TechNote 5

Carbohydrate metabolism

IN THIS TECHNOTE

Carbohydrates make up a large proportion of plant dry matter (DM) and are the major energy source for dairy cows. They are also the primary precursor for milk lactose and fat synthesis. In a lactating dairy cow, the rumen, liver and mammary gland are the main organs involved in carbohydrate digestion and metabolism.

5.1 Rumen fermentation

There are two main carbohydrate groups in feed: structural (cellulose and hemicellulose) and non-structural (soluble sugars and starches). These different carbohydrate types have different chemical bonds joining the sugar molecules together; however, the ruminant has microbes that can digest these bonds. The microbes break down the carbohydrates into simple sugars and then use these sugars for their own energy to grow and multiply. During this fermentation process, the microbes produce end products, which include gases, heat and volatile fatty acids (VFAs; Table1).

Table 1. *The end products of microbial fermentation of carbohydrates.*

End product	Function
Gases **carbon dioxide (CO_2) and methane (CH_4)**	The gases are expelled via belching and energy as methane is lost.
Heat	Unless heat is needed to increase the body temperature of the cow, heat energy is dissipated and lost.
Volatile fatty acids (VFAs)	The most important end products are VFAs; as they provide the cow with energy and affect performance and milk production.

For more details see TechNote 3: What's in a feed, and online eLearning activity: The role of carbohydrate; dairynz.co.nz/feedright-module-4.

5.2 Types of volatile fatty acids

Three main VFAs are produced from carbohydrate fermentation:

- acetic acid, as acetates,
- butyric acid, as butyrates,
- propionic acid, as propionates.

(Lactic acid, as lactates, is also produced in small quantities).

The proportion of each VFA produced, and the speed at which they are produced, depends on the carbohydrate source.

Soluble sugars, such as in molasses or fodder beet, are rapidly digested by rumen microbes and butyrate is the primary VFA produced. In contrast, starches, as in cereal grains and by-products, and structural carbohydrates, such as in good quality pasture, take longer to digest. The primary VFA produced from fermentation of starch is propionate, whereas, when structural carbohydrates are fermented, acetate is the predominant VFA produced. The impact that these VFAs have on milk production is summarised in Figure 1 and discussed in more detail in the following sections.

Figure 1. *The impact of the type of carbohydrate on VFA production and milk composition.*

CARBOHYDRATE TYPE		FEED TYPE	KEY VOLATILE FATTY ACID	MILK COMPOSITION
STRUCTURAL	HEMICELLULOSE CELLULOSE	PASTURE SOYA HULLS SILAGE	ACETATE	↑ MILK FAT
NON- STRUCTURAL	STARCH	CEREAL GRAINS BY-PRODUCTS	PROPIONATE	↑ MILK PROTEIN & VOLUME
	SUGARS*	MOLASSES FODDER BEET	BUTRATE PROPIONATE	↑ MILK FAT

**Changes in milk composition with the addition of sugars vary depending on the base diet.*

5.2.1 Acetate

Acetate is the primary VFA produced by the rumen microbes that ferment structural carbohydrates, such as in forages (Figure 2). The majority of the acetate is absorbed through the rumen wall, into the blood and then the liver. A small portion of acetate (~20%) that reaches the liver is oxidised, while the remainder passes through into the peripheral circulation (Figure 2). Once in the peripheral circulation, it is partitioned to the mammary gland, adipose (fat) tissue or muscle, depending on the energy status of the dairy cow.

Fat production

Acetate is the primary building block used to synthesise fatty acids. The acetates are joined together by enzymes to produce fatty acid chains that contain up to 16 carbons. These fatty acids are referred to as short or medium chain fatty acids. They are connected to a glycerol backbone (formed from glucose) to produce triglycerides that are secreted as milk fat.

In the lactating cow, acetate is primarily partitioned to the mammary gland to synthesise the short and medium chained fatty acids that make up about 60% of the fat secreted in milk. Longer chain fatty acids i.e. fatty acids that contain 16 carbons or more generally come from pre-formed fatty acids from the diet or mobilisation of body tissue.

In a cow gaining body condition, acetate will also be partitioned to adipose tissue, to synthesise fat for storage, and to muscle to provide energy for protein production.

5.2.2 Butyrate

Butyrate is the primary VFA produced by the rumen microbes that ferment sugars, e.g. from molasses or fodder beet (Figure 2).

Ketone body production

Butyrate is converted in the rumen wall to ß-hydroxybutyrate (BHBA): a ketone body that can be used by most tissues as an energy source. When the cow is in a state of negative energy balance, BHBA can also be produced in the liver from fatty acids that have been mobilised from body tissue.

Fat production

Butyrate is also a building block for fatty acids, however, it contributes only 8% of the total carbons in milk fatty acid chains (the remainder comes from acetate).

5.2.3 Propionate

Propionate is the primary VFA produced by the rumen microbes that ferment starch (Figure 2). Starch is high in feeds such as cereal grains e.g. barley, maize grain and wheat. All of the propionate is absorbed through the rumen wall and is transported to the liver. In the liver, most of the propionate is converted to glucose in a process called gluconeogenesis. This is a very important process in the dairy cow as ruminants do not absorb sugars straight from the rumen, but rather have to synthesise all of their required glucose in the liver.

> The dairy cow produces all of the glucose that she needs in her liver. No glucose is absorbed straight from the rumen.

Ruminants only have a limited capacity to absorb glucose post-ruminally. If any starch or sugar passes through to the small intestine, only a small amount can be absorbed, and transported to the liver. Therefore, post-ruminal absorption of glucose only makes a minimal contribution to the large glucose pool in the liver.

Lactose production

Glucose is the precursor for lactose, which is the major carbohydrate secreted in milk. Lactose acts to control milk volume by balancing the amount of water in the mammary gland lumen and the mammary gland secretary cells. This means the volume of milk produced each day is closely associated with the amount of lactose synthesised, which in turn is dependent on the amount of glucose produced in the liver.

Fat production

Butyrate can also be used as a building block to produce fatty acids that are secreted in milk; however, it only contributes to a small portion (about 8%) of the total carbons in milk fat (the majority of carbons come from acetate).

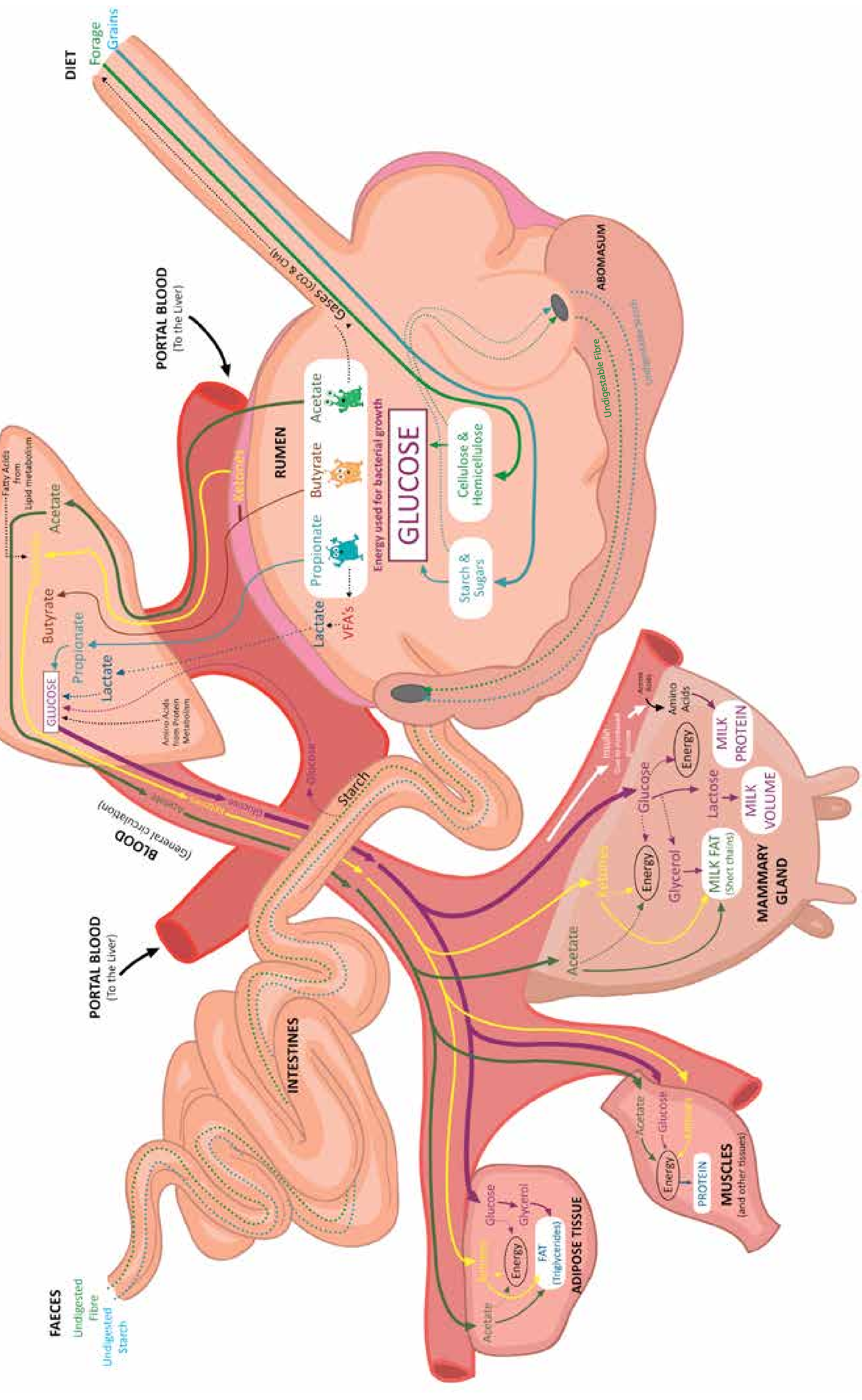
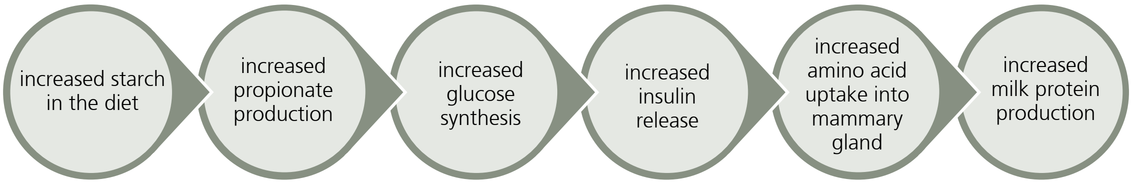


Figure 2. Carbohydrate metabolism in the dairy cow.

Milk protein production

Propionate levels influence the amount of milk protein synthesised by the cow. Greater propionate production increases glucose production which in turn increases the secretion of insulin, a hormone that regulates blood glucose concentrations. Insulin also regulates amino acid uptake by the mammary gland. Therefore, greater propionate production increases milk protein production (Figure 3).

Figure 3. *Steps leading to increased milk protein production.*

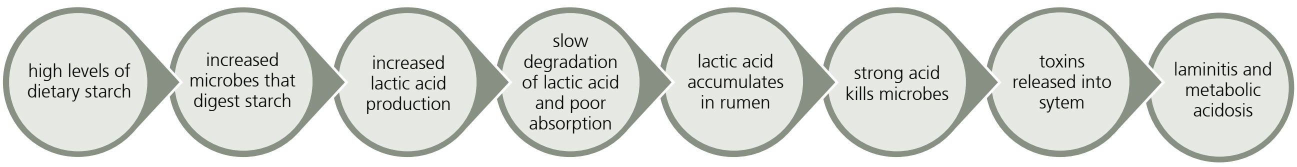


5.2.4 Lactate

Lactate is produced during microbial fermentation when there are high levels, or quick introduction of, starch in the diet (Figure 2). Normally, only a small amount of lactic acid is produced in the rumen and this acts as a precursor for glucose synthesis in the liver. However, if there are high levels of starch in the diet, or if it is introduced too quickly, the microbes that digest this starch multiply rapidly and produce more lactic acid (Figure 4). In contrast, the microbes that degrade lactic acid are very slow to respond, taking weeks to build up in the rumen. In addition, lactic acid is poorly absorbed from the rumen, so lactic acid begins to accumulate in the rumen. This creates a spiral effect. Because lactic acid is a stronger acid than the other VFAs, it causes rumen pH to drop rapidly, which favours microbes that produce lactic acid, while inhibiting those that degrade it.

Consequently, more and more lactic acid accumulates in the rumen. The strong acid environment attacks the rumen wall, reduces rumination and inactivaties or kills the microbes, resulting in a disorder known as rumen acidosis. Toxins released when the microbes die are absorbed systemically. If the amount of toxins absorbed exceeds the liver's ability to metabolise them, this can adversely affect many other parts of the body, e.g. the hoof wall, causing laminitis, and can result in metabolic acidosis and even death.

Figure 4. *Steps involved in rumen acidosis.*



Grazing cows are tolerant to a lower rumen pH, compared with cows fed a total mixed ration or high levels of supplement. This is due to the different carbohydrates, rumen microbial populations and subsequent fermentation products resulting from the different diets. With a pasture diet, acetate (acetic acid) is the primary acid produced and even if the production of lactic acid increases as rumen pH drops, lactic acid only accounts for a very small proportion (1%) of total acids produced in the rumen. Thus even at low rumen pH levels, the amount of lactic acid produced is well below levels associated with ruminal, or sub-acute ruminal acidosis.

Compared with cows fed a total mixed ration or high levels of supplement, grazing cows can tolerate a lower rumen pH, with no detrimental effects.

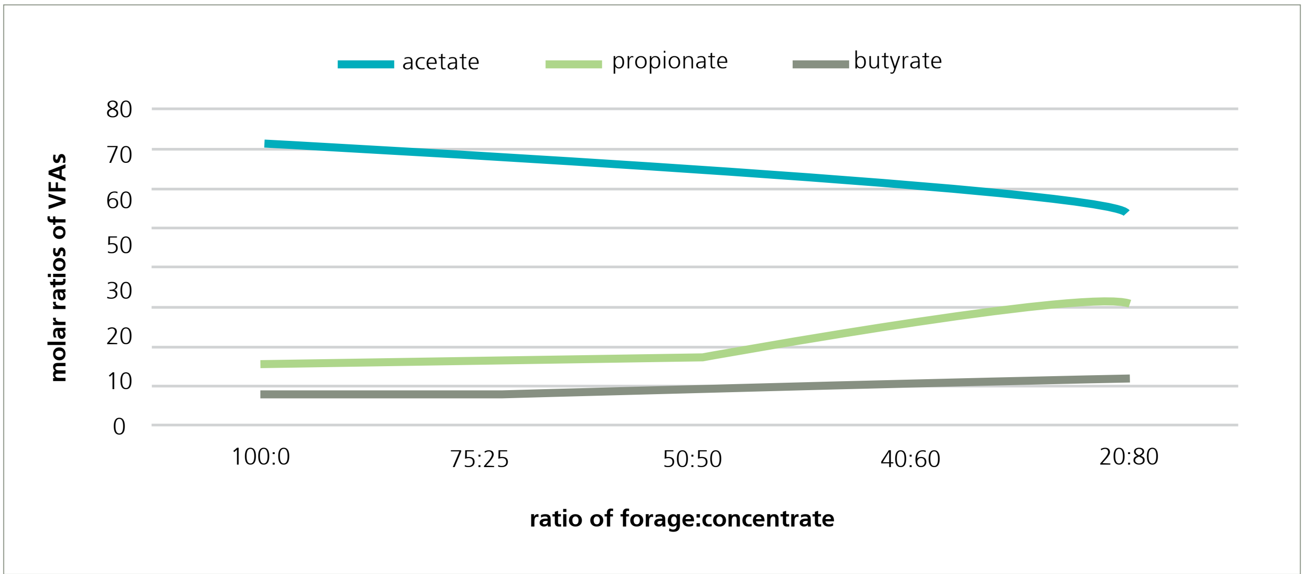
For more details see TechNotes 7: Lipid metabolism, 8: Fibre metabolism and 18: Allocate required nutrients, and online eLearning activity: The role of carbohydrate; dairynz.co.nz/feedright-module-4.

5.3 Effect of diet on VFA production

Forages are generally high in structural carbohydrates, while concentrate feeds are high in starch and sugar. The effect of diet change on the ratio of VFAs produced is highlighted in Figure 5. In a diet that contains 100% forages, acetate makes up approximately 70% of the VFAs produced, while propionate and butyrate make up 15 and 8% respectively.

As the proportion of concentrates (starches and sugars) increase in the diet, and forages decrease, the production of propionate, and to a lesser extent butyrate, increases, while the production of acetate decreases. When the diet contains 20% forages and 80% concentrates, acetate only makes up approximately 55% of the VFAs produced, while propionate and butyrate contribute 30 and 11% respectively.

***Figure 5**. Effect of diet change (forage: concentrate ratio) on VFA production.*



5.4 Further Reading

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