (1992) measured TEE and BMR in sedentary men and women enrolled in a 40-week training program. Subjects ran three times per week, and the duration of these running bouts increased over the course of the study, preparing the subjects to run a half-marathon. TEE increased over the first 8 weeks of training but then plateaued for the duration of the study even as the exercise workload increased. Instead, BMR (measured during sleep) decreased to accommodate the increased exercise (Westerterp et al. 1992); such metabolic adaptation to increased activity is thought to be a major reason that exercise-based weight loss programs fail to produce expected weight reduction over the long-term (Ross & Janssen 2001). Similar metabolic responses to increased activity have been reported in laboratory studies for a range of birds and mammals (Pontzer 2015).

This dynamic, adaptive view of metabolic physiology is supported by comparative studies of TEE across populations that differ in habitual activity level. Dugas et al. (2011) found no effect of socioeconomic development (a proxy of physical activity) on TEE in a global sample of 183 same-sex cohorts. My colleagues and I (Pontzer et al. 2012) found no difference in TEE between traditional Hadza hunter-gatherers and Westerners, after accounting for effects of lean mass, age, and sex. That same analysis (Pontzer et al. 2012) found that subsistence farmers had somewhat higher TEE, but the effect was variable; for example, among Bolivian farmers, men did not exhibit elevated TEE, but women did. This similarity in TEE among populations with different levels of physical activity is not restricted to humans. In a recent analysis of 19 populations representing 17 species of primate, controlling for body mass, my colleagues and I (Pontzer et al. 2014) found no difference in TEE between captive and wild primate populations.

These results indicate that the effects of habitual physical activity are muted by dynamic physiological responses that work to maintain TEE within a narrow range. This constrained TEE model, in turn, suggests that energy allocation among physiological activities is responsive over the long-term to changes in physical activity (Pontzer 2015). Indeed, physiological adaptation to increased workload is well documented. As noted above, Ellison and colleagues (Ellison & Lager



1986; Ellison 1990, 2001, 2003) have shown that even moderate increases in physical activity can diminish ovarian activity. Women in subsistence agriculture populations respond to seasonal increases in workload with decreases in ovarian hormone levels, a measure of reproductive investment (Ellison et al. 1993, Panter-Brick et al. 1993). Furthermore, traditional populations vary in levels of testosterone (an anabolic hormone) (Ellison et al. 2002) and leptin (involved in fat sequestration) (Bribiescas 2001). In birds (Deerenberg & Overkamp 1999, Wiersma & Verhulst 2005) and rodents (Perrigo 1987), increased physical activity has a limited effect on TEE, but it leads to decreased energy allocation to reproduction and somatic maintenance.

This is not to suggest that lifestyle and environment cannot affect TEE. Some professional athletes (Cooper et al. 2011) and subsistence farming populations maintain somewhat greater TEE than other populations (Kashiwazaki et al. 1995, 2009; Pontzer et al. 2012). Whether the elevated TEE of these populations represents a developmental response to a combination of intense physical activity and adequate food availability (see Pontzer 2015), or instead represents the upper limit of habitual TEE for humans, remains an open and important question for future research. In either case, the evidence that TEE is maintained within a relatively narrow physiological range holds important implications for investigations of energy expenditure and energy balance in humans and other primates.

First, it challenges the validity of the factorial method for estimating TEE. This method, commonly used for estimating daily energy requirements in human populations (FAO et al. 2001), estimates TEE by summing the caloric costs of a subject's daily activities (see sidebar, Methods for Determining Total Energy Expenditure); it assumes that all costs are additive and cannot account for adaptive and dynamic changes in allocation. Factorial estimates of TEE should be used cautiously for living populations and, ideally, validated against DLW measurements within the study population. Using the factorial method to estimate TEE for nonhuman primates or fossil hominins (e.g., Leonard & Robertson 1997, Key & Ross 1999, Aiello & Key 2002, Steudel-Numbers 2006, Snodgrass et al. 2007, Froehle & Churchill 2009) raises particular challenges, as validation against empirical measurements of TEE is often difficult or (for extinct populations) impossible.

Second, public health policy, particularly as it pertains to obesity and metabolic syndrome, may be improved by adopting an adaptive, dynamic view of metabolic physiology. The importance of regular exercise in promoting and maintaining good health is well established, but the mechanisms involved remain an area of active research. If TEE is constrained, increasing exercise energy expenditure would have a muted effect on TEE but would reduce energy expenditure in other, potentially harmful, physiological activities. Consistent with this hypothesis, exercise is associated with a reduction in inflammation response and other metabolic activity that is implicated in the development of chronic disease (Michigan et al. 2011, Roemmich et al. 2014, Silverman & Deuster 2014). Population differences in energy allocation, rather than in TEE, could underlie low rates of cardiovascular disease, diabetes, and other chronic illness and age-related decline in traditional populations (e.g., O'Dea 1991, Vasunilashorn et al. 2010, Pontzer et al. 2012, Pisor et al. 2013). Conversely, if physical activity has a limited effect on TEE, strategies for weight loss and healthy weight maintenance should focus on diet and food energy intake (Luke & Cooper 2013).

Third, insofar as TEE reflects physiological constraints, the physiological limits of TEE may be shaped in large part by genetics and may therefore be subject to evolution through natural selection (Sibly & Brown 2007, Pontzer & Kamilar 2009). Consequently, variation in TEE among species may reflect evolved, systemic changes in metabolic physiology rather than differences in physical activity. These evolved metabolic strategies are central to the ecology and physiology of a species.



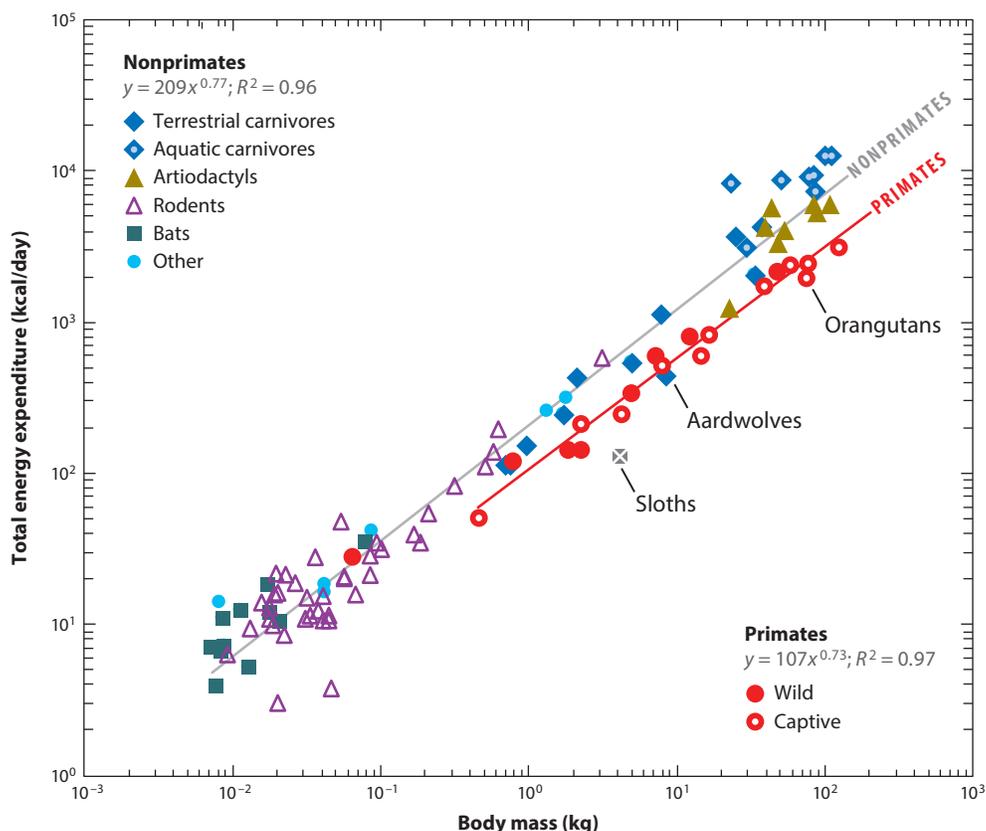


Figure 1

Total energy expenditure (TEE) versus body mass for primates ($n = 19$ populations, 17 species) and nonprimate eutherian mammals ($n = 86$ species). Data from Pontzer et al. (2014) and Simmen et al. (2015). Separate trend lines for primates (red) and nonprimates (grey) are shown. Trend line for primates excludes mouse lemurs (*Microcebus murinus*). See Pontzer et al. (2014) for an in-depth comparison of primate and nonprimate regressions. Among primates, orangutans are notable for having low TEE, which may reflect a metabolic strategy to reduce the risk of starvation during periods of low food availability (Pontzer et al. 2010). Two eutherian mammals > 1 kg fall below the primate trendline: aardwolves (*Proteles cristatus*) and sloths (*Bradypus variegatus*). Sloths and aardwolves, and perhaps orangutans, also exhibit low basal metabolic rate (BMR) (Nagy & Montgomery 1980, Williams et al. 1997, Pontzer et al. 2010).

EVOLUTION OF TOTAL ENERGY EXPENDITURE IN HUMANS AND OTHER PRIMATES

Considerable variation in TEE has been documented among species and clades, even when controlling for body size (Nagy et al. 1999, Pontzer et al. 2014). As discussed above, my collaborators and I have recently shown that primates, including humans, expend only half of the energy expected for a placental mammal of similar body mass (Pontzer et al. 2014) (**Figure 1**). The magnitude of difference is too large to be a result of differences in physical activity. To put human TEE in context, predicted TEE for a 65-kg eutherian mammal is 5,550 kcal/day (Pontzer et al. 2014), which exceeds all but the most extreme feats of human endurance and is clearly not sustainable over the long-term (Black et al. 1996, Cooper et al. 2011). As with human populations, lifestyle differences appear to have little effect on TEE in nonhuman primates. Captive (zoo and sanctuary)



and wild populations have similar TEE, and daily energy intake among wild populations closely matches TEE measured in captivity (Pontzer et al. 2014).

The reduction in TEE is found across the primate order, indicating that it evolved very early in the primate radiation. BMR does not show the same reduction across primates; monkeys and apes have BMR similar to other placental mammals, whereas BMR among lemurs and lorises is marginally lower (Snodgrass et al. 2007, Pontzer et al. 2014). My colleagues and I (Pontzer et al. 2014) have hypothesized that this divergence in BMR and TEE reflects the evolutionary increase in brain size among anthropoid primates. Initially, early primates, which were small bodied and had unremarkable brain sizes, evolved a reduced metabolic rate that would have decreased both BMR and TEE. As brain size later increased in primates, particularly in anthropoids, BMR also increased, reflecting the high metabolic cost of brain tissue (Elia 1992, Wang et al. 2011). Today, the highly encephalized anthropoid primates evince BMR similar to that of other placental mammals, whereas the less-encephalized strepsirrhine primates retain somewhat lower BMR.

The grade shift in TEE accounts for the slow rates of growth, reproduction, and aging evident among primates. Primates have the slowest life histories of any eutherian order (Charnov 1993, Charnov & Berrigan 1993). However, when rates of growth, reproduction, and senescence are plotted against metabolic rate rather than body mass, this difference in life history falls away (Pontzer et al. 2014).

The ultimate evolutionary reasons for changes in TEE remain largely unresolved and may well vary among different lineages (Brown et al. 2004, Sibly & Brown 2007, Pontzer & Kamilar 2009). Increased TEE may support greater reproductive output and thus be favored when food availability is high (Mueller & Diamond 2001), whereas lowering TEE may reduce the risk of starvation during food shortages as well as the risks, including predation, associated with foraging (Sibly & Brown 2007, Pontzer & Kamilar 2009). Species with particularly low TEE may be informative here. Two nonprimate eutherian mammals fall below the primate TEE/body mass trend line: three-toed sloths (*Bradypus variegatus*) and aardwolves (*Proteles cristatus*) (**Figure 1**). Sloths are notoriously sedentary, and their extremely slow metabolism may be part of a slow, cryptic lifestyle that reduces the risk of predation (Nagy & Montgomery 1980). Aardwolves have a highly derived diet, feeding almost exclusively on termites; their low TEE is thought to be an adaptation for reducing energy requirements and the risk of starvation (Williams et al. 1997). Similarly, orangutans (*Pongo pygmaeus*) exhibit very low TEE, even for a primate (**Figure 1**), and my colleagues and I (Pontzer et al. 2010) have proposed that their low metabolic throughput is an adaptation to reduce the risk of starvation during the severe but unpredictable periods of food shortage in their native habitats. These extreme cases suggest TEE may be a target of selection in the context of foraging ecology and predation, but the evolutionary relationships linking foraging ecology, TEE, and life-history strategies are not well understood and remain an important focus for future research.

Larger samples are needed to examine evolutionary changes in TEE within the hominoid clade, but the available evidence suggests that TEE has decreased substantially in orangutans and may have increased in our own lineage, independent of changes in mass and activity (Pontzer et al. 2010, 2014). Changes in TEE—the size of the daily “energy budget”—would hold important implications for reconstructing hominin evolutionary history (Pontzer 2012). Ecophysiological models for increased brain size and reproductive output in hominins have emphasized energetic trade-offs between brain and gut size (e.g., Aiello & Wheeler 1995, Isler & van Schaik 2009) or locomotor cost (Navarrete et al. 2011), an approach that assumes the daily energy budget, TEE, is fixed. However, if the energy budget can expand and contract over evolutionary time, these models need to account for potential changes in TEE as well as trade-offs in energy investment and allocation.



SUMMARY

TEE in humans and other primates has traditionally been viewed as a simple product of body size and activity level (FAO et al. 2001). Although this perspective persists in some areas of ecology and public health, a large and increasing set of studies from free-living populations across a broad range of populations and species provides a much more dynamic and complex view of our metabolic physiology. TEE in humans and other primates is remarkably low compared with that of other placental mammals, a previously unappreciated aspect of the primate phenotype that appears to correspond with primates' distinctively slow life histories. Physical activity is an important component of TEE, but variation in physical activity among individuals or populations has less effect on TEE than is often assumed. Instead, in humans and other species TEE appears to be maintained within a relatively narrow, evolved, and species-specific physiological range. The ecological and evolutionary pressures shaping TEE and BMR in humans and other primates are important areas for future research and discovery.

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