

Postprint: Evaluation System for Dietary Nutritional Balance and Nutritional-Physiological Status in Peripartum Dairy Cows

Authors: Sun Bofei, Yu Chao, Cao Yangchun, Cai Chuanjiang, Li Shengxiang, Yao Junhu

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Abstract

The perinatal period represents a critical stage in the lactation cycle of dairy cows, encompassing essential physiological processes such as fetal growth and development, health maintenance, mammary gland renewal and repair, and the initiation of lactation. Feeding management during this period is intimately associated with cow health and lactation performance. While research has progressively elucidated the principal physiological and metabolic characteristics of perinatal dairy cows, the evaluation systems for dietary nutritional balance and organismal nutritional-physiological status remain incomplete. Current assessments predominantly rely on single biomarkers to reflect physiological status, which exhibit limited representativeness, and comprehensive index evaluation systems have been seldom applied. This article provides a comprehensive review and discussion of integrated evaluation systems for nutritional balance and nutritional physiology in perinatal dairy cows, aiming to furnish scientific basis and technical reference for further clarifying the patterns of nutritional balance and metabolic characteristics, determining nutrient requirement parameters, and developing refined feeding protocols during the perinatal period.

Full Text

Dietary Nutrient Balance and Physiological Status Evaluation System for Transition Dairy Cows

SUN Bofei¹, YU Chao², CAO Yangchun¹, CAI Chuanjiang¹, LI Shengxiang¹, YAO Junhu^{1*}

¹College of Animal Science and Technology, Northwest A&F University, Yangling 712100, China

²Shangluo Animal Husbandry Industry Development Center, Shangluo 726000, China

Abstract: The transition period represents a critical phase in the lactation cycle of dairy cows, encompassing key physiological processes such as fetal development, health maintenance, mammary gland remodeling, and lactation initiation. Management during this period is intimately linked to cow health and lactation performance. While the primary metabolic characteristics of transition dairy cows have become relatively well-defined through extensive research, comprehensive evaluation systems for dietary nutrient balance and physiological status remain incomplete. Current assessments typically rely on single biomarkers to reflect physiological condition, which lack representativeness, and integrated index evaluation systems have rarely been applied. This review synthesizes and discusses comprehensive evaluation systems for nutrient balance and physiological status in transition dairy cows, aiming to provide scientific foundations and technical references for further elucidating nutrient balance patterns and metabolic characteristics, determining nutritional requirement parameters, and implementing precision feeding strategies.

Keywords: nutrient balance; comprehensive evaluation index; transition dairy cow

The transition period in dairy cows comprises two stages: the prepartum period (21 days before calving) and the postpartum period (21 days after calving). During late gestation, the fetus reaches its maximum size, compressing the rumen and reducing its volume. Concurrent changes in rumen microbial flora and declining function of digestive, metabolic, and transformative organs, coupled with complex neuroendocrine regulation, result in significantly reduced dry matter intake (DMI) [1-2]. Meanwhile, substantial nutrients are required for fetal growth, maternal maintenance, and lactation initiation, leading to markedly increased nutritional demands. Consequently, cows often experience negative balance for multiple nutrients, with negative energy balance (NEB) receiving the most attention, followed by negative protein balance (NPB) [2-3]. To meet these demands, cows adaptively mobilize stored fat, protein, and other nutrients from body tissues for milk synthesis and self-maintenance. Since postpartum DMI recovery lags behind the increase in milk yield, body weight and condition progressively decline during early lactation (Figure 1 [Figure 1: see original paper]), predisposing cows to various clinical and subclinical metabolic diseases that threaten health, reduce lactation and reproductive performance, and may even impact their entire productive lifespan [4].

Figure 1 Dynamic changes in dry matter intake, milk yield, and body weight throughout a complete lactation cycle of dairy cows [5]

Precise assessment of nutrient balance during the transition period forms the foundation for developing nutritional and management strategies. Currently, mature evaluation systems include: (1) the NRC (2001) and Cornell Net Carbohydrate and Protein System (CNCPS) nutritional models; (2) the

Metabolic Glucose (MG) system, which has not yet been applied to transition cow nutrition evaluation; (3) physiological function indicator systems that utilize concentrations of specific metabolites in blood and urine, such as plasma or serum non-esterified fatty acids (NEFA), β -hydroxybutyric acid (BHBA), and 3-methylhistidine (3-MH), to reflect metabolic and health status; and (4) comprehensive index systems that integrate multiple biomarkers to construct composite indices with improved sensitivity and reliability.

1. NRC (2001), CNCPS Nutritional Models, and MG System

The NRC (2001) systematically elaborated the fundamental principles of dairy cow nutrition metabolism, established requirements and feeding management protocols for major nutritional parameters across different breeds, physiological stages, and body conditions, and provided numerous classical models including nutrient balance calculation systems and intake and performance prediction equations. The CNCPS system provides detailed fractionation of dietary carbohydrates and proteins, 充分考虑不同类型和来源碳水化合物和蛋白质的利用率, 更加精确; 整合以上模型, CPM-Dairy software integrates these models and offers evaluation, prediction, and optimization functions, primarily including assessment of dietary nutrient balance, prediction of nutritional requirements, health and production performance, and yields of certain substances [such as microbial crude protein (MCP)], and optimization of feed formulation. To comprehensively evaluate energy supply and demand in the rumen and small intestine, Lu Dexun et al. [6-8] applied systems theory to animal nutrition, constructed a theoretical framework for glucose nutrition regulation in ruminants, and pioneered the concept of MG. MG provides a more accurate indicator, concept, and model for evaluating glucose requirements in dairy cows, though no reports have yet applied the MG system to transition cows. Evaluation of nutrient balance in transition dairy cows should employ the most advanced nutritional indicators, primarily including net energy for lactation (NEL), MG, and metabolizable protein (MP).

1.1 NEL Based on the physiological characteristics of transition cows, energy requirements differ between prepartum and postpartum periods, and energy balance (EB) assessment should be considered separately [9-10]. The prepartum energy balance (EBpre) is calculated as follows:

$$EB_{pre} = NEI - (NE_m + NE_p)$$

Where NEI is net energy for lactation intake (MJ/d), calculated as $NEI = DMI \times \text{dietary energy level (as NEL)}$; NE_m is net energy for maintenance (MJ/d), calculated as $NE_m = \text{metabolic body weight (BW}^{0.75}) \times 0.080$; and NE_p is net energy requirement for pregnancy (MJ/d), calculated as $NE_p = [(0.00318 \times \text{days pregnant} - 0.0352) \times (\text{calf birth weight}/0.45)]/0.218$.

Postpartum energy balance (EBpost) is calculated as:

$$EB_{post} = NEI - (NE_m + NEL)$$

Where $NEL = (0.0929 \times \text{milk fat percentage} + 0.0547 \times \text{milk protein percentage} + 0.0395 \times \text{lactose percentage}) \times \text{milk yield}$.

1.2 MG MG refers to the total amount of glucose available to the animal after digestion, absorption, and transformation of dietary nutrients [7-9], calculated as:

$$MG = POEG + BSEG = 0.09 \times K1 \times Pr + 0.9 \times K2 \times BS$$

Where POEG is glucose produced from ruminal propionate via hepatic gluconeogenesis; BSEG is glucose absorbed from rumen-bypass starch degraded in the small intestine with assistance from glucose transporters; K1 is ruminal wall absorption rate of propionate (%); Pr is propionate production from ruminal fermentation (mmol/d); K2 is small intestinal digestibility of rumen-bypass starch (%); BS is dietary rumen-bypass starch content (g/d); and MG is expressed in g/d.

Additionally, research by Han Fei [11] established methods for measuring ruminal propionate absorption rate, while Lan Xuqing [12] evaluated MG in common dairy feed ingredients, providing methodological foundations and baseline data for MG system development and application.

1.3 MP Similar to NEL, protein balance (PB) assessment in transition cows is divided into prepartum and postpartum periods, though estimation formulas are more complex because small intestinal protein originates from three sources: microbial crude protein (MCP), rumen-undegraded protein (RUP), and endogenous crude protein (ECP), each with corresponding prediction equations.

Prepartum protein balance (PBpre) is calculated as:

$$PBpre = (MPFeed + MPMCP + MPECP) - (MPm + MPP + MPgrowth)$$

Postpartum protein balance (PBpost) is calculated as:

$$PBpost = (MPFeed + MPMCP + MPECP) - (MPm + MPL + MPgrowth)$$

Where MPFeed is MP provided by the diet (g/d), calculated as $MPFeed = DMI \times MP$; MPMCP is MP from MCP (g/d), calculated using CPM-Dairy software; MPECP is MP from ECP (g/d), calculated as $MPECP = 0.4 \times 11.8 \times DMI$; MPm is MP requirement for maintenance (g/d), calculated as $MPm = 4.1 \times BW^{0.5} + 0.3 \times BW^{0.6} + (DMI \times 30 - 0.5 \times [(MCP/0.80) - MCP]) + MPECP/0.67$; MPP is MP requirement for pregnancy (g/d), calculated as $MPP = \{[(0.69 \times \text{days pregnant}) - 69.2] \times (\text{calf birth weight}/45)\}/0.33$; MPL is MP requirement for lactation (g/d), calculated as $MPL = (\text{milk yield} \times \text{milk protein percentage})/0.67$; and MPgrowth is MP requirement for growth, calculated using CPM-Dairy software (NRC [2001] also provides corresponding formulas).

2. Physiological Function Indicators

2.1 Energy Balance Negative energy balance (NEB) during the transition period enhances lipolysis in adipose tissue, releasing large amounts of NEFA into circulation. Some NEFA enters the mammary gland for milk fat synthesis, while another portion enters the liver for energy metabolism. When NEFA are completely oxidized to carbon dioxide (CO₂) and water (H₂O), energy supply is efficient and harmless. However, incomplete oxidation of NEFA yields low energy efficiency and generates large quantities of ketone bodies, primarily BHBA, predisposing cows to ketosis [4,13]. Additionally, high concentrations of NEFA and BHBA can damage hepatocytes and reduce hepatic gluconeogenic capacity [14]. Consequently, blood concentrations of NEFA, BHBA, and glucose are commonly used as markers of energy metabolism in transition cows, along with hormones related to carbohydrate and lipid metabolism (insulin, glucagon, epinephrine, leptin, etc.).

2.2 Protein Balance Body protein mobilization serves as an important substrate source for milk protein synthesis and hepatic gluconeogenesis in transition cows, representing a self-regulatory physiological response to NEB and NPB [15]. 3-MH is a methylated amino acid present in actin and myosin that is released during muscle protein mobilization and degradation. Therefore, 3-MH is widely recognized and applied as a blood marker of protein mobilization in transition cows [3,15-16].

2.3 Liver Function Selection of indicators for assessing liver function in transition cows is based on two aspects: (1) liver function tests from human medicine, and (2) specific physiological metabolism and metabolites unique to transition cows. Commonly used liver function indicators include albumin (ALB), glutamic-pyruvic transaminase (GPT), glutamic-oxaloacetic transaminase (GOT), alkaline phosphatase (AKP), total bilirubin (TBIL), lactate dehydrogenase (LDH), total cholesterol (TC) and its fractions, all measured in plasma or serum. Understanding the biological significance of each indicator is prerequisite for liver function assessment. For example, GOT is an intracellular enzyme located within hepatocytes that is only released when hepatocytes are damaged or ruptured, causing elevated blood GOT activity. Therefore, blood GOT activity is commonly used to reflect liver health status [10,14].

2.4 Body Health Affected by nutrient negative balance, oxidative stress, endocrine changes, and other stressors, transition cows experience varying degrees of immunosuppression, making them susceptible to invasion by pathogenic microorganisms and resulting in various diseases [17]. Indicators commonly used to reflect immune function include concentrations of pro-inflammatory cytokines [interleukin-1 (IL-1), interleukin-2 (IL-2), interleukin-4 (IL-4), interleukin-6 (IL-6), and tumor necrosis factor- (TNF-)] in plasma or serum [13,18], neutrophil phagocytic capacity and oxidative burst activity [19], and peripheral blood T-lymphocyte subsets (CD4+/CD8+) [13]. Cows mobilize body reserves

to alleviate nutrient negative balance, and as calving approaches and occurs, adipose tissue mobilization increases, lipid metabolism intensifies, free radical accumulation increases, and antioxidant capacity declines, predisposing cows to oxidative stress. Plasma or serum total antioxidant capacity (T-AOC), thiobarbituric acid reactive substances (TBARS), and malondialdehyde (MDA) concentrations can reflect antioxidant status [20]. Additionally, activities of glutathione peroxidase (GSH-Px), superoxide dismutase (SOD), catalase (CAT), and paraoxonase 1 (PON1) are important indicators of antioxidant capacity [21], though whether antioxidant enzyme activities alone can truly reflect animal antioxidant capacity remains questionable. Bernabucci et al. [22] found that plasma GSH-Px activity peaked on the day of calving, possibly representing a self-regulatory function to scavenge free radicals by promoting synthesis of related antioxidant enzymes. Therefore, non-enzymatic antioxidants such as vitamins A and E should receive adequate attention and be incorporated into antioxidant evaluation systems [23].

3. Comprehensive Index Evaluation System

3.1 Revised Quantitative Insulin Sensitivity Check Index (RQUICKI)

Due to unique physiological and metabolic characteristics, transition cows are prone to insulin resistance and decreased insulin sensitivity, reducing insulin capacity to regulate glucose and lipolysis [24]. RQUICKI can be used to assess insulin sensitivity in animals and humans; higher RQUICKI values indicate greater insulin sensitivity and lower risk of insulin resistance, calculated as:

$$\text{RQUICKI} = 1 / [\log (\text{NEFA}) + \log (\text{glucose}) + \log (\text{insulin})] \text{ [25-26]}$$

Where plasma or serum NEFA, glucose, and insulin concentrations are expressed in mmol/L, mmol/L, and pmol/L, respectively.

3.2 Liver Activity Index (LAI) To systematically evaluate liver function and body health in transition cows, Trevisi et al. [26] developed the LAI indicator, calculated from plasma or serum ALB (g/L), TC (mmol/L), and vitamin A (g/dL). First, partial indices (PI) for each of the three indicators are calculated at 7, 14, and 28 days postpartum:

$$\text{PI}(\text{ALB},7\text{d}) = (\text{7-day plasma or serum ALB concentration} - \text{herd mean plasma or serum ALB concentration}) / (\text{herd standard deviation of plasma or serum ALB concentration})$$

$$\text{PI}(\text{ALB},14\text{d}) = (\text{14-day plasma or serum ALB concentration} - \text{herd mean plasma or serum ALB concentration}) / (\text{herd standard deviation of plasma or serum ALB concentration})$$

$$\text{PI}(\text{ALB},28\text{d}) = (\text{28-day plasma or serum ALB concentration} - \text{herd mean plasma or serum ALB concentration}) / (\text{herd standard deviation of plasma or serum ALB concentration})$$

$$\text{PI}(\text{ALB}) = [\text{PI}(\text{ALB},7\text{d}) + \text{PI}(\text{ALB},14\text{d}) + \text{PI}(\text{ALB},28\text{d})] / 3$$

PI(TC) and PI(vitamin A) are calculated similarly. LAI is then calculated as:

$$\text{LAI} = [\text{PI(ALB)} + \text{PI(TC)} + \text{PI(vitamin A)}] / 3$$

Subsequent validation revealed that cows with low LAI had significantly higher blood concentrations of NEFA, BHBA, and haptoglobin, more severe body fat mobilization and condition loss, greater inflammatory responses, and significantly reduced lactation and reproductive performance [27], along with lower DMI and energy utilization efficiency [28]. These findings demonstrate that LAI can serve as a sensitive indicator for evaluating energy metabolism and health in transition cows, with a typical range of $-1.5 < \text{LAI} < 1.5$.

3.3 Liver Functionality Index (LFI) The large sample volume and high analysis costs required for LAI measurement often limit its large-scale application. Therefore, Trevisi et al. [29] proposed the LFI concept, which requires fewer samples and lower testing costs, incorporating three indicators: ALB, TC, and TBIL. LFI is more practical, allowing comparison of both within-herd differences and between-farm differences in transition cow management. The calculation formulas are:

$$\text{Subindex of ALB (SI-ALB)} = 50\% \times \text{C3} + 50\% \times (\text{C28} - \text{C3})$$

$$\text{Subindex of TC (SI-TC)} = 50\% \times \text{C3} + 50\% \times (\text{C28} - \text{C3})$$

$$\text{Subindex of TBIL (SI-TBIL)} = 67\% \times \text{C3} + 33\% \times (\text{C3} - \text{C28})$$

$$\text{LFI} = (\text{SI-ALB} - 17.71) / 1.08 + (\text{SI-TC} - 2.57) / 0.43 - (\text{SI-TBIL} - 6.08) / 2.17$$

Where C3 and C28 represent plasma or serum concentrations at 3 and 28 days postpartum, respectively, with ALB, TC, and TBIL concentrations expressed in g/L, mmol/L, and mol/L, respectively.

The LFI range is $-12 < \text{LFI} < 5$. An $\text{LFI} > 0$ indicates appropriate nutrition and management during the transition period and good cow health. Similar to LAI, LFI demonstrates good sensitivity; cows with low LFI exhibit: (1) lower DMI and milk yield, with more severe body condition loss; (2) higher blood haptoglobin and ceruloplasmin concentrations, indicating reduced liver function; and (3) elevated blood NEFA and BHBA concentrations, enhanced lipolysis, increased liver burden, and greater risk of fatty liver and ketosis [30]. Thus, LFI effectively reflects typical physiological characteristics, body condition, and postpartum lactation performance in transition cows.

3.4 Oxidative Stress Index (OSi) Numerous indicators measure oxidative-redox status in dairy cows, including blood T-AOC, MDA concentration, reactive oxygen species (ROS) accumulation, antioxidant enzyme activities, and non-enzymatic antioxidant concentrations. However, the representativeness of single indicators remains controversial, and unified models and methods for evaluating animal antioxidant status are lacking, compromising credibility of comparisons between individuals and groups [17,31-32]. The essence of oxidative stress is an imbalance between oxidants and antioxidants, and only comprehensive consideration of both can truly reflect animal redox status [33-34]. Celi

[32] first proposed in dairy cows that the ratio between pro-oxidants and anti-oxidants could characterize oxidative stress degree and disease risk, with larger ratios indicating increased accumulation of free radicals such as ROS and/or insufficient antioxidants, predisposing cows to oxidative stress. Building on this, Abuelo et al. [31] proposed the oxidative stress index (OSi), calculated as:

$$\text{OSi} = \text{ROS} / \text{SAC}$$

Where SAC (serum antioxidant capacity) is expressed in mol HClO/mL (representing micromoles of hypochlorous acid required to oxidize all antioxidant substances in 1 mL of serum), and ROS is expressed in Carratelli units (CarrU), with 1 CarrU equivalent to the oxidative capacity of 0.08 mg hydrogen peroxide per 100 mL serum. OSi is expressed in CarrU/(mol HClO/mL).

Research indicates that OSi more accurately and precisely reflects antioxidant status in transition cows compared to single indicators, with the most severe oxidative stress occurring immediately after calving. Furthermore, antioxidant supplementation should begin 30 days prepartum [31].

3.5 Transition Cow Index (TCI) The Transition Cow Index (TCI) was developed by American veterinarian Nordlund during 2005-2006 based on extensive data from over 550,000 multiparous cows across more than 4,000 farms. A patent application was filed on March 30, 2006, and granted on February 15, 2011 (Patent No. US7886691B2). TCI has been rapidly promoted throughout the United States and Canada, with global exclusive agency rights held by Cooperative Resources International (CRI) [35-37]. Grounded in Dairy Herd Improvement (DHI) testing, TCI provides scientific foundations and reference indicators for comprehensively evaluating transition cow management. The TCI formula is:

Expected 305-day milk yield for current lactation = (Intercept constant) 1476 + (0.2941 × actual 305-day milk yield in previous lactation) + (155.95 × days in milk at first test day in current lactation) + (-3.7218 × total days in milk in previous lactation) + (calving code value for current lactation) + (calving month value) + (-80.4888 × last somatic cell score in previous lactation) + (3.8618 × dry period days) + (calving code value in previous lactation) + (bovine somatotropin use code value in current lactation) + (breed code value) + (parity code value in previous lactation) + (milking frequency code value in current lactation) + (bovine somatotropin use code value in previous lactation × actual 305-day milk yield in previous lactation) + (milking frequency code value in previous lactation) [35-36].

Note that relevant code values are region- and herd-specific; details can be found in Zhang Tingqing [35].

TCI = Potential 305-day milk yield for current lactation - Expected 305-day milk yield for current lactation

A TCI > 0 or TCI = 0 indicates appropriate transition period management,

good cow health, and the ability to exceed (or meet) the lactation target for the current cycle. A $TCI < 0$ indicates unreasonable management requiring improvement, with cows experiencing health or metabolic problems that may prevent achieving target lactation performance. The coefficients and constants in the TCI formula are based on big data from North American farms; China currently lacks such baseline data, and indiscriminate application may introduce errors and fail to accurately reflect farm management status. During implementation, farm managers should meticulously record information on nutrition, reproduction, veterinary care, and lactation, and strengthen data sharing between farms to build a Chinese dairy cow database.

3.6 Comprehensive Climate Index (CCI) Transition cows are more sensitive to environmental parameter changes and more susceptible to heat stress. The temperature-humidity index (THI) is commonly used to evaluate heat stress, determined by ambient temperature (T_a) and relative humidity (RH):

$$THI = (0.8 \times T_a) + [(RH/100) \times (T_a - 14.3)] + 46.4 \text{ [38]}$$

While widely applied in dairy heat stress management, THI does not account for wind speed (WS) and solar radiation (RAD), limiting its precision. Based on over a decade of continuous research, Mader et al. [39] proposed a novel heat stress evaluation indicator—CCI—which comprehensively considers contributions of T_a , RH, WS, and RAD to heat stress in dairy cows. The calculation formula comprises three correction factors for RH, WS, and RAD, plus T_a :

Relative humidity correction factor (RHCF), wind speed correction factor (WSCF), and solar radiation correction factor (RADCF) are calculated as follows:

$$RHCF =$$

$$WSCF =$$

$$RADCF =$$

Where T_a , RH, RHCF, WS, WSCF, and RAD, RADCF are expressed in $^{\circ}C$, %, m/s, and W/m^2 , respectively.

The final CCI formula is:

$$CCI = T_a + 1.8 \times RHCF + 0.6 \times WSCF + 5.5 \times RADCF$$

CCI provides farm managers with more advanced and precise heat stress evaluation standards, offering scientific foundations for precise heat stress management during the transition period and other physiological stages. Given the complexity of CCI calculations, computer software development should be considered, integrating thermohygrometers, anemometers, and solar radiation meters to create farm heat stress assessment systems that monitor both CCI and THI simultaneously for fully automated real-time monitoring.

4. Conclusion

Transition dairy cows experience negative balance of energy, protein, and multiple nutrients, with declining metabolic function in the liver, rumen, and other organs, weaker antioxidant and immune function compared to other stages, and high susceptibility to metabolic and other diseases that threaten health and limit efficient expression of postpartum lactation performance. Application of NRC (2001) and CNCPS models, the MG system, and CPM-Dairy software can comprehensively evaluate nutrient balance patterns in transition cows. Integration of physiological function indicators and comprehensive index evaluation systems facilitates systematic elucidation of overall metabolic patterns and physiological mechanisms during the transition period, providing theoretical foundations and technical support for determining nutritional requirements and developing more precise nutritional regulation and management strategies.

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Note: Figure translations are in progress. See original paper for figures.

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