REVIEW OF NUTRIENT PARTITIONING

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Introduction

Advances in animal productivity during the last century are remarkable, as modern dairy cows can produce more than ten times what their ancestors did just seven decades ago and the annual rate of milk yield increase does not appear to be diminishing (Collier et al., 2005). In addition to simply synthesizing more, the efficiency of producing milk has also markedly improved. Consequently, the inputs (feed, electricity, labor, barn space, etc.) necessary for making milk and the generated waste products per unit of milk produced have obviously decreased (Table 1; Bauman, 2000). This improved production efficiency is critical for sustaining farm economics, consciousness environmental stewardship and for satiating a growing global appetite for high quality protein.

Despite incredible gains in the North American average milk production, there remain notable differences (i.e. > 5,000 kg) in average milk yield/cow between farms (even within farms from the same region and utilizing similar genetics and comparable feedstuffs) and this is likely in part due to farm management differences. However, within herds there is large variability between individual cows even though genetics, diet and management style do not differ. From an on-farm prospective, this is undoubtedly costly because low-producing cows are not as profitable. In addition, the unpredictability is also expensive because cows in a pen are fed based on an expected (average) yield, therefore low and high producing cows are over-fed and under-fed, respectively. As a result, the low producing cows likely put on too much condition and yield in the high producing cows is probably limited by nutrient/energy availability.

The yield variation amongst cows begs the obvious questions: 1) what is the biological basis for differences in production efficiency? and 2) can these physiological systems be manipulated?

Table 1. Performance and efficiency comparisons of Northeast American cows

Variable	Year 1930	 1965	 1999
Performance and Inputs			
Milk yield, kg/d	6.4	17.7	30.9
Milk yield/feed intake, kg/d	0.70	1.26	1.57
Use of net energy intake, %			
Maintenance	70	45	32
Milk synthesis	30	55	68
Animal Waste Products			
Fecal output/milk yield, kg/kg	3.1	1.7	1.4
Urine output/milk yield, L/kg	3.1	1.1	0.6

Adapted from Bauman, 2000.

Sources of potential variation in production efficiency include nutrient digestion and absorption, efficiency of nutrient utilization, maintenance costs and nutrient partitioning. Although digestibility and nutrient absorption are heavily dependent upon dietary manipulation (Tyrrell and Moe, 1975), there appears to be little variability in the extent that which individual cows can digest and absorb a particular diet (Bauman et al., 1985). Likewise, although differences exist in the efficiency of utilizing metabolizable energy for a productive purpose between feedstuffs (i.e. dietary fat vs. fiber) there appears to be little inconsistency between individual cows (Bauman et al., 1985). There are obviously differences in maintenance costs in cows that differ in size and body composition, but the difference between maintenance requirements per unit of metabolic body size is very small and thus it does not appreciably contribute to the overall variation in production efficiency (Bauman et al., 1985; Collier et al., 2005).

The primary source of yield variation between cows (and the principal reason for the annual increase in milk yield/cow [and probably all productive indices since livestock domestication]) is nutrient partitioning. Nutrient partitioning was originally conceptualized by Hamman (1952) and can be broadly described as a change in tissue/system priority at a given plane of nutrition. For example (Table 2), how are metabolizable nutrients and tissue reserves “directed” towards the mammary gland in one animal, but in another animal on the same plane of nutrition those dietary derived nutrients are partitioned into tissue storage? It is the difference in how animals change the hierarchy of tissue/system priority that primarily explains why some cows give more milk, why some growing animals deposit protein at the expense of lipid and why high-producing cows de-emphasize the reproductive system in early lactation (Collier et al., 2005).

Table 2. Example of animal difference in nutrient partitioning

Variable[a]	Cow A	Cow B
Initial body weight (kg)	517	519
Diet intake	Equal	
Live weight change (kg)	+39.1	-51.8
Milk yield (3.5% kg/d)	12.3	26.3

[a] For the first 67 DIM
Adapted from Bauman et al., 1985

The mechanisms responsible for nutrient partitioning include both homeostatic and long-term homeorhetic adaptations that incorporate probably every tissue and physiological system in the body. Some of these homeorhetic changes are mediated by changes in circulating anabolic and catabolic hormones, hormone membrane receptors and intracellular signaling pathways. The coordinated change in how tissues and systems are re-prioritized includes a plethora of hormones (Table 3; and almost certainly ones that have not been discovered yet), but this brief review will primarily concentrate on insulin and somatotropin (growth hormone). For a more extensive description of nutrient partitioning see classic reviews authored by Bauman and Currie, 1980; Bauman et al., 1985; Bell and Bauman 1997; Chilliard et al., 2000 and Collier et al., 2005.

Glucose-Sparing

Understanding the homeorhetic mechanisms responsible for physiological and metabolic adjustments lactating and growing animals initiate during periods of inadequate nutrition provides some insight as to how high producing animals prioritize valued tissues (mammary and muscle) compared to lower producing herd mates when on a high-plane of nutrition. These changes in post-absorptive nutrient partitioning occur to support a dominant physiological state (i.e. milk and skeletal muscle synthesis; Bauman and Currie, 1980) and one-well described homeorhetic strategy is the “glucose sparing” effect that both lactating and growing animals utilize when on a lowered-plane of nutrition.

Lactation: Early lactation dairy cattle enter a unique physiological state during which they are unable to consume enough nutrients to meet maintenance and milk production costs and animals typically enter into negative energy balance (NEBAL; Figure 1; Drackley, 1999). Negative energy balance is associated with a variety of metabolic changes that are implemented to support the dominant physiological condition of lactation (Bauman and Currie, 1980). Marked alterations in both carbohydrate and lipid metabolism ensure partitioning of dietary and tissue derived nutrients towards the mammary gland, and not surprisingly many of these changes are mediated by endogenous somatotropin (Table 3) which naturally increases during periods of NEBAL (Figure 1; Bauman And Currie, 1980).

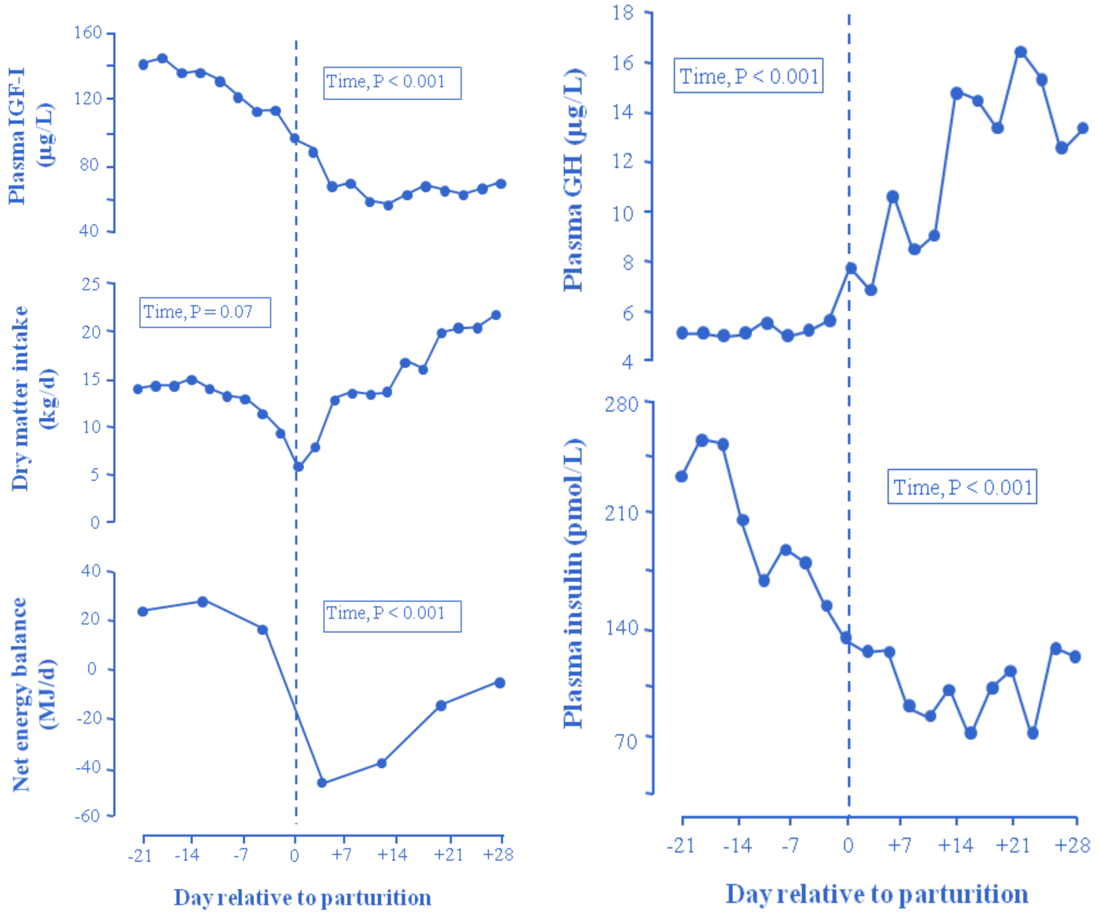

Figure 1. Temporal pattern of whole-animal energetics and key hormones responsible for nutrient partitioning in transitioning lactating Holstein cows. Adapted from Rhoads et al., 2004

During NEBAL, somatotropin promotes non-esterified fatty acids (NEFA) export from adipose tissue by accentuating the lipolytic response to β-adrenergic signals (Figure 2) and by inhibiting insulin mediated lipogenesis and glucose utilization (Figure 3; Bauman and Vernon, 1993). This reduction in systemic insulin sensitivity is coupled with a decrease in circulating blood insulin levels (Figure 1). The reduction in insulin action allows for adipose lipolysis and NEFA mobilization (Bauman and Currie, 1980). Not surprisingly, reduced circulating insulin is also a key mediating factor by which high producing cows partition nutrients away from storage and towards mammary utilization (Figure 4)Increased circulating NEFA are typical in “transitioning” and malnourished cows and represent (along with NEFA derived ketones) a significant source of energy (and precursors for milk fat synthesis) for cows in NEBAL. The severity of calculated NEBAL is positively associated with circulating NEFA levels (Bauman et al., 1988; Dunshea et al., 1990) and it is generally thought that there is a linear relationship (concentration dependant process) between NEFA delivery, tissue NEFA uptake and NEFA oxidation (Armstrong et al., 1961). The magnitude of NEBAL and thus lipid mobilization, in large part explains why cows lose considerable amounts (> 50 kg) of body weight during early lactation.

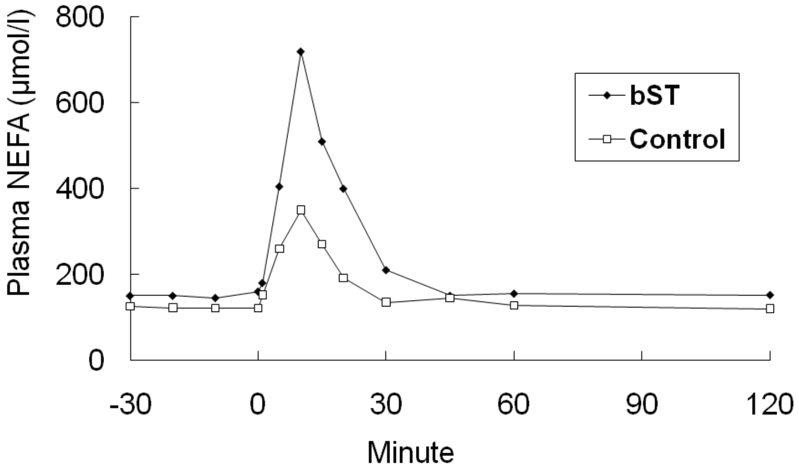

Figure 2. Effects on rbST on the non-esterified fatty acid (NEFA) response to an epinephrine challenge in lactating Holstein cows. Adapted from Sechen et al., 1990.

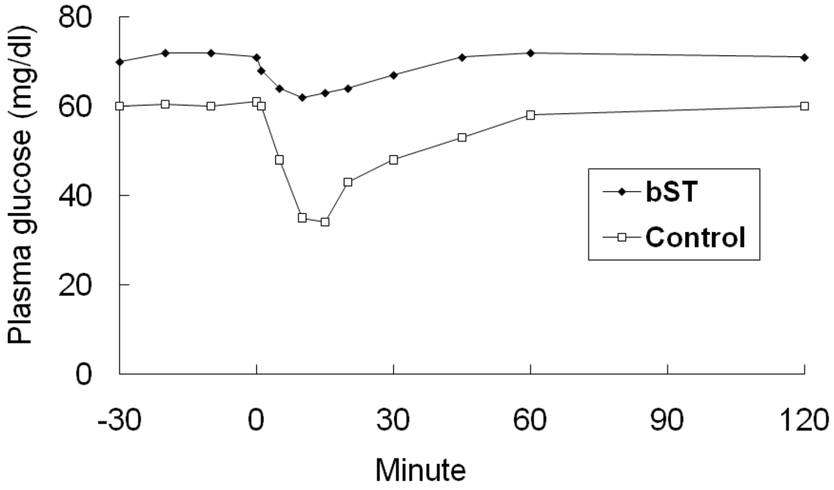

Figure 3. Effects of rbST on the glucose response to an insulin tolerance test in lactating Holstein cows. Adapted from Sechen et al., 1990.

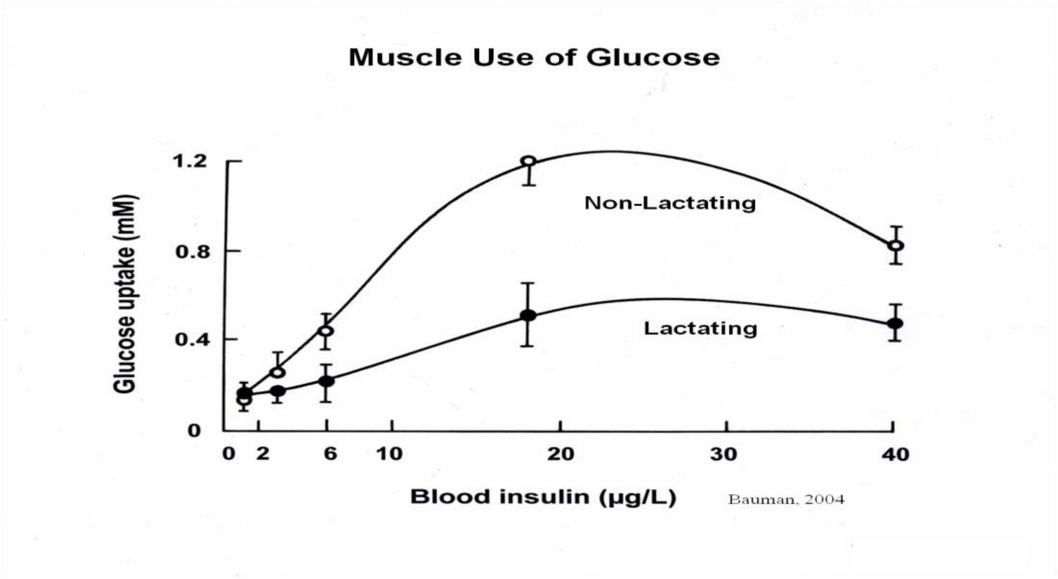

Figure 4. Plasma insulin levels in high and low yielding dairy cows.
Adapted from Bines and Hart (1982).

Post-absorptive carbohydrate metabolism is also markedly altered by NEBAL and this is also, in large part, mediated by reduced insulin action. During either early lactation or inadequate nutrient intake, glucose is partitioned towards the mammary gland and glucose's contribution as a fuel source to extra-mammary tissues is decreased (Bell, 1995). This can be observed when comparing insulin's effectivenesss at stimulating muscle glucose uptake in lactating and non-lacting animals (Figure 5). The early lactation or NEBAL induced hypoglycemia accentuates catecholamine's adipose lipolytic effectiveness (Clutter et al., 1980). This is a key "glucose sparing" mechanism because elevated NEFA levels decreases skeletal muscle glucose uptake and oxidation and this is referred to as the "Randle Effect (Randle, 1998). The fact that insulin simultaneously orchestrates both carbohydrate and lipid metabolism explains why there is a reciprocal relationship between glucose and NEFA oxidation. Ultimately, these are homeorhetic adaptations to maximize milk synthesis at the expense of tissue accretion (Bauman and Curie, 1980). A cow in NEBAL could be considered "metabolically flexible" because she can depend upon alternative fuels (NEFA and ketones) to spare glucose, which can be utilized by the mammary gland to copiously produce milk.

Table 3. Partial list of physiological adaptations that occur in lactating dairy cows.

Process/Tissue	Response
Mammary Gland	Increased number of secretory cells Increased nutrient use Increased blood supply
Food Intake	Increased appetite
Digestive Track	Increased size Increased absorptive capacity Increased rates of nutrient absorption
Liver	Increased size Increased rates of gluconeogenesis Increased glycogen mobilization Increased protein synthesis
Adipose Tissue	Decreased de novo fat synthesis Decreased preformed fatty acid uptake Decreased fatty acid reesterification Increased lipolysis and mobilization
Skeletal Muscle	Decreased glucose utilization Decreased protein synthesis Increased protoleolysis Increased oxidation of NEFA
Bone	Increased Ca and P mobilization
Plasma Hormones	Decreased insulin Increased somatotropin Increased glucagon Increased prolactin Increased glucocorticoids Decreased thyroid hormones Decreased IGF-I
Adapted from Bauman and Currie, 1980; Vernon, 1989, 1998; Chilliard, 1999; Collier et al., 2005.	

Growth: Inadequate nutrient consumption is associated with a variety of metabolic changes implemented to support the synthesis of high priority tissues like skeletal muscle (Van Milgen and Noblet, 2003). Marked alterations in both carbohydrate and lipid metabolism ensure partitioning of dietary derived and tissue originating nutrients towards muscle, and many of these changes are mediated by altered concentrations of anabolic and catabolic signals. One characteristic response is a reduction in circulating insulin coupled with a decrease in adipose insulin sensitivity. Compared to a well-fed pig, the reduction in insulin action allows for adipose lipolysis and NEFA mobilization (Mersmann, 1987). Increased circulating NEFA are typical in restricted-fed animals and represent a significant source of energy. The enhanced fatty acid oxidation during nutrient restriction is a classic strategy to "spare" glucose. Post-absorptive carbohydrate metabolism is also altered by reduced insulin action during feed restriction resulting in reduced glucose uptake by adipose tissue. In adipose tissue, the reduced nutrient uptake coupled with the prolonged net release of NEFA is a key homeorhetic mechanism implemented by malnourished pigs in order to maintain protein synthesis (Vernon, 1992).

Summary

Much of the historical progress in animal productivity and a large part of the current production variability is due to changes in nutrient partitioning. The coordination of nutrient trafficking is an incredibly complex system, but somatotropin and insulin play critical roles in how tissues/systems are reprioritized or de-emphasized during different physiological states. This reprioritization can primarily be described by the enlistment of glucose sparing mechanisms and both insulin and somatotropin play key roles in this adaptation. As the role of other key regulators of nutrient partitioning become clearer, it is likely that those systems will be taken advantage of to accelerate the improvement rate of production efficiency.

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