1. Introduction

One of the major goals of evolutionary physiology is to understand the intrinsic and the extrinsic factors that impose limitations on an animal's energy budget (McNab, 2002). Animals cannot expend energy at will and it is well known that a negative relationship exists between the rate of energy expenditure and the duration of activity that an organism is performing (Weiner, 1989; Peterson et al., 1990; Speakman, 2000). In this sense, burst metabolic rates of activity or thermoregulation performed during short periods of time (i.e. minutes, hours) cannot be sustained indefinitely because organisms are not in energy balance during the exertion (Hammond and Diamond, 1997). In fact, an important part of the expenditure is fuelled by the body's reserves, which are depleted while activity is maintained. On the other hand, during longer activity periods (i.e. days or weeks), energy expenditure must be fuelled by concurrent energy intake, which is known as the sustained metabolic rate (SusMR). Specifically, SusMR is defined as a 'time-averaged energy budget that an animal maintains over times sufficiently long that body mass remains constant because time-averaged energy intake equals time-averaged energy expenditure' (Hammond and Diamond, 1997).

An important difference between burst and long-term expenditures concerns the level they can achieve. Rates of expenditures sustained over longer periods are limited to a lower level than rates of expenditure sustained over shorter periods. Specifically, SusMR is almost five times lower than burst expenditures (Bozinovic, 1992; Bundle et al., 1999), and hardly exceeds seven times the resting levels (Peterson et al., 1990). For small mammals in particular, asymptotic ceilings on SusMR could limit individual reproductive effort (since offspring number and quality depends on milk production; Knight et al., 1986; Rogowitz and McClure, 1995; Rogowitz, 1996, 1998), activity (i.e. foraging and escape from predators), thermoregulatory capabilities and survival to long-term cold exposures (Konarzewski and Diamond, 1994; McDevitt and Speakman, 1994a), as well as other ecological processes, such as diet selection, geographical distribution and breeding ranges. This is because...
ceilings on sustainable energy expenditure represent the upper limit below which all energy-consuming activities performed by an individual must be engaged. Thus, given the important ecological and evolutionary consequences that sustained energy budgets have on many aspects of animal life, it is important to determine which factors are imposing ceilings on SusMR.

2. Early Ideas on Energy Budget Limitations

Poo et al. (1939) analysed the changes in weight and protein concentration of different internal organs during pregnancy and lactation in albino rats. As a final conclusion to this work the authors pointed out that whether the decrease in serum, clot and carcass protein is a depletion effect arising because the gastrointestinal tract was mechanically incapable of carrying the quantity of food containing only 16% of protein that was required to meet the increased demand [i.e. a digestive central limitation] is a question that can be answered by observing the effect of foods with higher protein concentrations. If with increase in total protein consumption we no longer find any decrease in the amount of protein allocated to these tissues, the simple depletion hypothesis is validated. But if this decrease is found even when more than adequate quantities of protein are taken, we must look for some other mechanism [i.e. a central non-digestive limitation or a peripheral one].

However, after this work there were no further attempts to determine what imposed a limit to SusMR, and the dominant view until the 1980s was that digestive processes limited energy budgets. This view was based on some circumstantial evidences, such as the existence of a maximal food consumption capacity (see Karasov and McWilliams, 2005) and the experimental evidence of a ‘digestive bottleneck’ (see Jeschke et al., 2002; Karasov and McWilliams, 2005).

However, during the 1960s and 1970s it was observed that digestive features (i.e. gut morphology and histology) of several species change on a seasonal basis, in parallel to alimentary and reproductive cycles (e.g. Davis, 1961; Myrcha, 1964, 1965; Juszczyk et al., 1966; Gebczynska and Gebczynski, 1971; Ankey, 1977). In addition, at the same time experimental studies demonstrated that changes in environmental factors, such as temperature (Geuze, 1971a,b) or diet quality (Miller, 1975; Moss, 1972), produce notorious adjustments in gut attributes. After these works, and the development of optimal digestion models (Sibly, 1981; Penry and Jumars, 1986, 1987), a myriad of studies demonstrated that the digestive system is probably the most reactive system to change in environmental conditions (for a review see Piersma and Lindstrom, 1997; Starck, 1999; McWilliams and Karasov, 2001; Naya and Bozinovic, 2004; Naya et al., 2007). All these studies on digestive flexibility indicate that if there is a digestive limit to SusMR, it is not a rigid, but a highly flexible one (Karasov and McWilliams, 2005).

3. Central, Peripheral or Optimal Design?

Drent and Daan (1980) reviewed the evidence on energetics of reproduction in birds, and reached the conclusion that a ‘prudent parent’ should not allocate
more than four times its basal level of energy expenditure to reproduction. At the same time, Kirkwood (1983) analysed maximum metabolizable energy intake in mammals and birds, and suggested the existence of a shared absolute ceiling for all the species evaluated. Finally, Peterson et al. (1990) reviewed the evidence of metabolic scope (i.e. the ratio between sustained and basal metabolic rate) for 37 species of vertebrates, and found that in all the cases the value was less than 7, and for most of the species it fell between 1.5 and 5. From these seminal papers to the present, there has been an increasing interest in understanding the effect of design constraints on energy budgets (e.g. Weiner, 1992; Speakman, 2000). Three hypotheses have been proposed to explain the physiological limits on energy budgets: (i) the ‘central limitation hypothesis’, where the shared central machinery limits SusMR; (ii) the ‘peripheral limitation hypothesis’, where the energy-consuming machinery limits SusMR; and (iii) the ‘symmorphosis hypothesis’, where the capacity of the central machinery closely matches that of the peripheral tissues.

3.1 The central limitation hypothesis

This hypothesis proposes that SusMR is limited by the central machinery involved in acquisition, processing and allocation of energy, resources and waste products. In this sense, metabolic limits are independent of the way energy is expended. That is, the same metabolic ceiling will be reached regardless of the mode of energy expenditure, and peripheral organs present always an excess capacity. Although there are different basic processes of central limitation (Speakman, 2000), historically, most authors have suggested that the capacity of energy assimilation is the principal limit for sustainable energy budgets. A way to evaluate the presence of metabolic ceilings, and at the same time to determine if they are centrally limited, comes from laboratory studies in which animals fed ad libitum are forced to reach their maximal SusMR under different modes of energy expenditure (e.g. lactation, thermoregulation and activity). If the central machinery is what limits SusMR, metabolic ceilings would reach the same value irrespective of the mode of energy expenditure (but see Bacigalupe and Bozinovic, 2002). However, it should be noted that this procedure does not allow the exclusion of a possible peripheral limitation (see below), because it could happen that by chance, different modes of energy expenditure have equal maximum values. Thus, a way to discriminate between both hypotheses is through a combination of peak energy demands. If central limitation really is the cause of the metabolic ceiling, one would expect a conflict in energy allocation when different high-energy-demanding activities are being performed simultaneously.

3.2 The peripheral limitation hypothesis

This hypothesis proposes that the central processing and transport organs may be able to supply energy and nutrients faster than the peripheral organs can convert and mobilize into work and heat. This implies that SusMR is peripherally limited,
i.e. at the site of energy use. Accordingly, the peripheral limitation hypothesis predicts different metabolic ceilings under different modes of energy expenditure. This is because limits are set by the proper limitations of tissues and organs where the energy is being used, while central organs present an excess capacity (Hammond and Diamond, 1997). Thus, like the central limitation hypothesis, a key way to empirically evaluate peripheral limitations on SusMR is from laboratory studies, in which animals fed ad libitum are pushed to their maximal SusMR under different modes of high-energy expenditure (e.g. lactation, thermoregulation and activity). In addition, in experiments that use a combination of peak energy demands, the peripheral limitation hypothesis predicts no conflict in energy allocation because central organs present an excess capacity.

3.3 The symmorphosis hypothesis

Perhaps organisms do not have excess capacities, and the capacity of central organs to supply energy has evolved to match expenditure capacity in peripheral tissues. This possibility, in which there is no limiting step on SusMR, rather an optimized design of organisms, is called symmorphosis (Taylor and Weibel, 1981). Basically, the principle of symmorphosis states that no extra structure is formed and maintained unless it is required to satisfy an organism’s functional needs (Taylor and Weibel, 1981). Although this principle was first proposed to study the relationship between structure and function in the mammalian respiratory system, it has since been established as a general hypothesis of economic design (Weibel et al., 1998; Weibel, 2000). Optimal design represents an almost perfect match between structure and function (Weibel et al., 1991; Weibel, 1998). As a result, the structural trait becomes the factor that sets the limit of functional performance (Weibel, 1998, 2000). An important prediction of this principle is that if functional needs change, then structural components must change accordingly. This is because the building and maintenance of structures, above what is actually needed, is costly (DeWitt et al., 1998). In the context of physiological limitations on SusMR, the symmorphosis principle predicts a match between central and peripheral organs and tissues. To test for this match, SusMR should be determined under different levels of demand (e.g. −10°C, 0°C and 10°C for SusMR during cold exposure). The next step is to evaluate the adjustment between the different SusMRs obtained, and the morphometric parameters of central and peripheral organs and tissues (e.g. the dry mass of these organs might be considered a good first approximation). Nevertheless, we must keep in mind that a better quantitative approach is necessary to test for symmorphosis (Weibel, 2000).

3.4 Sorting out the evidence

Many studies of mammalian energetics have confirmed that reproduction is the most demanding period in the life of a mammal female (e.g. Bronson, 1989). Moreover, energy expenditure in offspring during lactation is considered the most
demanding period of the reproductive cycle (Millar, 1979; Oftedal, 1984a,b; Sadleir, 1984; Thompson and Nicoll, 1986; Kenagy, 1987; McClure, 1987; Kenagy et al., 1989). In small-sized species, the amount of nutrients and energy that can be supplied from body reserves obtained prior to lactation is restricted, and thus these organisms strongly depend on an increase in food ingestion at this time (Oftedal, 2000). For these reasons, lactation in small rodents has been widely used as a key stressor in the study of limits to energy expenditure (Speakman and Krol, 2005). However, it should be noted that during lactation, considerable amounts of energy are not metabolized by the mothers, but exported as milk (Kenagy et al., 1989; Speakman and Krol, 2005). This determines that utilization of energy at the end of the system (SusMR) does not match sustained energy intake (SusEI), i.e. the variable that is assessed in most of the studies. Hence, in what follows, we will refer mainly to the current evidence on limitation to SusEI (see Speakman and Krol, 2005).

The fact that peak SusMR falls between two and seven times the basal metabolic rate (Drent and Daan, 1980; Kirkwood, 1983; Peterson et al., 1990) was originally interpreted as evidence for the existence of a central limitation to energy budgets, i.e. regardless of the particular mode of energy expenditure, shared features of energy acquisition and utilization limit energy expenditure to a common value. This idea was reinforced by some experimental results obtained during the last decades of the last century. For example, energy assimilation in the Djungarian hamster (Phodopus sungorus) was virtually the same during the peak of cold acclimatization and during lactation (Weiner, 1987). Indeed, a study that combined lactation with locomotor activity (Perrigo, 1987) showed that food intake reached a plateau at high levels of activity, after which mothers cannibalized some of their offspring (Mus musculus) or extended lactation (Peromyscus maniculatus). Finally, an experiment in mice in which litter size was manipulated found that food intake increased with litter size from 5 to 14 pups, but after this value mothers were not able to further increase their food consumption, and consequently, were not able to rear more pups (Hammond and Diamond, 1992). All these results seem to support the hypothesis of a central limitation, probably at the digestive level. However, as we already mentioned, the alternative hypothesis that food intake was peripherally limited cannot be discarded based on these data (Bacigalupe and Bozinovic, 2002; Speakman and Krol, 2005).

Others studies conducted during the same years provided information that was more in accordance with the peripheral limitation idea. For example, in golden-mantled ground squirrels (Spermophilus saturatus) it was observed that, although milk production approached the limit for largest litter size (five pups), mothers were able to increase their energy intake an additional 10% if exposed to cold temperatures (Kenagy et al., 1989). In addition, for Swiss-Webster mice it was demonstrated that energy assimilation rates were two times higher at the peak of lactation at room temperature (Hammond and Diamond, 1992, 1994) than those of virgin females at the peak of cold acclimatization (Konarzewski and Diamond, 1994), and that the effect on food intake of both factors combined was additive, i.e. mothers at 5°C increased their food consumption beyond the values considered the limit at the peak of lactation at room temperature (Hammond et al., 1994). These results suggest that the capacity of the mammary
glands may determine the limit of food consumption during lactation. In order to test this, variation in the number of teats was created surgically while simultaneously varying the number of pups reared, under the rationale that: (i) if the capacity of the mammary gland was limited, then, when mammary tissue was reduced in size, the remaining tissue would be unable to compensate; and (ii) if the capacity of the tissue was centrally limited by the supply of energy, then it would respond to the absence of tissue by expanding its capacity (Hammond et al., 1996). In this experiment it was found that mammary glands were unable to compensate milk production when their size was reduced, again supporting the hypothesis that the system capacity is limited at the site of energy use (i.e. peripherally, Hammond et al., 1996). Finally, three additional lines of evidence also suggested a peripheral limit to energy expenditure. First, contrary to what was observed in Swiss-Webster mice, in the deer mouse (*P. maniculatus*), maximal SusEI during cold exposure exceeded that at the peak of lactation (Koteja, 1996). Second, by manipulating pup numbers and the environmental temperature, Rogowitz (1998) demonstrated that pup demands do not drive the capacity of the mother to deliver milk energy. Third, lactating females fed on low-energy food were able to compensate the deficit by increasing their food intake (Speakman et al., 2001).

Nevertheless, in recent years, the emerging consensus on peripheral limitation on energy expenditure was undermined by a series of studies, conducted by Speakman and co-workers, who evaluated milk production in house mice at thermoneutrality (see Johnson and Speakman, 2001; Krol and Speakman, 2003a,b; Krol et al., 2003). These authors evidenced that, although food intake at 30°C (i.e. within the thermoneutral zone) was lower than at 21°C and 8°C, as predicted by the hypothesis of peripheral limitation, milk production mirrored the pattern of food consumption. This result agrees, at a first glance, with the idea that food intake was driven by pup demands. However, this was also the case because pup growth followed the same trend as food consumption: growth was greater at 8°C than at 21°C, and greater at 21°C than at 30°C. In other words, when these new data are considered together with all the previous evidence, the results can be explained by an extrinsic limitation due to pup demands, a central limitation by the digestive tract or a peripheral limitation by the mammary gland. As an alternative, Krol and Speakman (2003a,b) proposed the heat dissipation limit hypothesis, which states that the limit to SusEI is central and imposed by the capacity of the females to dissipate heat. This idea could explain why, at 21°C, lactation to support and increased litter size, or lactation plus an additional energy demand did not result in increased food intake or milk production (e.g. Koiter et al., 1999; Johnson et al., 2001). It also explains why at lower temperatures, lactating females are able to increase their food intake (e.g. Rogowitz, 1998; Hammond and Kristan, 2000; Johnson and Speakman, 2001), milk production and pup growth (Krol and Speakman, 2003a,b). More recently, the same authors suggested that the capacity to dissipate heat may influence lactational performance, and proposed two additional hypotheses: the seasonal investment hypothesis and the saturated neural control hypothesis (Speakman and Krol, 2005). The first hypothesis proposes that the reproductive value of mice offspring born early in the reproductive season (i.e. under cold temperatures) is higher than
that of offspring born later in the season, and that mothers use ambient tempe-
tures as a cue to determine their investment in offspring. The second hypothesis
states that endocrine stimulation of food intake reaches a maximum during the
latter half of the lactation period, and consequently, food consumption cannot be
augmented whatever sort of manipulation is performed on animals; only ambient
temperature acting via a different signalling route can do that. However, current
data did not offer unequivocal support for any of these hypotheses (Speakman
and Krol, 2005).

4. Concluding Remarks

It has been proposed that different patterns of energy expenditure among species
(i.e. central versus peripheral, and within this latter category, differences in levels
and modes of energy expenditure) could be related to each species’ life-history
strategy (Koteja and Weiner, 1993; Koteja, 1995, 1996; Hammond and Diamond,
1997). Accordingly, there is an implicit consideration that SusMR is adaptive.
However, at this moment, it is difficult to confirm this assertion (but see Koteja
et al., 2000). Empirical data on physiological limitations on energy budgets is
scant. Only a few studies have been explicitly designed to measure SusMR, and
evidence shows that sustained energy expenditure does not exceed seven times
the resting expenditure (Speakman, 2000). This fact raises two important ques-
tions: (i) Why is energy expenditure during long periods only slightly elevated
above resting requirements compared to energy expenditure during short
periods?; and (ii) Do organisms function at their physiological limits (Speakman,
2000)?

The answer to the first question has been associated with the potential decrease
in fitness a mammal may experience if it expends more energy than it routinely
does (Murie and Dobson, 1987; Wolf and Schmidt-Hempel, 1989; Stearns, 1992;
Daan et al., 1996; Finkel and Holbrook, 2000; Speakman, 2000). However, the evi-
dence for this trade-off (i.e. energy expenditure versus fitness) is not conclusive
(Tuomi et al., 1983; Hare and Murie, 1992; Speakman, 2000). Regarding the sec-
ond question, organisms could function at or near their physiological limits, but are
prevented from doing so because of energy limitations imposed by the environment
(e.g. Stenseth et al., 1980; Speakman, 2000). At present, there is no sufficient evi-
dence to offer definitive answers to these questions and neither are we able to con-
clusively identify which physiological factors may impose limits on SusMR. Hence,
there is a need for insightful studies that aim to unravel the type of physiological
limits on SusMR (i.e. central, peripheral or symmorphosis) and the steps at which
these limits occur.

Acknowledgements

We thank OEG and Biomathematic labs (Facultad de Ciencias, Udelar, Uruguay)
for the use of their facilities. This work was funded by FONDECYT 3060046
(Chile) to DEN.
References


Genz, J.J. (1971b) Light and electron microscope observations on the gastric mucosa of the frog {Rana esculenta}: II. Structural alternations during hibernation. Zeitschrift für Zellforschung 117, 103–117.


**Author Query:**

[AU1] Ofedal, 2000 is not in the list.