Balance Between Dietary Physically Effective Fiber and Grain Rumen Degradable Starch Affects Chewing Activity and Nutrient Apparent Digestibility in Dairy Cows: Postprint

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Date: 2017-10-11T00:00:00+00:00

Abstract

Dietary physically effective fiber is an indicator that expresses the nutritional value of dietary fiber by integrating both physical and chemical characteristics, and it plays a vital role in chewing activity, rumen function, and health status of dairy cows. Rumen-degradable starch contained in grains constitutes the primary energy source for microbial protein synthesis. There exists a certain balance relationship between dietary physically effective fiber and grain-derived rumen-degradable starch. This paper reviews the effects of dietary physically effective fiber and rumen-degradable starch, as well as their combined effects, on chewing activity and apparent digestibility in dairy cows, with the aim of further deepening the understanding of the balanced relationship of dietary carbohydrates.

Full Text

Balance of Dietary Physically Effective Fiber and Cereal Rumen Degradable Starch Affects Chewing Activity and Nutrient Apparent Digestibility in Dairy Cows

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Abstract: Dietary physically effective fiber is an index that expresses the nutritional value of dietary fiber by considering both physical and chemical properties,

playing a crucial role in chewing activity, rumen function, and overall health status of dairy cows. Cereal rumen degradable starch serves as the primary energy source for microbial protein synthesis in the rumen. A certain balance exists between dietary physically effective fiber and cereal rumen degradable starch. This paper reviews the effects of dietary physically effective fiber, cereal rumen degradable starch, and their combined effects on chewing activity and apparent digestibility in dairy cows, aiming to deepen understanding of the carbohydrate balance relationship in diets.

Keywords: physically effective fiber; cereal rumen degradable starch; carbohydrate balance; chewing activity; apparent digestibility; dairy cows

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Carbohydrates constitute the primary energy source in ruminant diets, accounting for 60–70% of dietary composition, and mainly include fibrous carbohydrates (FC) and non-fibrous carbohydrates (NFC). FC is primarily influenced by forage combination effects, type, quality, particle size, and maturity, whereas NFC depends on cereal source, processing method, and ruminal effective degradability. With advancing research on precision feeding of dairy cows, dietary formulation quality is no longer measured simply by the concentrate-to-forage ratio but rather focuses on investigating truly functional nutrients. For instance, research on dietary roughage has evolved from analyzing single chemical components like neutral detergent fiber (NDF) to considering physically effective fiber (peNDF) that accounts for both physical and chemical properties. Similarly, concentrate starch research has progressed to examining cereal rumen degradable starch (RDSG). In recent years, numerous studies have investigated peNDF, RDSG, and dietary combinations both domestically and internationally. This paper employs chewing activity and nutrient apparent digestibility as response parameters to explore patterns in how dietary combinations affect feed intake and digestive performance in dairy cows.

1. Carbohydrate Balance Relationship in Dietary Combinations

Forage quality and level significantly impact dairy cow health and production costs. Evaluation of single forage types has reached a basic consensus with consistent assessment criteria. However, in practical production, forages do not function simply in isolation; positive, zero, or negative combination effects may occur [**?**]. Although many scholars have investigated forage combination effects, no comprehensive consensus has emerged regarding overall performance, cost, and benefit, similar to that for single forage evaluation. This may be attributed to the excessive variety of roughage materials available for ruminants (silage, hay, agricultural or industrial by-products, etc.) and the highly complex combination types. Physically effective fiber refers to the ability of fiber' s physical

characteristics to stimulate animal chewing activity and establish the stratification of rumen contents into two phases. Its primary source is the roughage component in total mixed rations (TMR), varying with roughage type and content, chop length or particle size, and maturity (toughness). Appropriate peNDF ensures rumen fluid pH remains within a certain range and stimulates saliva secretion through chewing activity, thereby maintaining rumen and overall animal health.

Cereal rumen degradable starch refers to starch from cereals that can be utilized and degraded by rumen microorganisms. As the main component of NFC, it serves as the primary substrate for volatile fatty acid (VFA) fermentation, providing energy and glucose for the rumen microbial population. peNDF promotes essential chewing activity, induces feeding and rumination behavior, and stimulates saliva secretion to neutralize acidic substances, while RDSG degradation produces VFAs that supply energy for microbial protein synthesis. Zebeli et al. [**?**] proposed that the balance between peNDF and RDSG represents an important index for assessing rumen health. Through linear regression analysis, when rumen fluid pH > 6.2, the ratio between the two should not be less than (1.45 ± 0.22). Further research on this balance is needed for three reasons: First, some experimental data employ single-factor analysis with single forage sources, yet forage combinations in practical production often exhibit combination effects, making the narrow focus on forage type scientifically inadequate. Second, some studies analyze only rumen fluid pH data without incorporating other indicators (such as chewing activity and nutrient apparent digestibility) as response parameters, and the critical threshold values for rumen fluid pH reflecting health status remain controversial. Third, numerous studies have investigated peNDF, RDSG, and forage grading index (GI) as single factors, but fewer have explored carbohydrate balance relationships.

2. Factors Affecting Chewing Activity in Dairy Cows

Chewing activity includes two stages: eating and rumination, where total chewing time = eating time + rumination time.

2.1. Forage peNDF

Forage can be manipulated to regulate peNDF through various methods: altering chop length (long, short, chopped), changing sources (hay, corn silage, agricultural or industrial by-products), selecting particle toughness or size (early bloom, full bloom, or mixing time), and adjusting forage proportions. Li et al. [**?**] used alfalfa hay as the sole forage source and regulated peNDF content by changing alfalfa hay length, finding that as dietary peNDF content increased, both eating and rumination time in dairy goats increased significantly, with highly significant effects. Moreover, the time required for eating, rumination, and total chewing per unit of important nutrients [dry matter (DM), NDF, and peNDF] changed significantly, likely because pronounced fluctuations in alfalfa hay particle size substantially altered chewing behavior. Kammes et al. [**?**] changed

forage sources to alter peNDF, comparing alfalfa hay and orchardgrass as sole forages for mid-lactation dairy cows, and found no significant changes in eating time, rumination time, or total chewing time between the two treatments. The effects of each important nutrient content (DM, NDF, and peNDF) on eating, rumination, and total chewing time were also not significant, suggesting that changing forage sources may have relatively weaker effects on chewing activity. Ramirez et al. [**?**] altered peNDF by using different forage particle sizes and found that, at the same nutritional level, the high-particle-size forage group had significantly longer eating and rumination times than the low-particle-size group, with highly significantly longer total chewing time. These results likely occurred because forage particle size exerts relatively obvious effects during feed intake and rumination in dairy cows, though such data are scarce or rarely applied in practice due to difficulties in measuring forage particle size (e.g., inconsistent mixing uniformity). Zebeli et al. [**?**] used a two-factor design changing both forage proportion and length to alter peNDF in late-lactation dairy cows and found that the high-forage-proportion and long-forage group had significantly higher eating, rumination, and total chewing times than other groups, though no interaction effect on chewing activity was observed. Current research indicates that altering forage peNDF can directly affect dairy cow chewing activity, with varying effects depending on the modification method.

2.2. RDSG

NFC serves as an energy source for rumen fermentation and microbial protein synthesis, with RDSG as its main component adjustable through cereal source (barley, wheat, etc.) and processing method (grinding, steam-flaking, etc.). Lechartier et al. [**?**] formulated six different dairy cow diets with varying RDSG content by selecting different cereal sources for mid-lactation cows and found that the high-RDSG group had highly significantly lower rumination and total chewing times than the low-RDSG group, while eating time did not differ significantly. The significant differences in rumination and chewing time likely occurred because high dietary RDSG content affects rumination far more than feed intake. RDSG changes primarily influence digestion and degradation after entering the mouth and rumen rather than palatability, which explains why RDSG does not affect chewing activity in dairy cows and goats as directly as forage peNDF. Research indicates that dietary RDSG content for high-producing dairy cows should be 5.5–29% (DM basis), with RDSG intake of 1.2–6.6 kg/d [**?**]. Under conditions of similar peNDF but different NFC degradability, ruminant chewing activity differs substantially [**?**], demonstrating that RDSG participates in and influences dietary regulation of ruminants. Forage peNDF is not the sole determinant affecting dairy cow chewing activity, necessitating combined consideration of both peNDF and RDSG.

2.3. Dietary Carbohydrate Balance Relationship

Zebeli et al. [**?**] expressed the interaction between peNDF and RDSG as a ratio, while Yao [**?**] used alternative representations [peNDF to RDSG, forage neutral detergent fiber (FNDF)/rumen degradable starch (RDS)], where peNDF exists in two forms retained on 8.00 mm and 1.18 mm sieve screens. Although numerous studies have calculated peNDF and RDSG individually, comprehensive statistical data for both are scarce, leading to incomplete data analysis, though the essence lies in different carbohydrate dietary combinations. Multiple studies have conducted various dietary combinations by changing forage sources, cereal sources, forage length and particle size, grain processing methods, and different roughage and cereal contents \cite{10–17}. Comparisons across different processing methods (coarse vs. fine grinding), concentrate-to-forage ratios (high vs. low), and chop lengths (long vs. short) revealed that when forages included alfalfa silage, barley silage, and alfalfa hay, and cereals included barley, corn gluten meal, soybean meal, and rapeseed meal, increased rumination time and total chewing time were not affected by barley processing method, and barley grain size showed no potential to promote chewing in dairy cow diets [**?**]. In a factorial design examining concentrate-to-forage ratio and forage particle size, both factors significantly affected rumination time but not eating time, with interactive effects on eating and rumination times but not on total chewing time [**?**]. However, no consistent patterns emerged for eating and rumination time per single nutrient (DM, NDF, peNDF, etc.), possibly because different dietary combinations result in varying digestion rates within animals. When corn silage served as the sole forage, three diets with peNDF contents of 11.5%, 10.3%, and 8.9% showed no significant differences in eating and rumination times, though total chewing time increased significantly with increasing peNDF content. Increased intake of long forage particles did not affect DM and NDF intake [**?**]. Using the same experimental method but replacing corn silage with barley silage yielded different results: three diets with peNDF contents of 13.8%, 11.8%, and 10.5% significantly affected rumination and total chewing times, which increased with peNDF content, while eating time remained unchanged [**?**]. Different forage sources significantly affected dairy cow chewing activity, though the overall increase in peNDF content may also have contributed to these divergent results. In two similar trials using corn silage as the sole forage with steam-flaked barley or cracked dried corn as grain sources, changing grain source did not significantly affect eating time. In the corn grain trial, both concentrate-to-forage ratio and forage length significantly affected total chewing time, whereas in the barley group, only concentrate-to-forage ratio had a significant effect.

In summary, various dietary combinations created by altering forage sources, cereal sources, forage length and particle size, grain processing methods, and different roughage and cereal contents have produced different effects on dairy cow chewing activity. Based on current research, with chewing activity as the response parameter, dietary influencing factors rank as: forage length or particle size $>$ cereal type $\geq$ forage source $>$ grain processing method.

3. Factors Affecting Dietary Nutrient Apparent Digestibility

Dietary nutrient apparent digestibility is an indicator of nutrient digestion in the animal' s gastrointestinal tract, serving as a response parameter that simply, directly, and intuitively reflects dietary digestion within animals.

3.1. Forage peNDF

Stojanovic et al. [**?**] combined alfalfa forage with corn silage and regulated four different peNDF levels (21.41%, 20.22%, 19.21%, and 16.80%) by changing forage length. When fed to early-lactation dairy cows, the 19.21% peNDF group showed highly significantly higher apparent digestibility of crude protein (CP) and ether extract (EE) than the other three groups. Behgar et al. [**?**] adjusted forage source (alfalfa and soybean hulls) and particle size (coarse vs. fine) to alter peNDF for early-lactation cows and found that the alfalfa-fine combination diet had significantly higher apparent digestibility of organic matter (OM) and NDF than other combinations. Soybean hulls had adverse but non-significant effects on nutrient apparent digestibility. Zebeli et al. [**?**] altered peNDF by changing forage quality (high vs. low) for dry cows and found that the high-quality forage group had significantly higher apparent digestibility of DM, CP, NDF, OM, and peNDF than the low-quality group. Alamouti et al. [**?**] adjusted peNDF by changing alfalfa hay length and forage quality for mid-lactation cows and found no significant differences in dietary DM, OM, CP, or NDF apparent digestibility among groups, though the short-length, low-quality group showed a decreasing trend in whole-tract apparent digestibility. In summary, forage can regulate peNDF through source, length, and proportion, but when feeding cows at different stages (early, mid, late lactation, and dry period), forage source quality exerts more important effects on nutrient apparent digestibility.

3.2. RDSG

Silveira et al. [**?**] adjusted three RDSG levels through different proportions of barley (steam-flaked) and corn (cracked dried) as the base, feeding early-lactation cows and finding that the high-RDSG group had highly significantly higher apparent digestibility of starch and EE than the low-RDSG group. Castillo-Lopez et al. [**?**] adjusted RDSG through dried distillers grains with solubles (DDGS) content in rumen-fistulated cattle and found higher nutrient apparent digestibility in the high-RDSG group. However, in Kammes et al. [**?**], when forage peNDF content differed substantially, whole-tract nutrient apparent digestibility also differed. Poorkasegaran et al. [**?**] adjusted RDSG using different cereal sources (barley, corn, and wheat) and found higher nutrient digestibility in the low-RDSG group, possibly due to different forage NDF contents. Cereals can adjust RDSG through processing form, content proportion, and different sources, indicating that single cereal factors are important but not sole determinants of nutrient apparent digestibility, necessitating combined investigation of peNDF and RDSG.

3.3. Dietary Carbohydrate Balance Relationship

Gehman et al. [**?**] used corn silage, alfalfa hay, and mixed hay as forage sources and regulated the peNDF to RDSG relationship through different inclusion levels of wet corn distillers grains for mid-lactation cows, finding that the high-level wet distillers grains group had highly significantly higher apparent digestibility of DM, NDF, NFC, and CP than other groups. Different dietary formulations showed substantial differences in digestibility, likely due to the diversity, high fermentability, and good palatability of feed combinations using multiple ingredients. However, Castillo-Lopez et al. [**?**] used the same experimental design with different inclusion levels of dried corn distillers grains for lactating cows and obtained very different whole-tract nutrient apparent digestibility results compared to wet distillers grains, with no significant differences among groups in their trial. This may indicate that RDSG exerts more important effects on nutrient apparent digestibility than forage peNDF. Yang et al. [**?**] used barley silage as the sole forage without other hays, feeding lactating cows with barley meal and steam-flaked corn as starch sources, and found no significant differences in dietary nutrient apparent digestibility among groups, with relatively low digestion levels, suggesting that single-feed-ingredient combinations without quality forage combinations are not very effective. Nasrollahi et al. [**?**] used different cereal sources and forage particle lengths with alfalfa hay and corn silage forage combinations for mid-lactation cows and found that cereal particle length more directly affected dietary nutrient apparent digestibility. Many types of dietary combinations can be achieved through forage source or type, length or particle size, quality level, and cereal source, proportion, and processing method, or through different TMR mixing times, all regulating carbohydrate balance by changing peNDF and RDSG. Regarding nutrient apparent digestibility, RDSG may more directly and significantly affect dietary nutrient digestion within animals.

In summary, chewing activity and nutrient apparent digestibility as response parameters can reflect how different dietary combinations affect feed intake, digestion, absorption, and utilization in dairy cows (early, mid, late lactation, and dry period). Considering forage peNDF or RDSG alone is not the decisive factor affecting dietary quality; their combination should be considered for dietary carbohydrate balance. With chewing activity as the response parameter, dietary combination influencing factors rank as: forage length or particle size $>$ cereal type $\geq$ forage source $>$ grain processing method. With nutrient apparent digestibility as the response parameter, RDSG may more directly and significantly affect dietary digestion within animals. While single-factor research on dietary carbohydrate balance relationships is abundant, similar existing experimental data should be integrated for meta-analysis to increase parameter numbers and explore quantitative indicators of different carbohydrate balance relationships under the same dietary combination and the same carbohydrate relationship across different dietary combinations.

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