Ambient Temperature and Obesity

Douglas R. Moellering · Daniel L. Smith Jr.

Published online: 10 February 2012
© Springer Science+Business Media, LLC 2012

Abstract Homeotherms maintain an optimal body temperature that is most often above their environment or ambient temperature. As ambient temperature decreases, energy expenditure (and energy intake) must increase to maintain thermal homeostasis. With the widespread adoption of climate control, humans in modern society are buffered from temperature extremes and spend an increasing amount of time in a thermally comfortable state where energetic demands are minimized. This is hypothesized to contribute to the contemporary increase in obesity rates. Studies reporting exposures of animals and humans to different ambient temperatures are discussed. Additional consideration is given to the potentially altered metabolic and physiologic responses in obese versus lean subjects at a given temperature. The data suggest that ambient temperature is a significant

contributor to both energy intake and energy expenditure, and that this variable should be more thoroughly explored in future studies as a potential contributor to obesity susceptibility.

Keywords Ambient temperature · Obesity · Thermogenesis · Energy expenditure · Brown adipose tissue · Diet · Thermoneutral

Introduction

The contemporary trend of increased prevalence of overweight and obesity in developed countries, including the United States, has brought with it an increasing concern of associated morbidity and mortality [1]. Whether the trend continues and the incidence increases or plateaus at the current level [2, 3], an explanation for the underlying causes of this increase is somewhat disputed. Although it is well appreciated that a positive energy balance describes the situation where excess energy intake and/or decreased energy expenditure can clearly model weight gain, this descriptive statement does not address the underlying cause(s) and may not fully address the complexity of interactions that modulate both the food individuals eat nor the processes/activities that account for energy expenditure. In this regard, it has been suggested that multiple, less well appreciated factors may be additionally contributing to the increase in observed weight gain [4, 5]. Humans, like other homeothermic mammals, have an optimal body temperature that is most frequently above the temperature of the environment in which they live. Thus, a cooler ambient temperature (T_a) results in a higher metabolic rate to meet the increased thermogenic demand. With the advent and widespread adoption of climate control by heating and air conditioning in cars, homes,

D. R. Moellering
Department of Nutrition Sciences,
University of Alabama at Birmingham,
1670 University Blvd, Volker Hall G046A,
Birmingham, AL 35294-1900, USA

D. L. Smith Jr. (✉)
Department of Nutrition Sciences,
University of Alabama at Birmingham,
1530 3rd Avenue S, Webb 304A,
Birmingham, AL 35294-3360, USA
e-mail: dsmithjr@uab.edu

D. R. Moellering
Diabetes Research and Training Center,
University of Alabama at Birmingham,
Birmingham, AL, USA

D. R. Moellering · D. L. Smith Jr.
Nutrition Obesity Research Center,
University of Alabama at Birmingham,
Birmingham, AL, USA

and places of work, people enjoy a greater proportion of their daily lives in comfortable temperatures [4–6] that results in decreased energy expenditure for active thermal regulation—the thermoneutral zone (TNZ). It has been suggested that a greater amount of time spent within the TNZ and reduced variability (i.e., exposures to diurnal fluctuations to T_a) are associated with and contribute to increases in obesity rates, presumably through reductions of energy expenditure in the absence of cold or heat stress [4–7]. How this increase in the environmental comfort of life may be contributing to the rise in obesity and whether alterations in T_a exposure could offer a potential avenue to alter energy balance in a favorable way for weight loss or weight maintenance are discussed below.

Ambient Temperature: Energy Expenditure and Energy Intake

It is simple to recognize that if an individual eats more calories than they expend, the result should be weight gain. Additionally, a constant caloric intake concomitant with a significant decrease in energy expenditure—associated with reduced physical activity (or a sedentary lifestyle)—might also be expected to result in weight gain. Despite these obvious predictions and the contributions of each to energy balance, it has been difficult to ascribe either or both as the sole cause(s) of the increased overweight/obesity incidence in contemporary society. This has led some researchers to hypothesize that more subtle, but potentially significant factors, are individually or cooperatively contributing to a shift in the economy of energy balance and increase in obesity rates.

To be a significant contributor to the current obesity epidemic, any energy imbalance, no matter how big or small, must persist over an extended period of time. This has been clearly illustrated by modeling the impact of a fixed caloric excess (or reduced expenditure) on body weight gain [8, 9]. The initial imbalance results in additional body mass accrual (both fat and lean mass), and a new energy balance is established within a relatively short period of time where the calories that were previously in excess are now necessary for body weight maintenance due to the increased body size [9]. Instead, if a relative caloric excess is maintained constantly over time a slow, but consistent, rise to a higher body weight will be attained.

One ubiquitous factor influencing both energy expenditure and energy intake is the ambient or environmental temperature in which we live. Homeothermic organisms, including humans, maintain an optimal body temperature within a fairly narrow range under normal conditions at about 37°C [10]. However, many homeotherms spend the majority of their time in an environment where the T_a is

below their body temperature. This is acceptable as the basic processes of metabolism and physiology are subject to entropic loss resulting in heat production. Therefore, a thermal heat sink of lower T_a , where excess heat produced by metabolism can be dissipated, is beneficial for maintaining homeothermy. When the T_a drops below the lower limit of the TNZ, adaptive and thermogenic mechanisms are activated resulting in heat production and core body temperature preservation [11, 12]. Conversely, when T_a rises above the upper TNZ limit, physiologic processes to amplify heat dissipation are activated resulting in a metabolic increase [13, 14]. The temperature range where neither active heat generation nor dissipation is required for thermal homeostasis is defined as the TNZ. Metabolism (energy expenditure) is increased either above or below the TNZ (Fig. 1) [13–15]. Without adequate energy intake compensation (reduction) to offset the lowered metabolic demand at thermoneutrality, an energy imbalance should result contributing to weight gain. Similarly, under a fixed, basal energy intake condition, increases in energy expenditure associated with reductions in T_a could result in weight loss.

In homeotherms, T_a is not only associated with energy expenditure, but also energy intake [12, 13, 16–18]. Food intake functions both to meet physiologic needs of macro- and micronutrient requirements, but also serves as a significant source of energy for heat production and thermal homeostasis. When calories are insufficient, reductions in

Fig. 1 Energy expenditure and energy intake at different ambient temperatures (T_a s). The thermoneutral zone (TNZ; box area) is defined as the minimal basal energy expenditure when at rest in the absence of active thermogenesis or heat dissipation. Notice that as T_a decreases below the TNZ, energy expenditure increases. Conversely, as T_a increases above the TNZ, energy expenditure also increases. Food intake is modeled across the T_a range based on small mammal and human data. Protection against T_a with the addition of clothing or changes in body composition (e.g., obesity/excess adiposity) shifts the energy expenditure curve to the left, representing an altered energetic response to the same T_a for individuals of different body weights and adiposities. Thus, the TNZ of obese individuals may be expected to shift to a lower T_a range (box area)

body temperature are possible [19]. With heat loss to the environment dependent on T_a (the lower the T_a below body temperature, the greater the heat loss), a significant, inverse relationship exists between T_a and food intake [16]. This increase in food intake with lowered T_a is observed across a wide range of temperatures in multiple species [12], including humans [13, 20], although the amount of data collected on controlled human exposures to T_a , particularly above the TNZ, are limited compared with animal studies [16–18]. In general, exposure to T_a below the TNZ increases appetite and food intake, whereas T_a above the TNZ results in a heat stress suppressing food intake, while inducing an elevated metabolic response (Fig. 1) [17, 18]. This energetic divergence between intake and expenditure above the TNZ results in acute body weight and body fat loss in animals, with suggestive data available in humans [16–18, 21–23]. Restaurants have capitalized on this environmental factor realizing that air conditioning in the summer helps increase sales, while more subtle alteration of ambience such as room color can have an effect on temperature sensation with warm colors (reds, oranges, and yellows) permitting a lower T_a before cold is perceived [17, 24].

The variability of T_a and duration of exposure, whether chronic or acute, can have both individual and synergistic effects on energy intake patterns. Consistent cold exposure—housing and feeding—resulted in greater food intake than thermoneutral exposure in rats [25]. Similarly, rats that ate in the cold consumed more food than those fed at thermoneutrality, regardless of the general housing temperature, with greater weight gain in animals who lived at thermoneutrality but ate in the cold (vs eating at the same T_a) [25]. These results demonstrate the significant influence acute T_a exposure can have during food intake periods, but whether similar influences of acute cold exposure during dining would result in greater weight gain in humans requires further investigation.

Ambient Temperature and Diet-Induced Thermogenesis

The thermic effect of feeding, or diet-induced thermogenesis (DIT), following the ingestion of calories is associated with increases in metabolism and skin temperature [26, 27]. Obligatory DIT represents the processes necessary for digestion, absorption, etc. that are intimately associated with the caloric content and form of the food [28–30]. Facultative DIT refers to an adaptive thermogenic response where calories are converted to heat energy through metabolic processes such as mitochondrial uncoupling [28, 29]. T_a influences both the caloric intake and the thermogenic potential of DIT by increasing (low T_a) or decreasing (high T_a) the thermal sink of the environment in relationship to body temperature. Thus, a greater DIT response is possible in reduced T_a

conditions [26]. At T_a above the TNZ, food intake is further depressed, potentially resulting in negative energy balance due to the associated energy expenditure increase.

Multiple reports have demonstrated potential differences in DIT between lean and obese subjects. One difficulty with these studies is the interpretation of any measured deficit of DIT as causative or correlative with obesity. Consider for instance, DIT was significantly lower in obese versus lean men when comparing individuals with similar lean body mass [31]. Furthermore, obese subjects were shown to have an initial DIT deficit compared with normal weight controls, which was partially recovered after weight reduction by gastric banding [32]. Equally intriguing is a study where an artificial form of obesity was applied. Comparing lean and obese subjects, a significant deficit of DIT was observed in obese individuals [33]. However, the application of a physical, insulative barrier to the greater abdominal surface area of the lean subjects by wrapping them in a thermal blanket resulted in a significant suppression of DIT, demonstrating what the authors suggest is a leakage of heat across the abdominal wall relevant to the extent of DIT [33]. Considering these results together it appears that an established obese phenotype, whether adiposity or artificial in nature, has significant implications for energy dissipation related to DIT. Thus, the altered morphologic characteristics of obese individuals with their large, insulative barrier of adipose tissue, as assessed by lower abdominal skin surface temperature measurements, compared with core and peripheral skin temperatures [34, 35] may physically limit the amount of heat dissipation and blunt potential DIT responses to protect against a core hyperthermic response.

Yet, this does not rule out the possibility that individuals with reduced thermogenic capacity (through defective brown adipose tissue [BAT] or mitochondrial energetic economy [36]) could be biased toward a greater energetic efficiency and weight gain under specific temperature and diet conditions. In fact, more recent work in animal models has demonstrated the interdependence of metabolic potential and T_a in body weight gain and obesity-related phenotypes. Feldmann et al. [37] addressed a puzzling result in the thermogenesis field by assessing why BAT-defective rodents were normal body weight and not obese as expected. By using uncoupling protein 1 (UCP1) ablated mice and controls, their work demonstrated that a low T_a induces a thermic response that must be achieved metabolically either through BAT uncoupling or other mechanisms in a BAT-defective state [37]. However, protection from thermal stress by thermoneutral housing resulted in increased energetic efficiency with attenuated DIT, resulting in accelerated weight gain and obesity induction in BAT-defective mice even when fed a normal chow (low-fat) diet [37]. They concluded that “ambient temperature is qualitatively determinative for the outcome of metabolic studies,

that no other protein and no other mechanism can substitute for UCP1 in mediating diet-induced adrenergic thermogenesis, and that UCP1 activity can be determinative for obesity development in mice and possibly in humans” [37•]. Bearing in mind the limitations of translating animal results to human phenotypes, this study would suggest that individuals with defective BAT function may be more susceptible to excess weight gain under thermoneutral conditions, whereas semi-protected at a low T_a due to alternate mechanisms for cold-induced, elevated metabolism.

Ambient Temperature and BAT

In rodents, BAT is known to function in both cold-induced, nonshivering thermogenesis (NST) and facultative DIT [11, 29, 37•]. By manipulations of T_a , BAT depots can be expanded (cold T_a) or repressed (warm T_a) with sympathetic nervous system (SNS)–induced activity directly related to the activation potential of the tissue [11]. Adaptive responses in BAT function can be observed over a 1- to 2-week period upon shifting to a different T_a [11]. Additionally, a strong association between NST and DIT potential is present due to their shared mechanisms of action [11]. Even in the absence of functional BAT, cold-induced increases in energy expenditure are expected and observed due to other mechanisms of increasing energy expenditure (e.g., shivering, etc.) [38]. However, the facultative component of DIT may be exclusive to BAT and thus is irreplaceable in its function of dissipating excess caloric intake as heat [29, 37•]. As such, animals, and presumably people, with defective or suppressed BAT function may be expected to be more susceptible to weight gain during excess caloric intake [30, 37•, 39, 40]. Additionally, the suppression of BAT function in thermoneutral conditions would predict a decreased DIT. This energetic impairment would be expected to equally affect both lean and obese individuals, independent of BAT status, and could theoretically contribute to weight or fat gain in thermoneutral conditions. In human subjects, large differences in DIT between individuals and under different conditions are often observed [28, 41–43]. By measuring the thermogenic response to mild cold and overfeeding in humans, a highly correlated individual response to both stimuli was observed and was related to norepinephrine levels [41, 44]. Whether a shared mechanism of BAT was responsible for the SNS-related response in human subjects remains to be demonstrated.

Since 2009 a number of groups have utilized positron emission tomography and computed tomography (PET/CT) with 2-fluorodeoxyglucose label to demonstrate a metabolically active adipose tissue located in the cervical and shoulder region of healthy adults. Biopsies of tissue from these sites possess BAT histologic and biochemical markers [45•,

46•, 47]. Retrospective PET/CT studies of patients undergoing diagnostic scans for cancer had indicated the likelihood of BAT presence, showing BAT incidence associated with younger age, lower body mass index (BMI), and acute T_a influence (cold temperature activated) [48–51]. Previous anatomic and histologic observations in human cadavers had demonstrated cells with BAT-like characteristics including multilocular lipid droplets, numerous dense mitochondria, and rich vascular supply [52–56]. In conditions with expected high sympathetic activity, depletion of lipid content of the BAT was considered indirect evidence of activity and regulation [54, 57, 58]. Despite these earlier reports, a lack of capable technologies for identifying and studying BAT in vivo had hindered progress in determining the significance of BAT in humans, although it was proposed as a potential mediator of energetic balance [59, 60]. Greater than 90% of healthy, young adults that were studied exhibited inducible BAT activity under cold stimulation that was inversely related to BMI and percent body fat [46•], with other studies estimating about 60% of the total population as BAT positive [45•, 51, 61, 62]. Although BAT is clearly protective against obesity and diet-related metabolic impairment (and compromised in models of obesity and diabetes) in animal models [63], the clinical relevance in humans remains to be demonstrated [51, 60]. As additional technologies are developed to measure BAT quantity and activity in vivo [64–66], future studies will hopefully clarify the role, if any, BAT may play in body weight regulation and disease prevention.

Ambient Temperature and TNZ Estimation

With the advent of climate control through heat and air conditioning, secular trends for a reduced exposure to variability in T_a and a greater proportion of time spent in the TNZ have been proposed as contributors to energetic efficiency and weight gain/obesity due to reduced cold- or heat-induced metabolic responses [4•, 7]. Regarding the TNZ, it is worth noting that many of the studies that have measured the metabolic response to different T_a s may not be representative of diverse human populations and living environments. This is in part because multiple factors influence temperature perception including air speed, humidity, age, body size, body fat, clothing, acclimation, diet, activity, etc. [67]. We have all utilized some of these techniques to buffer against a temperature response (e.g., adding a coat during the winter, turning on fans during the summer). Therefore, a TNZ range can be most narrowly defined in a homogenous population of individuals where each of these factors is well controlled. Furthermore, physiologic, anthropometric, and morphologic differences between normal weight and obese subjects may be important as the additional insulation

provided by layers of adiposity should be protective against cold temperatures [68], but potentially disadvantageous during heat stress conditions [69, 70]. Therefore, as with body temperature, measurement variability between subjects, and at the site of measurement within individuals [71], it would appear necessary to acknowledge that no single T_a can be considered definitive as the point of thermoneutrality for all subjects; thus, physiologic and metabolic responses will likely differ between subjects exposed to different T_a s.

Although recent findings have reinvigorated an interest in thermal regulation and body weight gain, T_a within the range experienced in daily activities in developed countries has been proposed as a potential contributor to energy balance for some time [72]. After demonstrating a greater 24-h heat production at 22°C compared with 28°C it was concluded that “(a) environmental temperature may play a more important role than was previously recognized in the energy balance...[indicating] that mild cold should at least be considered as a factor that can affect the energy metabolism of people” [72]. Although a thermogenic response may be expected under cold-stimulated conditions, other physiologic responses (e.g., peripheral vasoconstriction) and behavioral modifications (e.g., clothing choice) could protect against small cold challenges, reducing any needed thermogenic response. When subjects were allowed clothing choice and energy expenditure was measured at 28°C and 20°C, cooler temperature was still associated with increased expenditure despite increased usage of clothing and bedding [73]. To what extent the selected clothing buffered the cold challenge within subjects was not measurable. Interestingly, 2 of 3 obese subjects demonstrated a lower than expected expenditure under the cooler condition, suggesting their basal expenditure level associated with thermoneutrality was potentially shifted toward a lower T_a under the tested conditions, although obese subjects as a group were not significantly different than lean subjects [73].

When measuring energy expenditure and energy intake in young, adult, healthy, normal body weight subjects, a continual response of increasing metabolic rate with decreasing T_a (even within the range of temperature normally encountered over a 24-h period), accompanied by an increased energy intake in cooler temperatures when fed ad libitum, is observed [26, 74–76]. In response to this mild cold, sleeping metabolic rate (SMR) and DIT were both increased, with DIT comprising a proportionally larger percentage of total daily energy expenditure [26]. This is particularly interesting as SMR would represent an individual's metabolic capacity in the absence of either food intake or physical activity, and might demonstrate greater energy expenditure during sleep in some individuals. An increased metabolic response to cold has been reported in winter [77, 78], and sometimes in summer [77], with peripheral vasoconstriction as measured by core minus distal skin

temperature related to total energy expenditure [77]. This highlights the seasonal effects on metabolism and various ways that individuals respond to cold stress (insulative:vasoconstriction vs metabolic:thermogenesis), which the authors point out could have potential implications for subject-specific energy balance [77]. A divergent response between lean and obese women to T_a is observed with heat loss being decreased at cool T_a in obese subjects (−2.1%) and increased in lean subjects (+7.8%; but not statistically significant) [79]. When comparing lean and obese men subjected to cooling, both groups had an increase in metabolism, but the relative increase was significantly larger in lean subjects [34]. Whether this is because of an innate defect in cold-induced thermogenesis or a blunted response due to the insulative protection of adiposity is not clearly delineated. Nevertheless, it is clear that although energy expenditure normally increases during cold exposure, differences between individuals of different body compositions and thermogenic capacities may dispose them to a greater or lesser sensitivity and metabolic response.

Ambient Temperature Reduction in Lean Versus Obese Subjects

Reduced Ambient Temperature

Consider a scenario of two individuals of similar age but vastly different body composition (one lean with a low percentage body fat and the other obese with a high percentage body fat) exposed to the same environmental temperatures. As discussed previously, the known effects of cold are an increased metabolic rate and food intake. Considering a thermoneutral temperature of about 22°C for the lean, clothed individual, a shift to 16°C would result in a cold stress met by an increased SNS response and increased thermogenesis. This would include an increase in peripheral vasoconstriction, heart rate, blood pressure, circulating fatty acids, insulin, thyroxine, and cortisol [80], with stimulation of BAT and increased food intake. In contrast, an obese individual exposed to 16°C would still be expected to mount a SNS response and small thermogenic response; however, the insulative properties of the excess adipose tissue would result in a suppressed cold response, as the obese individual would be closer to the lower limit of thermoneutrality or possibly within the range. The obese individual would demonstrate little or no activated BAT, but thermogenesis, if needed, may originate from other tissues (e.g., muscle). Additionally, the obese individual could increase food intake, but with a blunted DIT response relative to lean individuals [27, 31–33, 81]. Considering the presence of BAT in lean individuals and its relative limitation or absence in obese individuals, the adaptive/facultative DIT possible

in BAT would be significantly greater in the lean individual than the obese. Thus, a lower T_a would be expected to be “protective” against the development of a positive energy balance and weight gain for the lean individual, whereas low T_a could be metabolically insignificant or a potential contributor to a greater energetic efficiency of the obese individual, predisposing them to additional weight gain. Whether this could result in a positive feedback scenario where increased metabolic efficiency with increased body mass/fat mass at lower T_a biases to excess energy storage and additional weight gain needs to be further explored.

Elevated Ambient Temperature

In the case of a lean individual exposed to a high T_a , metabolism would be increased while food intake would be decreased. In short-term studies this has resulted in a negative energy balance and body weight and fat loss. Similarly, in an obese individual, exposure to T_a above the TNZ (which we argue could be shifted to a lower T_a upper limit due to increased adiposity) would also increase metabolism as processes are activated to increase heat dissipation against a smaller thermal gradient. Food intake would be reduced, resulting in a negative energy balance and body weight/fat loss. In both of these “hyperthermic” conditions, the relative contribution of DIT to energy expenditure (and energy balance) would be reduced as food intake is decreased and thermogenic mechanisms such as BAT would be suppressed during any chronic heat exposure acclimation.

Finally, consider the separation of T_a during meals versus daily activities and sleep/rest. Because acute exposure to T_a may increase energy intake, if meals were consumed in cool conditions followed by a transition to a warmer T_a , an unfortunate occurrence of mismatched intake and expenditure could occur. Whether this would result in excess weight gain in humans, and if obese individuals with suppressed DIT would be more susceptible could be explored in the future.

Ambient Temperature and Animal Models: Cautions and Considerations

The effects and interactions of T_a , nutrition, and weight gain may be most highly researched in animal models including rodents, chickens, and swine. Although each demonstrate T_a -dependent alterations in energy expenditure and intake [12, 82, 83], the applicability for predicting human responses suffers from a few limitations. Of relevance to cold- and diet-induced thermogenesis, both pigs and chickens possess BAT-like cells, but lack a functional *UCP1* gene [84, 85]. With the reinvestigated interest in the significance of BAT and its contribution to energy expenditure under

cold stimulation and diet conditions, caution should be applied in over-generalizing results from both of these organisms to humans, although their utility as a model of impaired BAT function may yet be exploited. Although most rodents possess BAT, their surface area-to-volume (or mass) ratio is significantly larger than with humans, resulting in a significantly greater thermal challenge under a given T_a exposure [11, 12, 29]. This is evidenced by the proportionally greater BAT mass relative to total body weight (~10-fold larger in mice than in humans), which is associated with a significantly greater metabolic increase in response to SNS BAT stimulation [11, 12]. However, thermoneutral housing may partially alleviate this cold-induced effect and improve the utility of the model for translational research [29, 86].

Conclusions

Ambient temperature can clearly influence both energy intake and energy expenditure, even within the range of T_a encountered in modern society. Additionally, time spent in the TNZ could be a contributor to greater energetic efficiency (decreased metabolic rate) and weight gain. Although conclusive data are still needed, it is not clear that lowering T_a would be effective in treating established obesity. Rather, current data support the hypothesis that an increased energy intake in response to mild cold, with a decreased DIT in obese subjects, could contribute to a positive energy balance and greater weight gain under mild cold conditions. Although it is well recognized that large interindividual differences in metabolic rate exist, a systematic assessment of metabolic responses to a range of T_a s may be informative for identifying individuals who are more “energetically efficient” and thus susceptible to excess weight gain. Specifically, measures of diet-induced thermogenesis, activity-related thermogenesis, and SMR at temperatures below, above, and within the TNZ may provide a more relevant portrait of the daily cycles of life compared with the imposed, artificial environments of clinical laboratory facilities. Future questions that will contribute to our understanding of T_a and obesity include:

- What is the metabolic response of lean versus obese subjects across a broad range of ambient temperatures? Is the TNZ simply shifted lower or expanded in the obese state?
- Can lowering T_a shift energy balance sufficiently to induce weight loss in the absence of dietary control in humans? Could raising T_a above the TNZ be used as a dietary suppressant, weight-loss regimen?
- Are the physiologic and metabolic responses to T_a above and below the TNZ a risk factor for cardiovascular complications?

- What is the free living, 24-h T_a exposure profile for humans in modern society? Can reduced T_a at night be utilized to increase energy expenditure and stimulate thermogenic potential for energy balance and weight maintenance? How do clothing, bedding, activity, and other variables influence these exposures? How do T_a exposures change with the seasons?
- Could intermittent, acute exposures to cold T_a (outside of meal times) provide sufficient stimulus to promote prolonged energy expenditure and BAT expansion or is chronic exposure necessary?
- Do T_a exposures during growth and development influence long-term metabolism and weight gain in humans?

Although more research is needed, it is becoming increasingly apparent that ambient temperature can have significant impacts on our energy expenditure, energy intake, and thus ultimately our energy balance. As a return to varied, natural ingredient diets is proposed for health, so too exposure to varied, natural range of ambient temperatures may be just what we need.

Acknowledgments Funding DRM, DLS - P60DK079626, DLS - P30DK56336.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
1. Olshansky SJ, Passaro DJ, Hershow RC, Layden J, Carnes BA, Brody J, Hayflick L, Butler RN, Allison DB, Ludwig DS. A potential decline in life expectancy in the United States in the 21st century. *N Engl J Med*. 2005;352:1138–45.
 2. Yanovski SZ, Yanovski JA. Obesity prevalence in the United States—up, down, or sideways? *N Engl J Med*. 2011;364:987–9.
 3. Flegal KM, Carroll MD, Ogden CL, Curtin LR. Prevalence and trends in obesity among US adults, 1999–2008. *JAMA*. 2010;303:235–41.
 4. Keith SW, Redden DT, Katzmarzyk PT, Boggiano MM, Hanlon EC, Benca RM, Ruden D, Pietrobelli A, Barger JL, Fontaine KR, Wang C, Aronne LJ, Wright SM, Baskin M, Dhurandhar NV, Lijoi MC, Grilo CM, DeLuca M, Westfall AO, Allison DB. Putative contributors to the secular increase in obesity: exploring the roads less traveled. *Int J Obes (Lond)*. 2006;30:1585–94.
 5. McAllister EJ, Dhurandhar NV, Keith SW, Aronne LJ, Barger J, Baskin M, Benca RM, Biggio J, Boggiano MM, Eisenmann JC, Eloheid M, Fontaine KR, Gluckman P, Hanlon EC, Katzmarzyk P, Pietrobelli A, Redden DT, Ruden DM, Wang C, Waterland RA, Wright SM, Allison DB. Ten putative contributors to the obesity epidemic. *Crit Rev Food Sci Nutr*. 2009;49:868–913.
 6. Johnson F, Mavrogiani A, Ucci M, Vidal-Puig A, Wardle J. Could increased time spent in a thermal comfort zone contribute to population increases in obesity? *Obes Rev*. 2011;12:543–51.
 7. Hansen JC, Gilman AP, Odland JO. Is thermogenesis a significant causal factor in preventing the “globesity” epidemic? *Med Hypotheses*. 2010;75:250–6.
 8. Weinsier RL, Bracco D, Schutz Y. Predicted effects of small decreases in energy expenditure on weight gain in adult women. *Int J Obes Relat Metab Disord*. 1993;17:693–700.
 9. Katan MB, Ludwig DS. Extra calories cause weight gain—but how much? *JAMA*. 2010;303:65–6.
 10. Benzing TH. Heat regulation: homeostasis of central temperature in man. *Physiol Rev*. 1969;49:671–759.
 11. Cannon B, Nedergaard J. Brown adipose tissue: function and physiological significance. *Physiol Rev*. 2004;84:277–359.
 12. Chaffee RR, Roberts JC. Temperature acclimation in birds and mammals. *Annu Rev Physiol*. 1971;33:155–202.
 13. Davis TR. The influence of climate on nutritional requirements. *Am J Public Health Nations Health*. 1964;54:2051–67.
 14. Herrington LP. The heat regulation of small laboratory animals at various environmental temperatures. *Am J Physiol*. 1940;129:123–39.
 15. Erikson H, Krog J, Andersen KL, Scholander PF. The critical temperature in naked man. *Acta Physiol Scand*. 1956;37:35–9.
 16. Brobeck JR. Food intake as a mechanism of temperature regulation. *Yale J Biol Med*. 1948;20:545–52.
 17. Herman CP. Effects of heat on appetite. In: Marriott BM, editor. *Nutritional needs in hot environments*. 1993. p. 187–214.
 18. Yates AA. Food intake, appetite, and work in hot environments. In: Marriott BM, editor. *Nutritional needs in hot environments*. 1993. p. 297–304.
 19. Keys A, Brozek J, Henschel A, Mickelsen O. *The biology of human starvation*. Taylor: University of Minnesota Press; 1950.
 20. Westerterp-Plantenga MS. Effects of extreme environments on food intake in human subjects. *Proc Nutr Soc*. 1999;58:791–8.
 21. Chaffee RR, Kaufman WC, Kratochvil CH, Sorenson MW, Conaway CH, Middleton CC. Comparative chemical thermoregulation in cold- and heat-acclimated rodents, insectivores, protoprimates, and primates. *Fed Proc*. 1969;28:1029–34.
 22. Chaffee RR, Allen JR. Effects of ambient temperature on the resting metabolic rate of cold- and heat-acclimated *Macaca mulatta*. *Comp Biochem Physiol A*. 1973;44:1215–25.
 23. Jakubczak LF. Food and water intakes of rats as a function of strain, age, temperature, and body weight. *Physiol Behav*. 1976;17:251–8.
 24. Stroebele N, De Castro JM. Effect of ambience on food intake and food choice. *Nutrition*. 2004;20:821–38.
 25. Refinetti R. Effects of food temperature and ambient temperature during a meal on food intake in the rat. *Physiol Behav*. 1988;43:245–7.
 26. Westerterp-Plantenga MS, van Marken Lichtenbelt WD, Strobbe H, Schrauwen P. Energy metabolism in humans at a lowered ambient temperature. *Eur J Clin Nutr*. 2002;56:288–96.
 27. Booth G, Strang JM. Changes in temperature of the skin following ingestion of food. *Arch Intern Med*. 1936;57:533–43.
 28. Himms-Hagen J. Role of thermogenesis in the regulation of energy balance in relation to obesity. *Can J Physiol Pharmacol*. 1989;67:394–401.
 29. Cannon B, Nedergaard J. Nonshivering thermogenesis and its adequate measurement in metabolic studies. *J Exp Biol*. 2011;214:242–53.
 30. Jequier E. Thermogenic responses induced by nutrients in man: their importance in energy balance regulation. *Exp Suppl*. 1983;44:26–44.
 31. Segal KR, Gutin B, Albu J, Pi-Sunyer FX. Thermic effects of food and exercise in lean and obese men of similar lean body mass. *Am J Physiol*. 1987;252:E110–7.
 32. Thorne A, Hallberg D, Wahren J. Meal-induced thermogenesis in obese patients before and after weight reduction. *Clin Physiol*. 1989;9:481–98.
 33. Brundin T, Thorne A, Wahren J. Heat leakage across the abdominal wall and meal-induced thermogenesis in normal-weight and obese subjects. *Metabolism*. 1992;41:49–55.

34. Claessens-van Ooijen AM, Westerterp KR, Wouters L, Schoffelen PF, van Steenhoven AA, van Marken Lichtenbelt WD. Heat production and body temperature during cooling and rewarming in overweight and lean men. *Obesity* (Silver-Spring). 2006;14:1914–20.
35. • Savastano DM, Gorbach AM, Eden HS, Brady SM, Reynolds JC, Yanovski JA. Adiposity and human regional body temperature. *Am J Clin Nutr*. 2009;90:1124–31. *Demonstration by infrared thermography of the altered thermal profile of lean and obese individuals exposed to the same ambient temperature conditions.*
36. Krzywanski DM, Moellering DR, Fetterman JL, Dunham-Snary KJ, Sammy MJ, Ballinger SW. The mitochondrial paradigm for cardiovascular disease susceptibility and cellular function: a complementary concept to Mendelian genetics. *Lab Invest*. 2011;91:1122–35.
37. • Feldmann HM, Golozoubova V, Cannon B, Nedergaard J. UCP1 ablation induces obesity and abolishes diet-induced thermogenesis in mice exempt from thermal stress by living at thermoneutrality. *Cell Metab*. 2009;9:203–9. *By housing mice within their TNZ, a defect in thermogenesis reveals an increased energetic efficiency and propensity to increased weight gain and fat accrual. Thus, a gene by environment interaction disposes toward excess weight gain and obesity phenotypes only in the absence of cold stress.*
38. Liu X, Rossmeisl M, McClaine J, Riachi M, Harper ME, Kozak LP. Paradoxical resistance to diet-induced obesity in UCP1-deficient mice. *J Clin Invest*. 2003;111:399–407.
39. Himms-Hagen J. Impaired thermogenesis and brown fat in obesity. *Can J Surg*. 1984;27:125.
40. Rothwell NJ, Stock MJ. A role for brown adipose tissue in diet-induced thermogenesis. *Obes Res*. 1997;5:650–6.
41. Wijers SL, Saris WH, van Marken Lichtenbelt WD. Individual thermogenic responses to mild cold and overfeeding are closely related. *J Clin Endocrinol Metab*. 2007;92:4299–305.
42. Stock MJ. Gluttony and thermogenesis revisited. *Int J Obes Relat Metab Disord*. 1999;23:1105–17.
43. van Marken Lichtenbelt WD, Schrauwen P, van De KS, Westerterp-Plantenga MS. Individual variation in body temperature and energy expenditure in response to mild cold. *Am J Physiol Endocrinol Metab*. 2002;282:E1077–83.
44. Wijers SL, Saris WH, van Marken Lichtenbelt WD. Recent advances in adaptive thermogenesis: potential implications for the treatment of obesity. *Obes Rev*. 2008.
45. • Virtanen KA, Lidell ME, Orava J, Heglind M, Westergren R, Niemi T, et al. Functional brown adipose tissue in healthy adults. *N Engl J Med*. 2009;360:1518–25. *Documents the presence of metabolically active BAT in healthy adult humans by PET/CT scans.*
46. • van Marken Lichtenbelt WD, Vanhommerig JW, Smulders NM, Drossaerts JM, Kemerink GJ, et al. Cold-activated brown adipose tissue in healthy men. *N Engl J Med*. 2009;360:1500–8. *Documents the presence of metabolically active BAT in healthy adult humans by PET/CT scans using a mild cold ambient temperature exposure. Inverse associations of BAT activity with body weight and body fat are reported.*
47. Saito M, Okamatsu-Ogura Y, Matsushita M, Watanabe K, Yoneshiro T, Nio-Kobayashi J, et al. High incidence of metabolically active brown adipose tissue in healthy adult humans: effects of cold exposure and adiposity. *Diabetes*. 2009.
48. Hany TF, Gharehpapagh E, Kamel EM, Buck A, Himms-Hagen J, von Schulthess GK. Brown adipose tissue: a factor to consider in symmetrical tracer uptake in the neck and upper chest region. *Eur J Nucl Med Mol Imaging*. 2002;29:1393–8.
49. Nedergaard J, Bengtsson T, Cannon B. Unexpected evidence for active brown adipose tissue in adult humans. *Am J Physiol Endocrinol Metab*. 2007;293:E444–52.
50. Cypess AM, Lehman S, Williams G, Tal I, Rodman D, Goldfine AB, Kuo FC, Palmer EL, Tseng YH, Doria A, Kolodny GM, Kahn CR. Identification and importance of brown adipose tissue in adult humans. *N Engl J Med*. 2009;360:1509–17.
51. Nedergaard J, Bengtsson T, Cannon B. Three years with adult human brown adipose tissue. *Ann N Y Acad Sci*. 2010;1212:E20–36.
52. Heaton JM. The distribution of brown adipose tissue in the human. *J Anat*. 1972;112:35–9.
53. Tanuma Y, Tamamoto M, Ito T, Yokochi C. The occurrence of brown adipose tissue in perirenal fat in Japanese. *Arch Histol Jpn*. 1975;38:43–70.
54. Tanuma Y, Ohata M, Ito T, Yokochi C. Possible function of human brown adipose tissue as suggested by observation on perirenal brown fats from necropsy cases of variable age groups. *Arch Histol Jpn*. 1976;39:117–45.
55. Nnodim JO. The occurrence of brown adipose in man inhabiting the tropics. *Z Mikrosk Anat Forsch*. 1990;104:721–8.
56. Lever JD, Jung RT, Nnodim JO, Leslie PJ, Symons D. Demonstration of a catecholaminergic innervation in human perirenal brown adipose tissue at various ages in the adult. *Anat Rec*. 1986;215:251–9.
57. Huttunen P, Hirvonen J, Kinnula V. The occurrence of brown adipose tissue in outdoor workers. *Eur J Appl Physiol Occup Physiol*. 1981;46:339–45.
58. Huttunen P, Kortelainen ML. Long-term alcohol consumption and brown adipose tissue in man. *Eur J Appl Physiol Occup Physiol*. 1990;60:418–24.
59. Himms-Hagen J. Obesity may be due to a malfunctioning of brown fat. *Can Med Assoc J*. 1979;121:1361–4.
60. Himms-Hagen J. Does brown adipose tissue (BAT) have a role in the physiology or treatment of human obesity? *Rev Endocr Metab Disord*. 2001;2:395–401.
61. Orava J, Nuutila P, Lidell ME, Oikonen V, Noponen T, Viljanen T, Scheinin M, Taittonen M, Niemi T, Enerback S, Virtanen KA. Different metabolic responses of human brown adipose tissue to activation by cold and insulin. *Cell Metab*. 2011;14:272–9.
62. Lee P, Greenfield JR, Ho KK, Fulham MJ. A critical appraisal of the prevalence and metabolic significance of brown adipose tissue in adult humans. *Am J Physiol Endocrinol Metab*. 2010;299:E601–6.
63. Cannon B, Nedergaard J. Metabolic consequences of the presence or absence of the thermogenic capacity of brown adipose tissue in mice (and probably in humans). *Int J Obes (Lond)*. 2010;34 Suppl 1:S7–S16.
64. Hu HH, Smith Jr DL, Nayak KS, Goran MI, Nagy TR. Identification of brown adipose tissue in mice with fat-water IDEAL-MRI. *J Magn Reson Imaging*. 2010;31:1195–202.
65. Hamilton G, Smith Jr DL, Bydder M, Nayak KS, Hu HH. MR properties of brown and white adipose tissues. *J Magn Reson Imaging*. 2011;34:468–73.
66. Branca RT, Warren WS. In vivo brown adipose tissue detection and characterization using water-lipid intermolecular zero-quantum coherences. *Magn Reson Med*. 2011;65:313–9.
67. Wagner JA, Robinson S, Marino RP. Age and temperature regulation of humans in neutral and cold environments. *J Appl Physiol*. 1974;37:562–5.
68. Anderson GS. Human morphology and temperature regulation. *Int J Biometeorol*. 1999;43:99–109.
69. Buskirk ER, Lundegren H, Magnusson L. Heat acclimatization patterns in obese and lean individuals. *Ann N Y Acad Sci*. 1965;131:637–53.
70. Chung NK, Pin CH. Obesity and the occurrence of heat disorders. *Mil Med*. 1996;161:739–42.
71. Livingstone SD, Grayson J, Frim J, Allen CL, Limmer RE. Effect of cold exposure on various sites of core temperature measurements. *J Appl Physiol*. 1983;54:1025–31.

72. Dauncey MJ. Influence of mild cold on 24 h energy expenditure, resting metabolism and diet-induced thermogenesis. *Br J Nutr.* 1981;45:257–67.
73. Warwick PM, Busby R. Influence of mild cold on 24 h energy expenditure in ‘normally’ clothed adults. *Br J Nutr.* 1990;63:481–8.
74. Westerterp-Plantenga MS, van Marken Lichtenbelt WD, Cilissen C MS, Top S. Energy metabolism in women during short exposure to the thermoneutral zone. *Physiol Behav.* 2002;75:227–35.
75. Wilkerson JE, Raven PB, Horvath SM. Critical temperature of unacclimatized male Caucasians. *J Appl Physiol.* 1972;33:451–5.
76. Yoshimura M, Yoshimura H. Cold tolerance and critical temperature of the Japanese. *Int J Biometeorol.* 1969;13:163–72.
77. van Ooijen AM, van Marken Lichtenbelt WD, van Steenhoven AA, Westerterp KR. Seasonal changes in metabolic and temperature responses to cold air in humans. *Physiol Behav.* 2004;82:545–53.
78. Kashiwazaki H, Dejima Y, Suzuki T. Influence of upper and lower thermoneutral room temperatures (20 degrees C and 25 degrees C) on fasting and post-prandial resting metabolism under different outdoor temperatures. *Eur J Clin Nutr.* 1990;44:405–13.
79. Blaza S, Garrow JS. Thermogenic response to temperature, exercise and food stimuli in lean and obese women, studied by 24 h direct calorimetry. *Br J Nutr.* 1983;49:171–80.
80. Celi FS, Brychta RJ, Linderman JD, Butler PW, Alberobello AT, Smith S, Courville AB, Lai EW, Costello R, Skarulis MC, Csako G, Remaley A, Pacak K, Chen KY. Minimal changes in environmental temperature result in a significant increase in energy expenditure and changes in the hormonal homeostasis in healthy adults. *Eur J Endocrinol.* 2010;163:863–72.
81. Steiniger J, Karst H, Noack R, Steglich HD. Diet-induced thermogenesis in man: thermic effects of single protein and carbohydrate test meals in lean and obese subjects. *Ann Nutr Metab.* 1987;31:117–25.
82. Jensen AH, Kuhlman DE, Becker DE, Harmon BG. Response of growing-finishing swine to different housing environments during winter seasons. *J Anim Sci.* 1969;29:451–6.
83. Young BA. Cold stress as it affects animal production. *J Anim Sci.* 1981;52:154–63.
84. Berg F, Gustafson U, Andersson L. The uncoupling protein 1 gene (UCP1) is disrupted in the pig lineage: a genetic explanation for poor thermoregulation in piglets. *PLoS Genet.* 2006;2:e129.
85. Mezentseva NV, Kumaratilake JS, Newman SA. The brown adipocyte differentiation pathway in birds: an evolutionary road not taken. *BMC Biol.* 2008;6:17.
86. Overton JM. Phenotyping small animals as models for the human metabolic syndrome: thermoneutrality matters. *Int J Obes (Lond).* 2010;34 Suppl 2:S53–8.