3) CARBOHYDRATE METABOLISM IN DAIRY COWS

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TYPES OF CARBOHYDRATES

Carbohydrates are the most important source of energy and the primary precursors of fat and sugar (lactose) in cows' milk. The microorganisms living in the rumen allow the cow to obtain energy from fibrous carbohydrates (cellulose and hemicellulose) which are bound with lignin in plant cell walls or fiber. Since fiber is bulky it is retained in the rumen where the cellulose and hemicellulose are fermented slowly. As plants mature, the lignin content of fiber increases and the extent of cellulose and hemicellulose fermentation in the rumen decreases. Fiber in the form of long particles is essential to stimulate rumination. Rumination enhances the breakdown and fermentation of fiber. It stimulates ruminal contraction, and it increases the flow of saliva to the rumen. Saliva contains sodium bicarbonate (baking soda) and phosphate salts which help to keep the acidity (pH) of the rumen content almost neutral. Rations lacking fiber generally result in a low percentage of fat in the milk and contribute to digestive disturbances (e.g., displaced abomasum, rumen acidosis).

Non-fibrous carbohydrates (starches and simple sugars) are fermented rapidly and almost completely in the rumen. Non-fibrous carbohydrates increase the energy density of a diet, which improves the energy supply and determines the amount of bacterial protein produced in the rumen. However, non-fibrous carbohydrates do not stimulate rumination or saliva production and, in excess, they may impede fiber fermentation.

Thus, the balance between fibrous and non-fibrous carbohydrates is important in feeding dairy cows for efficient milk production. Figure 1 summarizes the transformation of carbohydrates in various organs. In a lactating dairy cow, the rumen, the liver and the mammary gland are the major organs involved in the metabolism of carbohydrates.

VOLATILE FATTY ACID PRODUCTION IN THE RUMEN

During ruminal fermentation, the population of microorganisms (chiefly bacteria) ferments the carbohydrates to produce energy, gases (methane - CH₄ and carbon dioxide - CO₂), heat, and acids. Acetic acid (vinegar), propionic acid and butyric acid are volatile fatty acids (VFA) and make up the majority (>95%) of the acids produced in the rumen (Table 1). Also, the fermentation of amino acids produces some acids called iso-acids. The energy and the iso-acids produced during fermentation are used by the bacteria to grow (i.e., primarily to synthesize protein). The CO₂ and CH₄ are eliminated through belching, and the energy of the CH₄ is lost. Unless heat is necessary to maintain body temperature, the heat produced during fermentation is dissipated. The VFA, end-products of microbial fermentation, are absorbed through the rumen wall.
Figure 1: Overview of carbohydrate metabolism in dairy cows
Most of the acetate and all the propionate are transported to the liver, but the majority of butyrate is converted in the rumen wall to a ketone body called $\beta$-hydroxybutyrate. Ketones, are important sources of energy (fuel for combustion) for most tissues in the body. Ketones come primarily from the butyrate produced in the rumen, but in early lactation, they also come from the mobilization of adipose tissue.

**GLUCOSE PRODUCTION IN THE LIVER**

Most of the propionate is converted to glucose by the liver. In addition, the liver can use amino acids for glucose synthesis. This is an important process because there is normally no glucose absorbed from the digestive tract and all the sugar found in the milk (about 900 g when a cow produce 20 kg of milk) must be produced by the liver. An exception arises when cows are fed large amounts of concentrates rich in starch or a source of starch resistant to ruminal fermentation. Then, the starch that escaped fermentation reaches the small intestine. The glucose formed during intestinal digestion is absorbed, transported to the liver and contributes to the supply of glucose to the cow.

Lactate is another possible source of glucose in the liver. Lactate is found in well preserved silages, but lactate production in the rumen occurs when there is excess starch in the diet. This is undesirable because the rumen environment become acidic, fiber fermentation stops and in extreme cases the cow stops eating.

### Table 1: Volatile fatty acids produced by ruminal fermentation

<table>
<thead>
<tr>
<th>Name</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic</td>
<td>CH$_3$-COOH</td>
</tr>
<tr>
<td>Propionic</td>
<td>CH$_3$-CH$_2$-COOH</td>
</tr>
<tr>
<td>Butyric</td>
<td>CH$_3$-CH$_2$-CH$_2$-COOH</td>
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**LACTOSE AND FAT SYNTHESIS IN THE UDDER**

During lactation, the mammary gland has a great need for glucose which is used primarily for the formation of lactose (milk sugar). The amount of lactose synthesized in the udder is closely associated with the amount of milk produced per day. The concentration of lactose in milk is relatively constant and water is added to the amount of lactose produced by the secretory cells until the lactose concentration is about 4.5%. Thus, milk production in dairy cows is strongly influenced by the amount of glucose that can be derived from the propionate produced in the rumen.

Glucose is converted to glycerol which is used as the "backbone" of milk fat synthesis. Acetate and $\beta$-hydroxybutyrate are used for the formation of the fatty acids that are attached to glycerol to form milk fat. The mammary gland synthesizes saturated fatty acids that contain from 4 to 16 carbons (short chain fatty acids). About half of milk fat is synthesized in the mammary gland. The other half comes from the lipids in the diet, including a small amount of unsaturated fatty acids with more than 18 carbons (long chain fatty acids).

The energy required for the synthesis of fat and lactose in the udder comes from the combustion of ketones, but acetate and glucose may also be used as energy sources in the cells of many tissues.

**THE EFFECT OF DIET ON RUMEN FERMENTATION AND MILK YIELD**

The source of carbohydrates in the diet influences the amount and ratio of VFA produced in the rumen. The microbial population converts the fermented carbohydrates to about 65% acetic acid, 20%
propionic acid and 15% butyric acid when rations contain a large proportion of forages. In this case, the supply of acetate may be adequate to maximize milk fat production, but the amount of propionate produced in the rumen may limit the amount of milk produced because of limited supply of glucose (especially in early lactation).

The non-fibrous carbohydrates (present in many concentrates) promote the production of propionic acid whereas the fibrous carbohydrates (present primarily in forages) stimulate the production of acetic acid in the rumen. In addition, the non-fibrous carbohydrates yield more VFA (i.e., more energy) because they are fermented faster and more completely.

Thus, feeding concentrates usually result in an increased VFA production and an increased percentage of propionate at the expense of acetate (Figure 2). When large amounts of concentrates are fed (or when forages are finely ground), the percentage of acetic acid may drop below 40%, while the percentage of propionic acid may increase above 40%. Milk production may be increased because of the increased supply of glucose coming from propionate, but acetic acid for fat synthesis may be in short supply. In general, this shortage of acetic acid is associated with reduction in fat production and a low percentage of fat in the milk. In addition, excess propionate relative to acetate makes the cow use the available energy for fatty tissue deposition (body weight gain) rather than milk synthesis.

Thus, excess concentrates in the ration may lead to fat cows. Continued feeding of this type of ration may have a detrimental effect on the health of the cow, which is more likely to have a difficult calving and to develop fatty liver or ketosis. On the other hand, not enough concentrate in the ration limits energy intake, milk production and milk protein production.

In summary, changes in the proportion of forage and concentrate in the diet has a profound effect on the amount and the percentage of each VFA produced in the rumen. In turn, the VFA strongly influence:

- Milk production;
- Milk fat percentage;
- The efficiency of conversion of feed to milk;
- The relative value of a ration for milk production as opposed to fattening.