EQUINE APPLIED AND CLINICAL NUTRITION

HEALTH, WELFARE AND PERFORMANCE

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SECTION A Nutritional Foundations

Fat and fatty acids

Lori K. Warren, Kelly R. Vineyard

Historically fats and oils have been added to equine diets in relatively small quantities to improve the luster and shine of the hair coat, as well as to reduce dust, eliminate fines and aid in feed processing, such as pelleting. Although fat continues to be used today for some of the same reasons, recognition of the ability of horses to assimilate large amounts of dietary fat has encouraged inclusion of greater quantities in the diet. Fat's high energy density and efficiency of utilization have made it the "go-to" nutrient when additional calories are needed or as an alternative energy source to nonstructural carbohydrates (NSC). The characteristics and feeding potential of fat have inspired a great deal of research and led to the creation of high-fat feeds and supplements that are now widely available. Of late, there has been interest in the role that specific fatty acids (e.g., omega-3 and omega-6) play in various physiological functions. The purpose of this chapter is to summarize what is currently known about the horse's ability to utilize dietary fat and the benefits that potentially can be derived from fat-supplemented diets. The chapter concludes with some practical guidelines for including fat in the diet of horses.

Structural chemistry and nomenclature

Similar to other classes of nutrients, fats are chemically and structurally diverse. The structure of fat has direct bearing on its physical properties, as well as its biological behavior and activity. The naturally-occurring fats in forages and cereal grains exist as a mixture of simple lipids (di- and triacylglycerol, nonesterified fatty acids, waxes and sterols) and complex lipids (glycolipids, and phospholipids) (Hargin & Morrison 1980, Harwood 1996, Zhou et al 1999). By comparison, fats and oils added to equine diets consist mostly of triacylglycerols, which are also commonly referred to as triglycerides. Triacylglycerols consist of three fatty acids esterified to a 3-carbon glycerol molecule (Fig. 7.1). Each fatty acid is a hydrocarbon chain, which can vary in length from 2 to 28 carbons. However, the esterified fatty acids present in most feedstuffs are usually 12 to 22 carbons in length. Nonesterified fatty acids (NEFA) unbound from the glycerol backbone typically make up a very small portion of the fat. In fact, the presence of such "free" fatty acids in a feed or oil is used as an indicator of fat rancidity (oxidation).

Besides length, fatty acids can also differ in their degree of saturation or unsaturation (Figure 7.1). Fatty acids that contain no double bonds between carbon atoms are referred to as saturated fatty acids. Fatty acids with one or more double bonds are referred to as mono- or polyunsaturated fatty acids, respectively. Saturated fatty acids have a high melting point. Fat sources rich in saturated fatty acids, such as animal lard or tallow are solid at room temperature. In contrast, unsaturated fatty acids have a lower melting point, making the fat liquid (i.e., oil) or near liquid at room temperature. Most plant-based fats have relatively high unsaturated fatty acid content; notable exceptions are coconut oil and palm oil. In practice, the term "fat" is commonly used when referring to either solid fats or liquid oils. The usage of "fat" in this chapter will collectively represent the fatty acids, triacylglyercol and other complex lipid components in feeds and oils.

Each fatty acid has a carboxylic acid group at one end of the carbon chain and a methyl group at the other terminus. The carboxyl carbon is referred to as the delta (Δ) carbon, whereas the methyl carbon is the omega (ω or *n*) carbon (Fig. 7.1). Both of these landmarks have been used to reference the position of the double bond(s) in a fatty acid (i.e., the numbering of carbons in the chain can begin at either the Δ or ω carbon). The reference to the omega carbon is often favored when describing essential fatty acids. However, the international nomenclature system preferred by lipid biochemists references the position of double bonds from the delta terminus.

The length of a fatty acid, its degree of unsaturation, and the position of the double bonds within the fatty acid all dictate its biological function. As mentioned, there are numerous methods of nomenclature to identify each fatty acid based on these characteristics. In this chapter, the trivial name of the fatty acid (e.g., linoleic acid) and the shorthand numerical symbols are provided. The latter will consist of two numbers separated by a colon. The number to the left of the colon is the number of carbons in the fatty acid chain and the number to the right denotes the number of double bonds. Where appropriate, the specific omega family (e.g., *n*-3, *n*-6) that the fatty acid belongs to is also noted. For

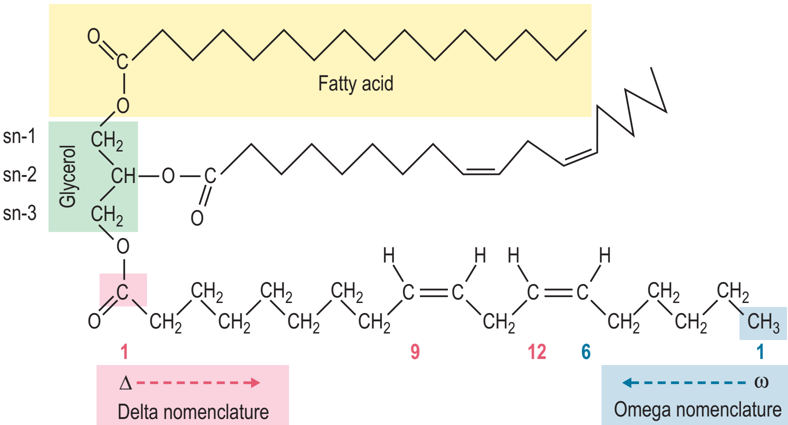

Figure 7.1 **Example structure of a triacylglycerol composed of glycerol esterified to three fatty acids. This triacylglycerol has a 16-carbon saturated fatty acid (palmitic acid, 16:0) in the sn-1 position and two 18-carbon polyunsaturated fatty acids (linoleic acid, 18:2*n*-6) in the sn-2 and sn-3 positions. The numerical locations of the double bonds in reference to either the delta or omega terminal carbon have been highlighted in the third fatty acid.**

example, the shorthand nomenclature for linoleic acid is 18:2*n*-6, indicating it is an 18-carbon fatty acid with two double bonds and is a member of the omega-6 family (Fig. 7.1). Although the nomenclature system presented herein is susceptible to some ambiguity, it remains the most widely used for identifying specific fatty acids in the scientific and popular literature. The reader is referred elsewhere for a more detailed tutorial on fatty acid nomenclature, including the more formal naming system recognized by the International Union of Pure and Applied Chemists and the International Union of Biochemistry (IUPAC-IUB 1976, Fahy et al 2005).

Key Points

- Dietary fats are chemically and structurally diverse, and may include triacylglycerol, phospholipids, glycolipids and other lipids.
- Plant sources of fat most often consumed by horses are generally rich in unsaturated fatty acids.
- The omega nomenclature system identifies the placement of double bonds from the methyl end of the fatty acid chain.

Fat digestion and absorption

Digestive physiology

Comprehensive study of the mechanisms of fat digestion and absorption in horses has not been performed. Although the basic process is likely similar in all animals, available research has found some aspects unique to equines. Thus, this section will describe the process of fat digestion that is presumed to be in place in horses, as well as highlight those aspects that are known to differ.

In general, digestion of fat consists of three phases: (1) mechanical disruption of large fat droplets into finely dispersed, emulsified particles; (2) enzymatic hydrolysis of lipid esters (i.e., triacylglycerol, phospholipids, and cholesterol esters); and (3) conversion of the water-insoluble products of lipolysis into a soluble form that can be readily absorbed. Mechanical disruption of fat begins in the oral cavity with chewing and continues in the stomach with physical churning. These processes emulsify dietary fat, resulting in the formation of small lipid droplets that provide a larger surface area for the attachment of enzymes and bile salts as the chyme flows through the small intestine.

Enzymatic digestion of fat begins in the stomach. In horses, the zymogen (chief) cells of the fundic mucosa are known to produce large amounts of gastric lipase that exhibits its peak activity at pH 4 (Moreau et al 1988). While it is presumed that gastric lipase initiates hydrolysis of triacylglycerols, the extent of fat lipolysis taking place in the equine stomach is unknown. In other species, the fatty acids released in the stomach are thought to be involved in priming the release of gastrointestinal hormones, which contribute to the emulsification of fat in the duodenum. Cholecystokinin is secreted from the duodenal mucosa in response to partially digested fats and proteins, and triggers the release of bile and pancreatic enzyme secretion. Additionally, the presence of gastric acid in the upper small intestine triggers the release of secretin, which in turn stimulates secretion of bicarbonate from the pancreas.

The products of digestion present in the lumen of the duodenum are one of many factors thought to regulate the rate of gastric emptying. For many species, it is generally believed that fat causes a greater inhibition of gastric emptying than carbohydrate (Meyer et al 1986); however, conflicting results have been reported for equids. Wyse et al (2001) fed ponies a small concentrate meal (0.4–0.6 g/kg BW) of oats and bran to which was added 0, 35 or 70 ml of soybean oil, resulting in meals containing approximately 0, 24 or 38% fat, respectively. Both fat-added meals resulted in a significant delay in gastric emptying compared to a meal without oil as measured by the ^{13}C-octanoic acid breath test. Using a similar technique, Geor et al (2001) found that the addition of corn oil (10%) to a sweet feed meal (2 g/kg BW) slowed gastric emptying in horses. Further, this effect was not influenced by the diet the horse was habituated to (with or without added fat), nor by a 4- or 8-week period of adaptation to a fat supplemented diet. By comparison, consumption of a high fat diet induces adaptation in humans, ultimately reversing the slowing effect of a fatty meal and enhancing gastric emptying (French et al 1995). Unfortunately, the specific role that fat plays in gastric emptying in horses is somewhat confounded in the studies of Wyse et al (2001) and Geor et al (2001), as control and fat-added test diets were not isocaloric. In other species, meal volume, caloric density, viscosity, and osmolality have also been shown to influence gastric motor function (Meyer et al 1986). A possible effect of viscosity was noted by Wyse et al (2001), where a delay in gastric emptying similar to that caused by the addition of soybean oil was observed when an indigestible oil (Olestra®) was added to the test meal. In contrast to these results, a series of studies performed by Lorenzo-Figueras et al (2005) demonstrated that small (0.5 g/kg BW) isocaloric meals high in carbohydrate or containing 8 or 12.3% fat had similar effects on gastric emptying (measured with the ^{13}C-octanoic acid breath test) and proximal gastric tone (measured with an intragastric barostat) in horses. Additional research is needed to clarify the effects of fat on gastric emptying in horses, as the mechanism may differ from other monogastrics that routinely consume greater amounts of dietary fat.

The proposed process of fat digestion and absorption in the small intestine is depicted in Fig. 7.2. As the acidic fat emulsion leaves the stomach and enters the duodenum, it is neutralized and modified by mixing with bile and pancreatic juice. The horse lacks a gall bladder to store bile, and instead bile is continuously secreted by the liver directly into the duodenum. Pancreatic fluid supplies bicarbonate to neutralize the acidic chyme as well as enzymes that cleave fatty acids from triacylglycerol, phospholipids and cholesterol esters. On a relative basis, the equine pancreas produces much more lipase than any other digestive enzyme (e.g., amylase, trypsin) and the activity of pancreatic lipase has been shown to be similar between adult horses, pigs and rats (Lorenzo-Figueras et al 2007). Pancreatic lipase catalyzes the hydrolysis of fatty acids from the outer positions (sn-1 and sn-3) of triacylglycerol, yielding two NEFA and one monoacylglycerol. The activity and efficiency of pancreatic lipase are enhanced by bile salts and pancreatic colipase. Bile salts accumulate on the surface of lipid droplets, increasing the surface area of the oil–water interface and permitting water-soluble lipase to be effective. Colipase ensures adsorption of lipase to the emulsified substrate by acting as an anchor.

The products resulting from lipid hydrolysis in the small intestine assemble into mixed micelles. Micelles contain a monolayer of bile acids, monoacylglycerol and lysophospholipids, which surround a core of NEFA, cholesterol and fat-soluble vitamins. Micelles deliver the lipids to the brush border of the small intestine and, because of their small size, are thought to pass readily into the unstirred water layer at the surface of the microvillus membrane where they release NEFA and monoacylglycerol. A protein-independent diffusion model and protein-dependent mechanisms have been proposed for the uptake and transport of fatty acids across the apical membrane of the enterocyte, although the relative contribution of each mechanism to fatty acid uptake is still unknown (Mansbach & Gorelick 2007). In humans, FAT/CD36 and FABPpm have been identified as fatty acid transport/binding proteins that are important for fatty acid uptake at the intestinal brush border (Mansback & Gorelick 2007, Iqbal & Hussain 2009).

Once inside the enterocyte, fatty acids are transported via cytosolic fatty acid transport/binding proteins to the endoplasmic reticulum where they are re-esterified to form triacylglycerol and phospholipids. The nucleotide sequence of one of these, intestinal fatty acid binding protein (I-FABP), has been characterized in the horse and was shown to share 87% identity with human I-FABP (Nieto et al 2005). In healthy horses, the I-FABP gene was found to be highly expressed in small intestinal mucosa with low expression

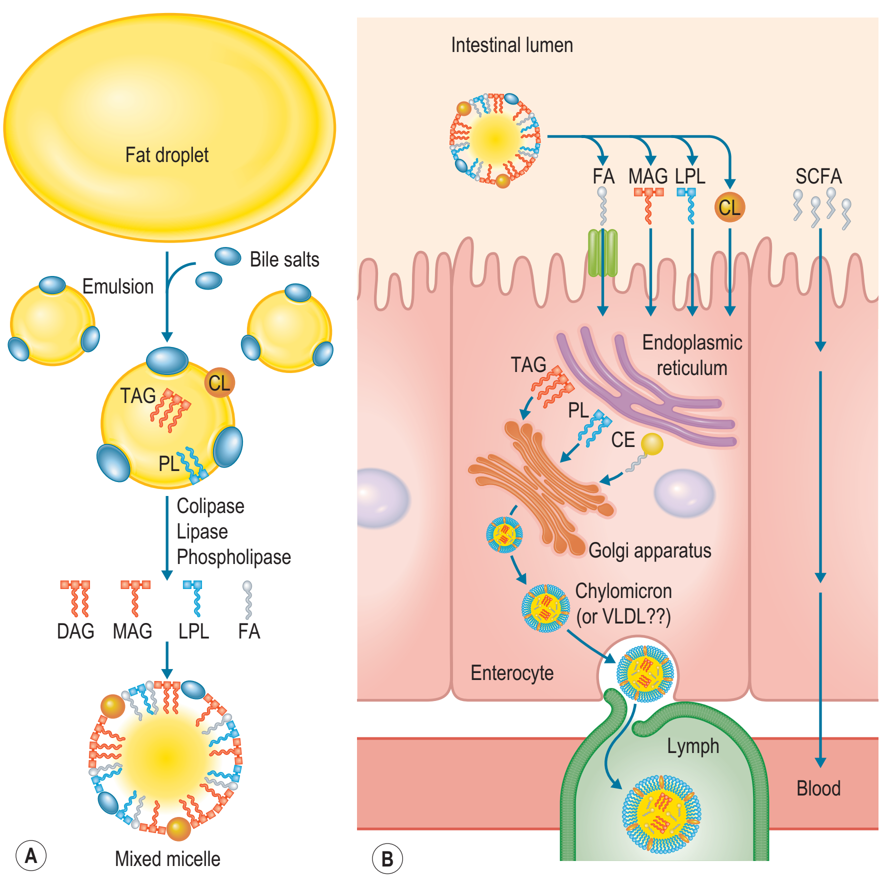

Figure 7.2 Illustration of fat digestion A) and absorption B) in the small intestine. CE = cholesterol ester; CL = cholesterol; DAG = diacylglycerol; FA = fatty acid; LPL = lysophospholipid; MAG = monoacylglycerol; PL = phospholipid; SCFA = short-chain fatty acid; TAG = triacylglycerol; VLDL = very low-density lipoprotein.

observed in the cecum and colon and virtually no expression in stomach mucosa (Nieto et al 2005).

For export into circulation, lipid products are repackaged within the enterocyte, creating a micellar particle with an outer monolayer of phospholipids, proteins and unesterified cholesterol, and a core of triacylglycerol, cholesteryl esters and fat-soluble vitamins. In most mammals, this enterocyte-derived lipoprotein is known as a chylomicron. However, it is unclear whether absorbed triacylglycerol is initially transported via chylomicrons in horses. A chylomicron-like lipoprotein has been identified in the non-fasting plasma of suckling foals, but not in mature horses or ponies maintained on forage and grain diets (see review by Watson et al 1993). Suckling foals were likely consuming more fat from mare milk compared to the mature horses evaluated. However, the fat content of the diet may not be the only factor influencing chylomicron formation as attempts to isolate this lipoprotein fraction from adult ponies following an acute oral fat load were unsuccessful (Watson et al 1993). In contrast, some investigators have reported very small concentrations of chylomicrons in the plasma of horses fed diets with or without added fat (e.g., Marchello et al 2000, van Dijk & Wensing 1989). However, the physical and chemical composition of the lipoprotein fractions were not described sufficiently in these studies to verify if these lipid fractions were in fact chylomicrons and not very low-density lipoproteins (VLDL). Although smaller and less dense, VLDLs are similar to chylomicrons in that they are triacylglycerol-rich. The lack of a chylomicron fraction in horses may reflect a mechanistic adaptation to relatively low fat, forage-based diets. In ruminants, dietary triacylglycerols are transported as modified VLDL when fed diets containing hay, silage and cereal grains, but chylomicrons are synthesized when large amounts of polyunsaturated fatty acids are infused into the small intestine (Byers & Schelling 1988). Even when present, ruminant chylomicrons are typically much smaller, lower in triacylglycerol, higher in phospholipids and less prevalent than described for humans (Byers & Schelling 1988). Differentiation of intestinally-derived chylomicrons (or modified VLDL) from liver-derived VLDL may prove difficult in the horse because the lipoprotein apo-B_{48}, secreted exclusively by the intestine in most mammals, is also secreted by the liver in horses (Greeve et al 1993). Although horses are capable of absorbing dietary fat (see the "Fat Digestibility" section), more study is needed to elucidate the process of triacylglycerol transport from the small intestine and how these mechanism(s) may be modified by diet.

The final phase of absorption involves the fusion of the triacylglycerol-rich lipoprotein (e.g., the chylomicron) with the basolateral membrane of the enterocyte and secretion into the extracellular space by exocytosis. This triacylglycerol-rich lipoprotein does not enter the plasma directly, but instead is excreted into the lacteals of the lymphatic system and eventually passes into circulation via the thoracic duct. Compared to the other products of absorption, dietary fats are unique in that they do not enter the hepatic portal vein and traverse the liver before entering systemic circulation. The exception are short- and medium-chained fatty acids (2 to 12 carbons), which are not re-esterified in the enterocyte and are instead rapidly absorbed into the capillary blood and transported to the liver bound to serum albumin.

The absorption of dietary fat takes place primarily in the distal duodenum and jejunum. Triacylglycerol-rich lipoproteins (e.g., chylomicrons, VLDL) transport absorbed fats and deliver them to the liver, adipose and other tissues. In man, the half-life of a triacylglycerol carried by a chylomicron released from an enterocyte is about 5 minutes, whereas the half-life of a whole chylomicron particle is approximately 13 to 14 minutes (Gurr et al 2002).

Similar to other nutrients, fats that are not digested and absorbed in the small intestine will pass into the hindgut. Based on the difference in ether extract between ileal contents and feces, Swinney et al (1995) reported that little to no fat disappearance occurred in the hindgut of miniature horses fed diets consisting of 35% forage and 65% concentrate that contained 5 to 25% added fat. This agrees with reports in ruminants, where loss of longer chain fatty acids from the rumen either by absorption across the ruminal epithelium or by catabolism to volatile fatty acids or carbon dioxide is minimal (Jenkins 1993). However, dietary fats that escape digestion in the equine small intestine have the potential to interfere with microbial fermentation in the hindgut. The amount of fat entering the hindgut has been shown to increase with increasing intake of soybean oil. Consumption of a concentrate diet with 0, 3.9 and 11% soybean oil resulted in 11, 20 and 99 g fat/kg DM of chyme entering the cecum, respectively (Coenen 1986). When the 11% fat-added concentrate was administered via nasogastric tube transit through the stomach and small intestine was accelerated, resulting in a larger quantity of fat entering the cecum (146 g/kg DM) and evident alterations to the microbiota (Coenen 1986). In ruminants, where the subject has been extensively studied, the negative impact of dietary fat on fiber digestion is believed to result from either the coating of feed particles or a direct toxic effect on rumen microorganisms (Hess et al 2008). The type of dietary fat is also relevant, whereby unsaturated fatty acids have been shown to have greater antimicrobial effects and promote greater inhibition of ruminal fermentation when compared to saturated fatty acids (Hess et al 2008). Presumably the same events would occur in the hindgut of horses, but further investigation on the effects of dietary fat on microbial fermentation using different fat sources and hay to grain ratios is warranted.

Fat digestibility

The digestibility of dietary fat is primarily affected by level of intake and type of lipid. The low levels of naturally-occurring fat in forages and cereal grains appears to be the most difficult for the horse to extract, with apparent digestibility of fat ranging from 5–57% in forages (Fonnesbeck et al 1967, Sturgeon et al 2000) and 55–76% in grains (Hintz & Schryver 1989). In contrast, diets supplemented with various sources of animal fat or vegetable oil have an apparent digestibility between 64% and 96% (Kane et al 1979, McCann et al 1987, Rich et al 1981, Swinney et al 1995, Bush et al 2001). After compiling data from five studies evaluating five basal diets (hay-grain mix, 23–37 g fat/kg DM) and 18 diets with added fat (76–233 g fat/kg DM), Kronfeld et al (2004) reported mean apparent digestibilities of 55% for forages, 81% for mixed diets including added fat, and 95% for added fats. Further modeling of this data indicated that the true digestibility of added fats was nearly 100% (Kronfeld et al 2004).

The reason for the differences in digestibility of naturally-occurring vs. supplemental fat sources is likely multifactorial. Animal fats and vegetable oils supplemented to equine diets are mostly in the form of freely available triacylglycerols. By comparison, fats in forages and grains are surrounded by plant cell wall components which may delay or prevent presentation to lipase in the small intestine. Modeling of data from several feeding trials led Kronfeld et al (2004) to suggest that enzymatic hydrolysis of fat might be slower as a consequence of the low fat intakes associated with forage and grains. In addition, although routinely used, ether extract methodology may not adequately characterize the types of lipid found in forages and cereal grains. Two-thirds of the lipid content in forage (Harwood 1996) and up to one-third in cereal grains (Hargin & Morrison 1980, Zhou et al 1999) is in the form of glycolipids and phospholipids that are incompletely extracted in ether. Similarly, forages contain waxes and other pigments that are extractable in ether but poorly digestible. Thus, if digestibility of fat in forages and cereal grains is based on ether extraction, the availability of naturally-occurring fat in forages and cereal grains might be underestimated as a significant portion of the lipid is not represented in the extract. The relatively small amount of fat, coupled with incomplete characterization of the lipid fractions digested, might also explain the wide variation in fat digestibility commonly observed with forages (see Fonnesbeck et al 1967).

Despite the fact that the digestive system of equids has evolved to process low-fat, high-fiber feeds, they appear quite capable of assimilating relatively large amounts of dietary fat (see reviews by Potter et al 1992, Kronfeld et al 2004, NRC 2007). Using data from a wide range of fat intakes (23–233 g/kg DM) Kronfeld et al (2004), demonstrated a linear relationship between fat intake (g/day) and fat absorbed (g/day), with an estimated daily endogenous loss of 0.22 g fat/kg BW. Additional modeling of these compiled data demonstrated that fat digestibility is maximized between 100 and 150 g/kg DM and sustained to at least 230 g/kg DM in horses adapted to fat-supplemented rations (Kronfeld et al 2004).

Few associative effects of dietary fat on the digestibility of other nutrients have been reported. In the studies compiled by Kronfeld et al (2004), the feeding of diets with up to 230 g fat/kg DM had no negative effects on the digestion of dry matter, crude protein, or fiber. The supplemental fat sources and the percent fat added to the total diet in Kronfeld's report included corn oil (5–20%), peanut oil (7.5–15%), tallow (7.5–15%), an animal–vegetable fat blend (7.5–15%), a blend of equal parts soy-lecithin and corn oil (10%), and a blend of equal parts soy-lecithin and soybean oil (10%). A similar lack of negative associative effects on nutrient digestibility have been reported by others with the addition of 5–15% corn oil (Kane et al 1979, Bush et al 2001, Lindberg & Karlsson 2001) and 8% linseed oil (Delobel et al 2008) to the concentrate portion of the diet. In contrast, a negative associative effect of soybean oil on crude fiber, neutral detergent fiber (NDF) and acid detergent fiber (ADF) digestion has been reported by Jansen et al (2000, 2001, 2002). In these studies soybean oil was added to the concentrate at a rate of 15–37%, resulting in 50–148 g fat/kg DM in the total diet. Other researchers have also found a negative effect on fiber digestion with fairly high levels of soybean oil inclusion in the concentrate portion of the diet (19–21%), but not lower levels (5–13%) (Godoi et al 2009, Morgado et al 2009). While reduced fiber intake associated with the feeding of high levels of soybean oil can possibly explain the reductions in fiber digestion observed by some (Godoi et al 2009, Morgado et al 2009), it does not explain the findings of Jansen et al (2000, 2001, 2002) who compared diets similar in energy and fiber by substituting corn starch and/or glucose for soybean oil. The mechanism by which soybean oil, but not other oils, might suppress fiber digestion is unknown. Higher fluxes of bile acids or fatty acids into the large intestine are not likely to be involved (Jansen et al 2007). A recent meta-analysis of 22 studies found that diets with added fat (15.5 to 217.5 g/kg DM) had no effect on digestion of crude protein or NDF but did result in a significant decrease in ADF digestibility (Sales & Homolka 2011). It is worth noting that this meta-analysis included the soybean oil supplementation studies of Jansen and coworkers. As ADF generally represents the least digestible fiber for the horse, the importance of this finding may have little practical relevance. To avoid potential negative effects on fiber digestion, the NRC (2007) recommended an upper limit of 0.7 g fat/kg BW (approximately 35 g/kg DM) when fat is supplemented in the form of soybean oil.

Only a small number of studies have evaluated the effect of fat supplementation on mineral absorption. In mature horses and ponies, absorption of calcium, phosphorus and magnesium appear to be largely unaffected by fat intakes of 80 to 98 g/kg DM (Davison et al 1991, McCann et al 1987, Meyer et al 1997). Although calcium absorption was not directly measured, growing horses fed a fat and fiber-based supplement (containing 11% corn oil) had lower radiographic bone density during the fall and winter months, but not the summer and spring months, compared to those fed an isocaloric supplement high in starch and sugar (Hoffman et al 1999). However, a follow-up study found no difference in radiographic bone density between weanlings provided fat and fiber when compared to starch and sugar-based feeds (Hoffman et al 2001). Given the potential for mineral availability to be decreased through the formation of fat-mineral soaps in the small intestine, additional study is needed to clarify the impact that high-fat diets have on the absorption of calcium and other minerals in growing horses.

The absorption of fat-soluble vitamins requires the presence of triacylglycerol and other fats in the small intestine. The impact of dietary fat on vitamin absorption has not been directly assessed in the horse. Kronfeld et al (2004) speculated that the lowered fat digestibility of traditional hay-grain diets may increase the risk of suboptimal vitamin A and E status. As evidence of this, ponies fed diets containing very low amounts of fat (0.05%) for 3 months were reported to have low plasma and tissue vitamin E concentrations, suggesting there may have been inadequate absorption of vitamin E (Sallmann et al 1991). The impact of dietary fat on vitamin absorption deserves further study, particularly as it may alter fat-soluble vitamin requirements in relation to dietary fat content.

Key Points

- The mechanics of fat digestion and absorption have received limited study in the horse.
- Dietary fat is principally digested and absorbed in the small intestine.
- Digestibility of fat from oils and other high fat feedstuffs is relatively high (85–100%).
- Inclusion of fat at up to at least 100 g/kg DM appears to have minimal impact on digestion of dry matter, crude protein, NDF or minerals.

Dietary sources of fat

Forages, cereal grains and most cereal by-products are naturally low in fat (i.e., <4% DM). Similarly, the use of highly efficient chemical methods to extract oils from oilseeds has resulted in oilseed meals (e.g., soybean meal) with relatively low fat content. There are, of course, some exceptions. For example, naked (hulless) oats and distillers grains may have 7–10% crude fat and oilseed meals generated from mechanical oil extraction may have up to 20% crude fat.

The fat content of equine diets can be augmented by a variety of fat-rich ingredients. The crude fat and fatty acid composition of feedstuffs commonly included in equine diets is provided in Table 7-1. Horses have been reported to accept a variety of plant oils added to their diet (depending on the processing method used for extraction), including canola, coconut, corn, cottonseed, flax (linseed), olive, palm, peanut, rice bran, safflower and soybean oils (Bush et al 2001, Delobel et al 2008, Duvaux-Ponter 2004, Frank et al 2004, Gatta et al 2005, Hallebeek & Beynen 2002, Holland et al 1998, Kronfeld et al 2004, Lindberg & Karlsson 2001, Meyer et al 1997).

Animal tallows and tallow-vegetable oil blends have also been used in horse rations (Holland et al 1998, McCann et al 1987, Rich et al 1981), although this practice is not as common today as it was 30 years ago and has been discouraged or prohibited in some countries based on perceived risk for transmission of bovine spongiform encephalopathy. In addition, palatability tests have generally indicated that horses have a preference for vegetable oils over animal fats (Bowman et al 1979, Holland et al 1998). More recently, interest in omega-3 fatty acids has led to the inclusion of marine fat sources in equine diets, including a variety of fish oils, seal blubber and algae to augment the omega-3 fatty acid content of the diet (Khol-Parisini et al 2007, King et al 2008, Vineyard et al 2010).

In addition to oils, which are essentially 100% crude fat, there are other feedstuffs that contain a relatively high percentage of DM (>20%) as crude fat; these include stabilized rice bran, heat-treated whole soybeans, flaxseed and sunflower seeds. Rice bran contains naturally high levels of phosphorus which can offset the ratio of calcium to phosphorus in the total diet. Because of this, some (but not all) companies have fortified their rice bran supplements with additional calcium to bring up the Ca : P ratio to more acceptable levels. Rice bran also contains an endogenous lipase that can be activated when the germ and bran are exposed to air. Unless deactivated by heat and moisture, the lipase can quickly hydrolyze the triacylglycerols and release fatty acids that are highly susceptible to oxidation. Modern mills stabilize rice bran after milling by passing the bran through an expander, a process which greatly reduces the potential for rancidity. Whole soybeans contain trypsin inhibitors that can interfere with protein digestion in monogastric animals; however, roasting or other processing methods that involve heating or toasting will generally inactivate this antinutritive factor.

Commercial concentrate rations with added fat typically include one or more of the oils or other high-fat feedstuffs described above. In general, products with a significant amount of added fat can be identified from the guaranteed analysis as having greater than or equal to 5% crude fat. Although horses can tolerate higher levels of fat in the diet, most fat-added concentrates available in the marketplace range from 5–14% crude fat. A variety of high fat supplements are also commercially available, the most common of which are stabilized rice bran and fat blends of varying composition and crude fat content. For horse owners, fat-added concentrates offer the advantage of convenience and also ensures that the feed is balanced with respect to other nutrients in the diet. In contrast, supplementing the basal ration with oil or other high fat feedstuffs can create nutrient imbalances that require additional fortification to correct, a practice that might negate any cost savings to the owner.

Key Points

- Forages and cereal grains that make up the bulk of most equine rations are generally low in fat (< 4% DM).
- Feedstuffs high in fat (20–100% DM) that can be added to equine rations include vegetable oils, marine oils, stabilized rice bran, flaxseed, and heat-treated soybeans among others.
- Horses have shown a preference for corn oil over other oils and vegetable oils over animal tallows and lards.
- Commercially available fat-added concentrates typically contain 5–14% crude fat.

Essential fatty acids

Linoleic acid (LA; 18:2*n*-6) and α-linolenic acid (ALA; 18:3*n*-3) are essential fatty acids (EFA) that must be supplied by the diet. Mammals lack the Δ12- and Δ15-desaturase enzymes necessary for desaturation of an 18-carbon fatty acid at the omega-3 (or Δ15) or omega-6 (or Δ12) positions. Therefore, LA and ALA cannot be synthesized in the body and are deemed "essential." By comparison, plants and algae contain ample amounts of the Δ12- and Δ15-desaturase enzymes and, as a result, LA and ALA are two of the most prevalent fatty acids found in plant tissues and oils.

An EFA deficiency has not been described for the horse, even in those consuming diets almost devoid of fat. Sallmann et al (1991) observed no clinical abnormalities in ponies fed very low fat diets containing 0.03% and 0.14% linoleic acid for 7 months. The absence of signs of deficiency in these ponies may have resulted from mobilization of body fat stores that could have met EFA needs during the prolonged period of low intake. In other species EFA deficiency is characterized by dry or scaly skin, dry coat, hair loss and decreased reproductive efficiency. The NRC (2007) has recommended a LA intake of 0.5% DM for horses although justification for this recommendation was not described. For a 500 kg horse with a DM intake of 2% BW,

Table 7-1 Average Crude Fat and Fatty Acid Composition (g/kg DM) of Feedstuffs Commonly Fed to Horses[a,b]

Feedstuff	Crude fat	SFA	MUFA	PUFA	Select omega-6 and omega-3 fatty acids					
					LA 18:2n-6	ALA 18:3*n*-3	AA 20:4*n*-6	EPA 20:5*n*-3	DPA 22:5*n*-3	DHA 22:6*n*-3
Forages										
Grass hay, cool-season	22.1	3.7	1.2	12.0	3.8	8.2	0	0	0	0
Grass hay, warm-season	20.0	5.3	0.6	8.2	3.6	4.6	0	0	0	0
Grass pasture, cool-season	25.0	4.0	1.5	13.8	4.5	9.3	0	0	0	0
Grass pasture, warm-season	24.4	6.3	0.7	15.0	3.9	11.1	0	0	0	0
Legume hay	25.5	5.2	0.8	11.8	3.9	7.9	0	0	0	0
Legume pasture	31.1	6.3	1.8	12.9	4.5	8.4	0	0	0	0
Concentrates										
Barley grain	23.0	4.8	3.0	11.1	10.0	1.1	0	0	0	0
Canola meal	54.0	4.3	27.4	16.9	12.1	3.5	0	0	0	0
Corn grain	47.4	6.7	12.5	21.6	21.0	0.7	0	0	0	0
Flax seed	421.6	36.6	75.3	287.3	59.0	228.1	0	0	0	0
Linseed (flax) meal	19.0	3.4	4.2	9.5	2.1	7.3	0	0	0	0
Oat grain	54.0	9.2	19.6	24.4	23.2	1.0	0	0	0	0
Rice bran	208.5	41.7	75.5	74.6	71.4	3.2	0	0	0	0
Soybean meal	16.0	3.1	2.7	7.2	5.9	1.0	0	0	0	0
Soybeans, whole roasted	216.2	31.3	47.8	122.1	107.6	14.4	0	0	0	0
Sunflower seeds	514.6	44.6	185.3	231.4	230.5	0.6	0	0	0	0
Wheat grain	24.7	4.5	3.4	9.8	9.8	0.5	0	0	0	0
Fats & oils										
Canola oil	1000	73.7	632.8	281.4	186.4	91.4	0	0	0	0
Coconut oil	1000	865.0	58.0	18.0	18.0	0	0	0	0	0
Corn oil	1000	129.5	275.8	546.8	532.3	11.6	0	0	0	0
Fish oil, Herring	1000	212.9	565.6	156.0	11.5	7.6	2.9	62.7	6.2	42.1
Fish oil, Menhaden	1000	304.3	266.9	342.0	21.5	14.9	11.7	131.7	49.2	85.6
Fish oil, Salmon	1000	198.7	290.4	403.2	15.4	10.6	6.8	130.2	29.9	182.3
Flaxseed (Linseed) oil	1000	94.0	202.0	660.0	127.0	533.0	0	0	0	0
Lard	1000	392.0	451.0	112.0	102.0	10.0	0	0	0	0
Olive oil	1000	138.1	729.6	105.2	97.6	7.6	0	0	0	0
Palm oil	1000	493.0	370.0	93.0	91.0	2.0	0	0	0	0
Peanut oil	1000	169.0	432.0	320.0	320.0	0	0	0	0	0
Rice bran oil	1000	197.0	393.0	350.0	334.0	16.0	0	0	0	0
Soybean oil	1000	156.5	227.8	577.4	504.2	67.9	0	0	0	0
Sunflower oil	1000	90.1	573.3	289.6	287.1	0.4	0	0	0	0
Tallow	1000	498.0	418.0	40.0	31.0	6.0	0	0	0	0

[a]SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; LA = linoleic acid; ALA = α-linolenic acid; AA = arachidonic acid; EPA = eicosapentaenoic acid; DPA = docosapentaenoic acid; DHA = docosahexaenoic acid.
[b]Data from: Palmquist 1988, Boufaïed et al 2003, Warren & Kivipelto 2007a, b, USDA-ARS 2010.

the NRC recommendation would amount to a daily intake of 50 g of LA. Across a variety of other mammalian species, a minimum of 1% of total dietary energy intake as LA has been given as a general recommendation to prevent EFA deficiency (Gurr et al 2002). Extrapolating this to a 500-kg horse consuming 20 Mcal DE/day, and assuming a conservative estimate of 50% availability, the LA requirement is 45 g/day. Thus, the NRC (2007) recommendation for LA in horses appears to approximate the minimum intake guideline for other mammalian species. This requirement is likely to be met in horses consuming adequate quantities of good quality forage and is easily met by diets supplemented with fat, as most high-fat feedstuffs and oils are rich in LA (Table 7-1). Currently there are no guidelines for minimum daily ALA intake, although a horse consuming adequate amounts of fresh forage and/or good quality hay will likely receive ample amounts of ALA in the diet (Table 7-1). Supplementation with both LA and ALA should be considered in horses receiving poor quality or limited amounts of forage for prolonged periods of time. Because an ALA requirement has not been established for horses or other herbivores, provision of ALA in amounts resulting in a 5:1 to 10:1 ratio of LA:ALA might be considered adequate, as this has been recommended for other species (NRC 2005).

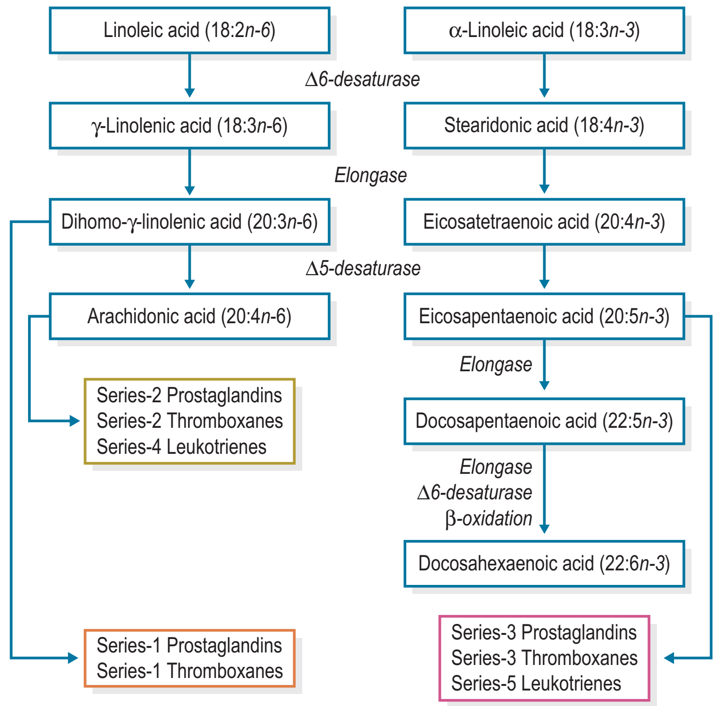

Figure 7.3 Elongation and desaturation of essential fatty acids and subsequent eicosanoid production.

Key Points

- Linoleic acid (omega-6) and α-linolenic acid (omega-3) cannot be made by the horse and must be supplied by the diet.
- **E**ssential fatty acid requirements have not been established for horses.
- Most equine diets will likely meet essential fatty acid needs unless poor quality rations are consumed for prolonged periods.

Omega-6 and omega-3 fatty acids

There has been a great deal of interest in the biological impact of different types of fatty acids supplied by various fat sources. In particular, omega-6 and omega-3 fatty acids have received attention for their roles in maintaining cell membrane fluidity and integrity, receptor and ion channel function, gene expression, neural and retinal development, and inflammation and immunity.

Both omega-6 and omega-3 fatty acids contribute to normal biological responses; however, the relative availability of omega-6 versus omega-3 fatty acids can influence the overall response. Linoleic acid (LA; 18:2*n*-6) is the "parent" omega-6 fatty acid and can be elongated and desaturated in the body to form the long-chain polyunsaturated fatty acids dihomo-γ-linolenic acid (DGLA; 20:3*n*-6) and arachidonic acid (AA; 20:4*n*-6) (Fig. 7.3). In the omega-3 family, α-linolenic acid (ALA; 18:3*n*-3) competes for the same elongase and desaturase enzymes to form eicosapentaenoic (EPA) and docosahexaenoic (DHA) acids. The initial step in this process catalyzed by Δ6-desaturase is thought to be rate-limiting, and studies in other species have indicated that there is a 1.5- to 3.0-fold higher Δ6-desaturase conversion rate for ALA compared with LA (Hussein et al 2005, Sprecher 2000, Sprecher et al 1995). The relative activities of Δ6- and Δ5-desaturase in horses have not been established. Nonetheless, horses appear to have the ability to synthesize the longer-chain polyunsaturated fatty acids from LA and ALA, as evidenced by the presence of AA, EPA and DHA in cell membranes despite not having consumed these fatty acids in the diet (Warren & Kivipelto 2008, Warren et al 2010).

In addition to competing for available enzymes, omega-3 and omega-6 fatty acids also compete for incorporation into cell membrane phospholipids. When greater quantities of EPA are present, it will be incorporated into cell membranes partially at the expense of AA (Calder 2006). The resulting changes in membrane fluidity and integrity, as well as cell receptor signaling and protein synthesis, can alter the biological response to trauma and infection. Furthermore, potent biological mediators known as eicosanoids are synthesized from the oxidation of EPA, DGLA and AA located in cell membranes. The eicosanoids, which include prostaglandins, leukotrienes and thromboxanes, mediate several events including inflammation, blood flow and pressure and blood clotting. DGLA and AA are precursors of the 1- and 2- prostaglandin and thromboxane series, whereas EPA serves as the precursor for the 3-series prostaglandins and thromboxanes and the 5-series leukotrienes (Fig. 7.3). In simplistic terms, eicosanoids derived from omega-6 fatty acids stimulate stronger pro-inflammatory responses, whereas those stemming from omega-3 fatty acids produce weaker inflammatory reactions. However, it is really the balance of the different eicosanoids produced that generates the final biological response. Because most cell membranes contain a greater concentration of AA than other 20-carbon fatty acids, AA is usually the principal precursor for eicosanoid synthesis (Calder & Grimble 2002).

Supplementation of omega-3 fatty acids

As an herbivore, the horse is adapted to a diet naturally high proportionally in omega-3 fatty acids. Forages, although low in total fat (2–4%), contain a significant portion of that fat (39–56%) as ALA (Boufaïed et al 2003, Warren & Kivipelto 2007a, b). In both fresh forage and hay, the proportion of ALA usually exceeds that of LA (Tables 7-1 and 7-2). In contrast, cereal grains, soybean meal, rice bran and most vegetable oils are enriched in the omega-6 fatty acid, LA. For example, corn oil and soybean oil contain over 50% LA, and the fat in rice bran contains approximately 35% LA (Table 7-1). A greater reliance on concentrates in the diets of performance horses, broodmares and growing horses generally results in a lower intake of omega-3 fatty acids from forage and, when oils are added to the diet, a higher intake of omega-6 fatty acids (Table 7-2). In humans, consumption of omega-6 fatty acids often greatly exceeds that of omega-3 fatty acids by a 20–25:1 margin (Calder & Grimble 2002, James et al 2000). Recent dietary recommendations have suggested a ratio of 5:1 to 10:1 of omega-6:omega-3 fatty acids as an ideal target for human diets (NRC 2005). Keeping these guidelines in mind, Table 7-2 shows a comparison of the average omega-6 and omega-3 intake from a variety of equine diets. According to the calculations and assumptions used in Table 7-2, most equine diets probably fall below the upper omega-6 to omega-3 ratio of 10:1, even with relatively high levels of omega-6 fatty acids provided from oil supplementation and using conservative estimates of fatty acid availability from forages in the small intestine. Such low omega-6:omega-3 ratios in equine diets compared to the typical human diet likely results from the potentially large contribution of ALA from forage. The ratio of omega-6 to omega-3 fatty acids is thought to be important because of the competitive nature of fatty acids and their different biological roles. However, there is also evidence that the absolute quantity of omega-3 or omega-6, more than the ratio, can influence conversion of precursor fatty acids to their longer chain derivatives, as well as the overall biological response (Goyens et al 2006). Much more work is needed in horses before an ideal omega-6:omega-3 ratio can be recommended, and to determine whether it is the ratio between these fatty acids or the amount consumed that has the biggest influence.

Given the potential anti-inflammatory and immunomodulatory activities ascribed to omega-3 fatty acids (Calder 2006), there has been interest in supplementing these fatty acids to the diets of horses. In addition to fresh grass and good quality hay, good sources of ALA in horse diets include flaxseed and flax (linseed) oil. The ALA content of canola and soybean oils tends to be higher than other vegetable oils, though still much outweighed by LA. Fish oil (e.g., menhaden, cod liver, salmon, herring) and algae supplements are sources rich in the long-chain omega-3 fatty acids EPA and DHA (Table 7-1). Marine-based oils are not without fault, however, as cod liver oil is known to be very high in vitamin A and some oils may be derived from fish contaminated with heavy metals such as copper or mercury, and organic pollutants such as PCBs or dioxins (Domingo et al 2007).

Flaxseed has been fed by horsemen for decades, most likely based on its anecdotal reputation for producing a shiny hair coat. Though generally well accepted by both horses and their owners, there remains some debate as to the ideal way to feed flaxseed. Feeding whole flaxseed is a safe and acceptable practice. Nonetheless, some insist that the flaxseed should be ground and/or stabilized in order to reap the full benefits. The practice of grinding flax may indeed be helpful, as grinding interrupts the hard outer seed coating, making the fat potentially more available for digestion in the small intestine. However, disruption of the seed coat also exposes the seed contents to air and therefore may hasten the oxidation and destruction of the fatty acids. Stabilization of ground flaxseed is intended to reduce the susceptibility of fatty acids to oxidation and is achieved by selection for mature and evenly colored seeds, the addition of natural and artificial antioxidants, or by employing further processing methods to protect the fat in the seed. Others claim that flaxseed must first be cooked before it can be fed to horses. Flaxseed contains cyanogenic glycosides that can interact with enzymes contained within the seed to release harmful cyanide (Oomah et al 1992). For this reason, some horsemen are compelled to boil flaxseed before feeding in order to volatilize and remove the cyanide. However, it is unlikely that harmful levels of cyanide are released with ingestion of flaxseed due to the ability of stomach acid to inactivate the enzymes contained within the seeds (O'Neill et al 2002). Whole flaxseed also contains more phosphorus (~0.65%) than calcium (~0.23%); thus if high quantities of flaxseed are fed, adjustments to the calcium:phosphorus ratio of the total diet may be necessary.

Feeding fish oil products to horses has sometimes been met with resistance due the unpleasant "fishy" odor, the increased expense, and limited availability compared to other oil sources. Some manufacturers of fish oil marketed specifically for horse consumption have been able to successfully reduce or even eliminate the "fishy" odor through further refining, as well as the addition of flavors

Table 7-2 Estimated Amounts of Omega-6 and Omega-3 Fatty Acids Available to a 500-kg Horse From Different Types of Diets[a,b]

Diet	Available omega-6 (g/day)	Available omega-3 (g/day)	Omega-6: omega-3 ratio
Pasture	25	75	0.3:1
Hay	35	60	0.6:1
Hay + Concentrate (4% crude fat)	50	25	2.0:1
Hay + Concentrate (6% crude fat)	135	30	4.5:1
Hay + Concentrate (10% crude fat)	275	35	7.8:1

[a]The estimates above were based on the following assumptions: a) 500-kg horse with a daily intake of 10 kg DM; b) hay + concentrate diets are based on total DM intake consisting of 50% hay and 50% as concentrate; c) concentrates are made up predominantly of cereal grains, grain byproducts and oil seed meals; d) corn oil, which is rich in omega-6, was used as the fat source for the concentrates with 6 and 10% crude fat; and e) 50% of the fatty acids in forages, 75% of the fatty acids in cereal grains, and 100% of the fatty acids in corn oil are available for absorption in the small intestine.
[b]Omega-6 and omega-3 fatty acids in example diets are predominantly in the form of linoleic acid and α-linolenic acid, respectively and are based on average fatty acid concentrations observed in commonly used feedstuffs (Warren et al 2007a, b, Vineyard et al 2010, Warren personal communication).

and fragrances that horses (or their owners) find more acceptable. The popularity of feeding fish oil preparations to horses has grown in recent years and availability of these products has increased. Another way to supply EPA and DHA from fish oil is with a dry "encapsulated fish oil" pellet that contains approximately 23% fat. The encapsulation process is utilized to stabilize the fatty acids in the fish oil and to improve palatability. As an alternative to fish oil, algal-derived DHA supplements are also becoming more widely available for inclusion in equine rations.

Potential benefits of omega-3 fatty acid supplementation

The majority of omega-3 fatty acid supplementation research in horses has focused on inflammation. The results of early studies showed promising effects of linseed oil supplementation, including decreased monocyte procoagulant activity along with lowered thromboxane and tumor necrosis factor-α (TNF-α) production (Henry et al 1990, Morris et al 1991). More recently, horses supplemented with 3% fish oil had reduced prostaglandin E_2 (PGE_2) production by cells harvested from bronchoalveolar lavage fluid (BALF) when compared to horses supplemented with corn oil; however, delayed-type hypersensitivity skin test response, antibody response to vaccination, and TNF-α production by stimulated BALF cells were not different between diets (Hall et al 2004a, b). The effects of long-chain omega-3 fatty acids supplied as seal blubber to horses with recurrent airway obstruction revealed no improvements in several measures of pulmonary function and no improvement in clinical signs after 10 weeks of supplementation (Khol-Parisini et al 2007). Horses fed 10% corn oil had higher levels of the acute phase protein fibrinogen at rest and following exercise compared to those fed 10% soybean oil or a low-fat control diet (Wilson et al 2003).

Although in vitro and ex vivo methods of measuring immune function are important for gaining basic knowledge of how dietary omega-3 fatty acids can affect inflammatory processes, evaluation of in vivo response is essential for evaluation of clinical significance. Unfortunately, only a handful of equine studies have attempted to quantify the anti-inflammatory effects of omega-3 fatty acid supplementation using an in vivo model. In response to endotoxin administration, a longer whole blood recalcification and activated partial thromboplastin time, but no differences in inflammatory eicosanoid production, were observed when horses received a diet containing 8% linseed oil (Henry et al 1991). In a small cross-over study, six horses known to have Culicoides hypersensitivity had reduced lesion size after injection with Culicoides antigen when supplemented with 0.1% BW flaxseed compared to placebo (simply described as "bran") for 42 days (O'Neill et al 2002). In contrast to these findings, the level of pruritus or lesional surface area did not change in a study of 17 horses with Culicoides hypersensitivity after 6 weeks of supplementation with 200 mL linseed oil (Friberg et al 1999).

Supplementation with omega-3 fatty acids has also been touted to benefit horses with osteoarthritis. These claims are primarily based on findings from research performed in humans with rheumatoid arthritis that indicate fish oil supplementation may improve symptoms (Berbert et al 2005, Cleland et al 1988, Lau et al 1993). Studies in horses, however, are extremely limited and the results must be interpreted with caution, as the etiology of rheumatoid arthritis and degenerative osteoarthritis are very different. In one study, horses supplemented with encapsulated fish oil tended to have a longer trot stride suggestive of less pain than those receiving corn oil, but serum PGE_2 and TNF-α were not different between treatments (Woodward et al 2007). An experiment performed on equine synovial explants reported that treatment with ALA at high doses (300 μg/ml) increased ALA content of explant cell membranes and inhibited PGE_2 production after challenge with LPS (Munsterman et al 2005). However, it is unclear how the ALA dose used in this experiment relates to physiological levels of dietary ALA that could potentially reach the synovial fluid in vivo. Manhart et al (2009) supplemented arthritic horses with EPA and DHA for 90 days and reported a reduction in total leukocytes in synovial fluid in arthritic joints, decreased plasma PGE_2 concentration, and a trend for reduced fibrinogen concentrations compared to horses receiving no supplementation; however, force plate analysis indicated no effect of supplementation on gait abnormalities associated with the osteoarthritis. Although the authors concluded that omega-3 fatty acid supplementation would benefit horses with osteoarthritis, the inflammatory markers measured in this study were non-specific and there was no improvement in clinical signs. Collectively, these studies provide some useful preliminary data but they do not offer strong evidence that omega-3 fatty acids can attenuate arthritic inflammation in horses. More comprehensive investigation is needed to characterize the effects of omega-3 fatty acid supplementation on degenerative osteoarthritis in horses.

In a series of studies investigating the effects of fatty acid supplementation on aspects of innate and acquired immunity, lymphocyte proliferation and neutrophil function were not affected by omega-3 fatty acid supplementation (Vineyard et al 2007, 2008, 2010). Lymphocyte PGE_2 production was reduced and antibody response to vaccination was increased when either omega-3 (as fish oil) or omega-6 (as corn oil) fatty acids were supplied as part of a high fat (100 g/kg) feed (Vineyard et al 2008). Horses fed omega-3 fatty acids as fish oil or milled flaxseed also had an earlier increase in skin thickness after intradermal phytohemagglutinin injection compared to nonsupplemented controls (Vineyard et al 2010). Results from these studies suggest that both omega-6 and omega-3 fatty acids play a role in immune function of clinically normal horses. Further study is needed to identify the effects of feeding fat to horses with autoimmune or inflammatory diseases and the potential for increasing dietary omega-3 fatty acid intake to modulate the severity and/or progression of disease.

There has also been interest in supplementing omega-3 fatty acids to enhance reproductive function. In a cross-over design study with six stallions, an increase in daily sperm output and percentage of morphologically normal sperm were observed after 90 days of supplementation with a supplement containing fish oil that provided 29 g of DHA + EPA per day; however, omega-3 supplementation did not alter progressive motility in fresh, cooled or frozen semen (Harris et al 2005). In another cross-over design study with eight stallions, supplementation with 75 g of total omega-3 fatty acids per day (of which 20 g/day is estimated to be DHA + EPA) for 98 days did not improve characteristics of fresh semen, but did improve sperm motility after cooling and freezing (Brinsko et al 2005). Both of these studies noted that greater improvements in response to omega-3 supplementation were observed in stallions that produced semen with poor tolerance to cooling or cryopreservation. Further studies are needed on a larger number of stallions to confirm these findings and establish how consistently long-chain omega-3 fatty acid supplementation can improve semen viability. In addition, studies are needed in broodmares to evaluate potential influences of omega-3 fatty acids on fertility and maintenance of pregnancy.

Key Points

- Longer chain (>20 carbons) omega-3 and omega-6 fatty acids have important biological roles in the body.
- Horses have some ability to synthesize the longer-chain omega-3 and -6 fatty acids from essential fatty acid precursors.
- Forages, flaxseed, fish oils, and some algae are typically rich sources of omega-3 fatty acids, whereas cereal grains, vegetable oils, and rice bran are high in omega-6 fatty acids.
- Although research in other species has shown supplementation with omega-3 fatty acids can positively influence inflammation and immune function, studies in horses have shown mixed results.

Potential benefits of increasing fat intake

Research has demonstrated several potential benefits associated with the addition of fat to the equine diet. Research on the anti-inflammatory and immunomodulatory properties of omega-3 fatty acids were described in the previous section. This section will focus on the use of fat to increase the energy density of the diet, temper glycemic response, lessen excitable behavior, alter metabolism to favor utilization of fat, and the potential for dietary fat to reduce thermal load.

Increasing the energy density of the diet

One of the most common reasons for supplementing fat is to increase the energy density of the diet. From a gross energy standpoint, fats contain approximately 2.25 times the energy by weight as carbohydrates. Using data from several studies in which fat intake ranged from 23 to 233 g/kg DM, and with the assumption that fat has gross energy of 9.5 Mcal/kg, Kronfeld et al (2004) estimated mean DE values of 5.2, 7.7 and 9.0 Mcal/kg for ether extract in forages, mixed feeds including added fats and added fats, respectively.

Fat is also an efficient energy source. As might be expected when a fat source is added to an existing diet, Kane et al (1979) observed an increase in digestible and metabolizable energy and energy balance (an estimate of net energy) when either 50 or 96 g corn oil/kg DM was added to a basal diet of oats. When a similar amount of gross energy was provided by replacing some of the forage and cereal grains in the basal diet with 150 g/kg DM of corn oil, tallow or a vegetable oil-tallow blend, increases in digestible and metabolizable energy and energy balance were still apparent (McCann et al 1987). In both of these studies, the amount of energy lost as heat was similar between fat-added and non-fat added diets, although when evaluated as a proportion of DE heat production was lower in diets with added fat. Kane et al (1979) reported that the conversion of metabolizable energy to net energy was 85% in diets containing 29 to 123 g fat/kg DM; however, according to energy and heat production values reported by the author, this estimate seems very high. Using energy values from McCann et al (1987), the conversion of DE to net energy was approximately 26% in diets containing fat, whereas only 17% of DE remained to support energy-requiring processes in diets without added fat. If the energetics of just the fat sources used by McCann et al (1987) are evaluated, the efficiency of conversion of DE to net energy averaged 44%. Collectively, these results indicate the net energy available for growth, work or production could be increased if a portion of daily energy intake is provided as fat. However, it must be noted that the studies of Kane and McCann evaluated energy balance in mature ponies with maintenance-only requirements; the conversion to net energy for tissue accretion or milk production may be more or less efficient and deserves further study. In addition, while Kane et al (1979) observed an increase in the efficiency of energy utilization with increasing fat content in the diet, it would be useful to evaluate the level of dietary fat that may optimize this response. It can be concluded that oils and other high fat ingredients offer an efficient way to increase the overall caloric intake of the horse. Furthermore, such practices permit an increase in energy without drastically increasing DM intake, which may be useful for broodmares, hard-working performance horses, and thin horses that may already be at their upper limit of DM intake.

Alternative to starch as a dietary energy source

Recognition of the energy density of oils and other high-fat feedstuffs has made them a popular alternative energy source to cereal grains. Used in this manner, fat allows the replacement of calories normally provided by NSC, thereby reducing the digestive and metabolic risks associated with diets high in starch and sugar (Kronfeld & Harris 2003).

Modulation of glycemic and insulinemic responses

Replacement of starch and sugar with isocaloric amounts of fat and fiber in concentrates fed to horses has been shown to lower postprandial glycemic and insulinemic responses (Williams et al 2001, Zeyner et al 2006). Some studies have reported similar effects when 10% corn oil was top-dressed on grain-based feeds, which the authors attributed to fat-mediated alterations in gastric emptying (Geor et al 2001, Pagan et al 1999). In contrast, the addition of 0.2 ml/kg BW (~8%) soybean oil or fish oil to a meal of cracked corn had no effect on glycemic or insulinemic responses (Vervuert et al 2010). In addition, a nonisocaloric substitution of 8% linseed oil for barley in a concentrate feed had no effect on mean glucose response to a meal of concentrate but reduced mean serum insulin concentration by half (Fayt et al 2008). Discrepancies between studies may be due to differences in the amount of fat added to the meal, but could also be a result of differences in the starch and sugar content of the meal. For example, Vervuert et al (2010) combined oil with a meal that provided 2 g starch/kg BW, whereas the studies by Geor et al (2001) and Pagan et al (1999) provided 1.5 to

5 g of sweet feed per kg BW. Meal volume, rate of intake, and other dietary constituents may also alter glycemic and insulinemic responses. The type of fat also may impact insulin response. In humans and rodents, the replacement of saturated fats and *trans* fatty acids with monounsaturated or polyunsaturated fats has beneficial effects on insulin sensitivity (Risérus et al 2009). Further studies in horses are warranted to examine the effect of adding different quantities or types of fat to a high-NSC meal on postprandial glucose and insulin responses, particularly in view of current recommendations to add fat (or substitute NSC with fat) to rations for older or insulin resistant horses that have trouble maintaining body weight.

Behavior

Horse owners often comment that dietary fat alters behavior; specifically that horses are more tractable when receiving a ration with added fat. Holland et al (1996) reported that spontaneous activity and reactivity to pressure, loud noise and visual stimuli were reduced in horses fed diets containing 10% soy lecithin and corn oil. More recently, Nicol et al (2005) found that weanlings fed diets high in fat and fiber cantered less frequently and for a shorter duration, spent more time investigating, and took less time to complete a handling test compared to foals fed an isocaloric diet high in starch and sugar. Horses in dressage training had lower resting cortisol concentrations and a reduction in the intensity of their responses to a startle reaction test when fed a fat-added diet (11% DM) compared to an isocaloric diet higher in starch (Redondo et al 2009). Thus, there appears to be merit in the claims by horse owners that fat supplementation favorably alters behavior when used to replace some of the NSC in the diet (see Chapter 25).

Metabolic adaptations and responses to exercise

In horses adapted to high-fat diets, metabolic adaptations appear to favor the utilization of fat as an energy source. Supplementation with fat is generally characterized by an increase in plasma cholesterol and phospholipids and a reduction in plasma triacylglycerol (Frank et al 2004, Geelen et al 1999, Orme et al 1997). Lipoprotein lipase activity is increased with fat adaptation, indicating that skeletal muscle may have increased capacity for uptake of NEFA from circulating triacylglycerol (Geelen et al 1999, 2000, Orme et al 1997). As well, a lower respiratory exchange ratio during low to moderate intensity exercise has been observed in horses adapted to a high fat diet, suggesting that the capacity for oxidation of NEFA is increased with fat supplementation (Dunnett et al 2002, Pagan et al 2002). However, a similar response was not observed at higher workloads, suggesting a greater reliance on carbohydrate during more intensive exercise (Dunnett et al 2002). In two studies, the feeding of a diet supplying 25–30% of DE from fat resulted in a >30% reduction in the production and utilization of glucose during low intensity exercise (30–35% VO_{2max}), as measured by isotopic enrichment with [6-6-d_2]-glucose (Pagan et al 2002, Treiber et al. 2008). Collectively, these findings indicate an increase in the utilization of fat with a concomitant decrease in carbohydrate utilization in fat-adapted horses exercising at low to moderate intensity; however, substrate oxidation does not appear to be altered at higher exercise intensities (> 50–60% VO_{2max}). Although these results suggest fat supplementation may exert a glycogen-sparing effect, assessments of glycogen utilization during either submaximal or maximal exercise have shown no difference between high and low fat diets (Eaton et al 1995, Essen-Gustavsson et al 1991, Harkins et al 1992, Pagan et al 1987).

The metabolic response to fat supplementation is apparent after just 3 weeks of supplementation (Hughes et al 1995, Orme et al 1997). However, these effects are transient and dependent on the continued inclusion of fat in the diet, as the response is abolished within 5 weeks of withdrawal of fat supplementation (Orme et al 1997). The metabolic response to oil supplementation has also been reported to vary between horses, depending on their ability to utilize fat as a fuel source during exercise (Dunnett et al 2002).

Because dietary fat cannot be used as a substrate for glycogen synthesis, there has been some concern that high-fat diets would hamper glycogen repletion following exercise. Despite a reduction in NSC content to accommodate the addition of fat to the diet, some studies have reported an increase in resting muscle glycogen concentration in horses fed high fat diets (Harkins et al 1992, Meyers et al 1989, Oldham et al 1990). In contrast, several other researchers have reported no change or even a slight decrease in resting muscle glycogen when horses were fed comparable levels of fat (Eaton et al 1995, Hyyppa et al 1999, Geelen et al 2001, Orme et al 1997, Pagan et al 1987). Hyyppa et al (1999) reported that acute supplementation with 400 g rapeseed oil following moderate intensity exercise reduced the rate of glycogen repletion; however, this effect was abolished when horses were adapted to a diet containing 50 g fat/kg DM for 3 weeks.

Thermal load

Digestion and assimilation of nutrients as well as nutrient catabolism are not 100% efficient and, as a result, up to 80% of consumed gross energy may be lost as heat. This heat increases the body's thermal load and must be dissipated in order to maintain normal body temperature. Although energy balance studies in horses at rest have not demonstrated a lowered heat production with fat supplementation (Kane et al 1979, McCann et al 1987), such diets have been proposed to reduce the thermal load of horses during exercise (Kronfeld 1996). Using a theoretical model to compare the energetic efficiencies and heat production of three diets that provided varying proportions of fermentable carbohydrate, hydrolysable carbohydrate and fat, Kronfeld (1996) calculated that a hay, oat and corn oil diet (45:45:10% of intake) would result in approximately 2% less heat during moderate to heavy exercise and a 5% reduction (1.2 Mcal or 5 MJ) in total daily heat load compared to a diet of hay and oats (50:50). Although this calculated reduction in total heat load is small, it might be enough to benefit horses living and competing in hot and/or humid environments. However, it must be emphasized that these reductions in heat load are theoretical; thus, the real impact of a high fat diet on thermal load in vivo is unknown.

Athletic performance

Fat supplementation is often lauded for its ability to improve athletic performance, but research to support this claim is inconclusive. Studies have reported an increased time to fatigue during maximal exercise (Eaton et al 1995), faster times when performing repeated sprints (Meyers et al 1989, Oldham et al 1990, Scott et al 1992), and higher cutting scores indicative of greater work effort (Webb et al 1987) when horses were supplemented with greater than 12 to 15% of daily DE intake as fat. In contrast, an equal number of studies have reported no change in performance with similar levels of fat feeding (Topliff et al 1983, Pagan et al 1987, Essen-Gustavsson et al 1991, Hyyppa et al 1999). Mechanisms proposed for improved performance with fat supplementation have included increased stamina as a result of altered substrate use and a glycogen-sparing effect, improved power-to-weight ratio resulting from reduced DM intake and bowl ballast, and a reduction in acidemia and metabolic heat generated during exercise (Kronfeld 1996, Kronfeld et al 1998). However, many these mechanisms are theoretical and unproven while others have yet to be directly associated with the small improvements noted in performance. Ultimately, evidence that adaptation to fat affects exercise capacity is lacking.

Key Points

- The addition of fat to equine rations provides a means of increasing the energy density of the diet and/or replacing carbohydrates as a calorie source.
- Benefits ascribed to fat-added rations, such as modulation of glycemic/insulinemic responses and behavior, are likely related to the simultaneous reduction in NSC intake.
- Habituation to fat-added diets results in metabolic adaptations that favor the utilization of fat during low- to moderate-intensity exercise, but not high intensity exercise.
- Evidence that fat-added diets exert a glycogen-sparing effect, reduce thermal load, and in particular improve athletic performance is inconclusive.

Potential clinical applications of fat-added diets

Gastric ulceration syndrome

Feeding fat to reduce the incidence and severity of gastric ulceration in horses has been recommended but evidence of a beneficial effect in horses is lacking. In ponies, supplementation of a hay diet with corn oil (45 ml administered PO) for 5 weeks reduced gastric acid production and increased gastric fluid PGE_2 concentration when compared to a diet of hay alone (Cargile et al 2004). Although gastric ulceration was not assessed, the authors concluded that corn oil could potentially be helpful in reducing risk of ulceration associated with nonsteroidal anti-inflammatory drug administration. In another study, investigators fed 240 mL of corn oil, refined or crude rice bran oils, or water to horses for 6 weeks to identify effects on gastric ulceration (Frank et al 2005). Oils were added to a relatively high grain diet (estimated at 40 : 60 hay : grain) and fed for 5 weeks, followed by a 7-day intermittent feed deprivation (ulcer-inducing) protocol in which the same high grain diet was offered on alternating days. Neither of the rice bran oils nor corn oil prevented the formation of gastric ulcers or affected the severity of non-glandular mucosal ulceration (Frank et al 2005). It is possible that fat supplementation could help attenuate existing gastric ulcer severity if it permits total intake of NSC to be reduced (see Chapter 34). In conclusion, more research is needed to identify if vegetable oils have specific properties that may help protect gastric mucosal integrity.

Chronic exertional myopathies

The addition of fat to the diet can help in the management of horses afflicted with chronic exertional myopathies, including recurrent exertional rhabdomyolysis (RER) and Type 1 and 2 polysaccharide storage myopathy (PSSM). Thoroughbreds with RER had lower serum creatine kinase activity when fed a high fat, low starch diet (20% and 7% of DE, respectively) compared to an isocaloric diet high in starch (40% of DE) (McKenzie et al 2003). It has been suggested that replacing a portion of the NSC with fat may help assuage excitability or nervousness in horses with RER, which are believed to trigger episodes. For horses with RER, it has been recommended that at least 15% of DE requirements be supplied by fat, in combination with less than 20% of the total daily DE as starch (Valberg 2010). Several studies have demonstrated a reduction in clinical signs in horses with PSSM fed low starch (< 5% of DE), fat-added (≥12% of DE) diets compared to high starch diets (Firshman et al 2003, Ribeiro et al 2004). The benefit of a low starch, high fat diet for PSSM horses is believed to be the result of less glucose uptake by muscle and increased availability of fatty acids for use by muscle during exercise. The challenge in feeding horses with PSSM is providing enough calories to provide energy during exercise, yet preventing excessive weight gain. To further complicate matters, many PSSM horses are not in training and/or are overweight; thus, the additional calories supplied by dietary fat would simply result in unwanted weight gain. Because of the variation in training status and body condition of horses with PSSM, the need for fat supplementation can vary. Nonetheless, oils and other high fat feedstuffs can be used in lieu of ingredients rich in NSC when additional calories are required in the diet. However, it is worth noting that a recent study found that fats containing short-chain fatty acids (< 10 carbons) are ill-suited for reducing signs of PSSM compared to longer-chain fatty acids (>14 carbons) (Borgia et al 2010). Very few fat sources included in equine diets are naturally low in short chain fatty acids. Coconut oil has approximately 14% short chain fatty acids and thus might not be an ideal source of fat for horses with PSSM. The reader is referred to Chapter 31 for further information on feeding horses with PSSM and RER.

Insulin sensitivity

In humans and other species, a high fat diet (>38% daily caloric intake) that is mostly saturated fat has been associated with the development of insulin resistance (Risérus et al 2009). By comparison, "high fat" diets for horses supply less fat calories (10–20% of DE) and the plant oils and other high fat ingredients commonly added to equine diets generally contain an abundance of unsaturated fatty acids (Table 7-1). Currently, there is no evidence that this level of polyunsaturated fatty acid-rich oil supplementation results in insulin resistance in horses.

In humans, replacement of saturated fatty acids in the diet with mono- or polyunsaturated fatty acids often results in improvement in insulin sensitivity in both healthy and type II diabetic patients (Risérus et al 2009). Although omega-6 and omega-3 polyunsaturated fatty acids have been shown to directly impact membrane fluidity, insulin receptor binding/affinity, glucose transport, hepatic gluconeogenesis, and/or gene expression, their ability to improve insulin sensitivity in humans and other species appears to be mostly related to the concurrent reduction in saturated fat intake that accompanies the addition of polyunsaturated fatty acids to the diet (Fedor & Kelley 2009, Manco et al 2004, Risérus et al 2009). That is to say, supplementing an existing diet, particularly one already high in (saturated) fat with polyunsaturated fatty acids has not been shown to positively impact insulin responsiveness. The effect of different types of fatty acids on insulin sensitivity has not been as thoroughly examined in horses, but available evidence suggests that horses may respond similarly to other species. Although insulin sensitivity was not directly evaluated, glycemic and insulinemic responses were similar when horses were fed a meal of cracked corn with or without the addition of 8% soybean oil or fish oil (Vervuert et al 2010). Fayt et al (2008) reported a lower mean insulin concentration when linseed oil (8%) was substituted for some of the barley in a concentrate feed; however, this might be explained in part by a lower total intake of NSC when linseed oil was included.

Healthy adult and growing horses have been shown to have higher insulin sensitivity when consuming a concentrate rich in polyunsaturated fat and fiber compared to an isocaloric concentrate high in starch and sugar (Treiber et al 2005, Quinn et al 2008). Hoffman et al (2003) reported that insulin sensitivity was similar between pastured horses supplemented with hay or a concentrate rich in fat and fiber, yet insulin sensitivity was greater on these diets compared to a diet of pasture plus a concentrate rich in starch and sugar. Thus, the higher insulin sensitivity observed in horses supplemented with fat (and fiber) in these studies is more likely the result of a reduction in NSC than an increase in fat intake per se.

A comparison of fat-added vs. non-fat added diets in horses that have been diagnosed as insulin resistant or those confirmed to have equine metabolic syndrome or pituitary pars intermedia dysfunction has not been reported. Nonetheless, the use of fat supplements rich in unsaturated fatty acids are currently considered to be acceptable for use in the diets of horses who have insulin resistance when calorie-dense feedstuffs are needed to maintain adequate body condition.

Colic

The daily feeding of vegetable oil has been wrongly perceived as having the ability to “flush” or “lubricate” the gut, thereby preventing impaction or sand colic. Nasogastric administration of relatively large quantities of mineral oil is a common medical treatment for colic (Singer & Smith 2002) and is sometimes used prophylactically for evacuation of sand from the gastrointestinal tract (Hotwagner & Iben 2007). However, mineral oil differs from vegetable oils because it is a petroleum product that is not digested and cannot be absorbed. In contrast, vegetable oils included in the diet at common feeding rates are almost completely digested in the small intestine; thus, very little likely remains to “flush” the other contents through the gastrointestinal tract. Although feeding or administering large quantities of oil to horse that is not adapted to fat may cause loose, oily feces (Schumacher et al 1997), this outcome reflects digestive distress and should be avoided.

Key Points

- Dietary fat can serve as a useful calorie source for horses with special feeding needs.
- By replacing NSC as a calorie source, dietary fat has the potential to reduce risk of gastric ulcers, maintain insulin sensitivity, and reduce clinical signs of chronic exertional myopathies.
- There is no evidence that feeding vegetable oil will “lubricate” the gut or reduce colic risk.

Practical guidelines for feeding fat to horses

Various sources of fat have successfully been added to the diets of growing horses, broodmares, performance horses, older horses, and those with special needs (NRC 2007, Potter et al 1992). This section compares available options for adding fat to equine rations and provides guidelines on how to introduce oils and other high fat feeds to the diet.

Options for inclusion of dietary fat

Several options exist for adding fat to equine diets, ranging from the addition of a variety of vegetable oils or high-fat feedstuffs to an existing ration to the use of a commercial fat supplement or fat-added concentrate. The choice of a specific fat source or the method of fat inclusion will depend on the availability of the fat source or product, the horse’s preference, the ease of incorporating the fat source into the feeding program, the owner’s goal for feeding fat, and cost. Many owners find commercial fat-supplemented feeds to be a convenient means of including fat in their horse’s diet. Such products also help to ensure the feed is balanced with respect to other nutrients in the diet. Most unfortified concentrates contain 2–4% crude fat, whereas “fat-added” feeds usually range from 5–14% crude fat. Fat fortification can raise the energy density of a concentrate by 10 to 50% (e.g., from 3.0 Mcal/kg to 4.5 Mcal/kg); thus commensurately less of a high-fat feed is needed to replace the quantity of a traditional concentrate. However, some commercial fat-added feeds contain additional fiber, which can neutralize the gain in energy density making it more similar to a traditional concentrate that is high in NSC.

Alternatively, horse owners may elect to top-dress oil on an existing ration. Preference tests have generally shown that horses prefer corn oil over other vegetable oils and vegetable oils over animal fats (Bowman et al 1979, Holland et al 1998) (Fig. 7.4). A standard measuring cup can hold 8 fl oz (250 ml) of water and 200 g (1.8 Mcal DE) of vegetable oil. One cup of oil is equivalent to approximately 10% of the maintenance DE requirement for a 500-kg horse. The DE of one cup of oil is equivalent to that provided in

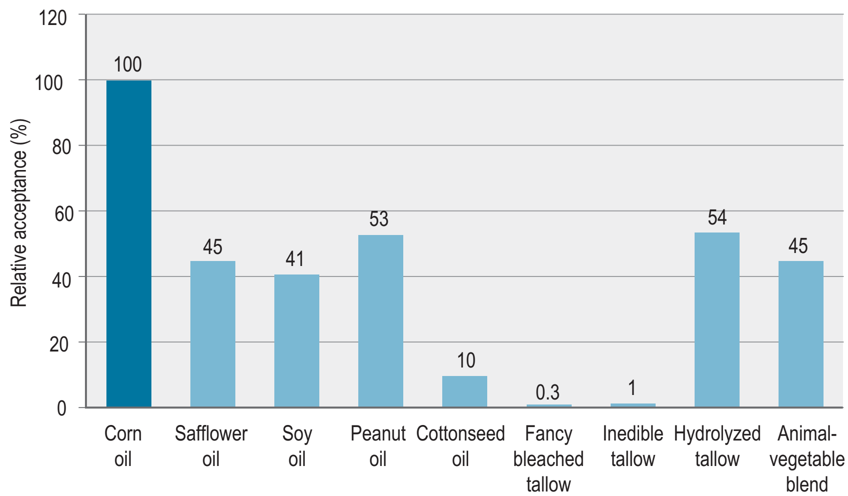

Figure 7.4 Relative acceptance of fats evaluated in palatability experiments compared to corn oil. *Data from* Holland et al (1998).

approximately 0.55 kg oats or rice bran and 0.50 kg corn. It should be cautioned that if oil is top-dressed on an existing ration, as opposed to using a fat-fortified feed, the diet may become unbalanced. It is especially important to evaluate the diets of growing horses and broodmares for nutrient deficiencies and imbalances that might be created by top-dressing oil. Oils provide calories, but they are devoid of protein and minerals. To a varying extent, oils also provide fat-soluble vitamins; however, many of the naturally-occurring tocopherols may be used in defense of lipid peroxidation during storage of the oil and are thus unavailable to aid in meeting the vitamin E requirements of the horse.

Amount of fat to include in the diet

The amount of fat to include in the diet will depend on the feeding goals. For example, it might only take a ½ cup (125 ml) of oil a day to add shine to a horse's hair coat, whereas 1 to 2 cups or more of oil per day for a 500-kg horse may be needed if the goal is to add a significant quantity of calories to the diet or to derive any potential performance benefits. Similarly, the specific feeding goal might dictate the type of fat that should be used. Table 7-3 summarizes the quantity, and in some cases the type, of dietary fat suggested or reported to be effective for a variety of desired outcomes. It should be noted that the quantities listed in Table 7-3 may not reflect the minimum level of fat needed to derive the specific benefit as this may not be established.

Inclusion of fat in the diets of performance horses is becoming commonplace. Anecdotally, some nutritionists recommend higher fat diets (8–10% DM intake, 20–25% of DE intake) for horses participating in more prolonged, submaximal activities, whereas lower fat intakes (5–6% DM intake, 10–15% of DE intake) are suggested for horses competing in racing or other high speed events (e.g., barrel racing). The philosophy behind such recommendations is rooted in the greater perceived need for carbohydrates as a substrate for muscle during maximal intensity, short-duration exercise. Fat supplementation does not appear to alter substrate oxidation in favor of the use of fat over carbohydrate at exercise intensities >50–60% VO_{2max} (Dunnett et al 2002). Thus, it's likely that diets for these horses should still contain a significant portion of hydrolysable carbohydrates to support higher intensity activities.

In contrast to the larger body of work evaluating fat supplemented diets for performance horses, little work has been carried out in broodmares and growing horses to establish ideal rates and types of dietary fat inclusion. While both groups would likely respond positively to fat as a calorie source, it is imperative that the diet as a whole remains balanced with regard to DE, protein, minerals and vitamins. Additional work is needed in young horses (especially those <1 year of age) to establish upper limits of fat inclusion (if it differs from mature horses), as well as verify the effects of high fat diets on absorption of calcium and other minerals crucial for bone development. Based on work at Virginia Tech, weanlings appear to do well when provided a feed with relatively low starch, high fiber and 10–15% crude fat, fed in a 1 : 1 to 1 : 2 ratio with forage (e.g., Hoffman et al 1999, 2001, Staniar et al 2007, Treiber et al 2005).

An adequate acclimatization period of up to 12 weeks may be required to reap the full benefits of fat supplementation, although some positive metabolic adaptations may be observed within 3–5 weeks of the introduction of fat into the diet (Dunnett et al 2002, Kronfeld & Harris 2003, Pagan et al 2002).

Upper limit of fat inclusion in equine diets

The upper limit of fat inclusion in equine diets has not been established for all sources of fat. Diets with up to 230 g fat/kg DM from added corn oil, peanut oil, tallow, and animal-vegetable fat blends appear to be acceptable to horses without negatively impacting digestion of other nutrients (Kronfeld et al 2004). In contrast, current information suggests that soybean oil should be limited to 0.7 g/kg BW/day (NRC 2007). Higher rates of fat inclusion may increase the risk for digestive disturbance, interfere with microbial fermentation of fiber in the hindgut, or reduce calcium absorption via formation of mineral-fat soaps. In addition, acceptance of high levels of dietary fat will likely vary between individual horses, based on palatability and texture preferences, as well as gastrointestinal tolerance. For example, some horses appear to dislike oils, but are more accepting of rice bran or flaxseed. Similarly, some horses will develop loose or greasy feces at lower levels of fat inclusion, while others will be able to consume relatively high quantities of fat with no apparent digestive problems. Although horses seem to tolerate relatively high levels of fat,

Table 7-3 Fat Source and Level of Inclusion in the Diet Shown to Produce Various Biological and Physiological Responses. Note That the Level of Inclusion Listed May Not Necessarily Represent the Minimum Amount Needed to Achieve the Desired Outcome

Biological or physiological response	Fat source used	Level of inclusion	Reference
Increase in plasma α-linolenic acid	Flaxseed	6 g ALA/100 kg BW	Stelzleni et al 2006
Increase in plasma eicosapentaenoic and decosahexaenoic acids	Fish oil (encapsulated)	2 g EPA+DHA/100 kg BW	King et al 2008
Skin improvement in response to Culicoides	Flaxseed	55 g ALA/100 kg BW	O'Neill et al 2002
Decrease in eicosanoid production	Fish oil (encapsulated)	7.2 g EPA+DPA+DHA/100 kg BW	Vineyard et al 2008
Decrease in eicosanoid production	Corn oil	43.2 g LA/100 kg BW	Vineyard et al 2008
Improved semen characteristics	Fish oil (encapsulated)[a]	3.1 g DHA/100 kg BW	Brinsko et al 2005
Reduced reactivity or excitability	Mix of soy lecithin and corn oil	200 g fat/100 kg BW	Holland et al 1996
Reduction in clinical signs of PSSM		≥ 13% of DE as fat[b]	Ribeiro et al 2004
Reduction in clinical signs of RER		15–25% of DE as fat[c]	McKenzie et al 2003
Decreased heat production during exercise	Vegetable oil	200 g oil/100 kg BW[d]	Kronfeld 1996
Metabolic adaptations to increase utilization of fat during exercise	Soybean oil	20% of DE as oil	Dunnett et al 2002

[a]25% DHA, 5% EPA.
[b]Paired with < 10% of DE from starch.
[c]Paired with < 20% of DE from starch.
[d]Based on theoretical calculations.

it is worth noting that in practice most rations are considerably lower than 230 g fat/kg DM, even with the use of so-called "high-fat" commercial feeds.

Introducing fat to the diet

Key to the success of any fat feeding program is gradual introduction of the oil or fat-added feed. Transition to high fat feeds or oils usually takes about 4 to 14 days in healthy horses. However, this will vary based on the quantity of fat fed and between individual horses. If top-dressing oil on an existing ration, a conservative approach is to start with ¼ cup (~60 ml) per meal and increase the amount by ¼ cup every 2–3 days until the desired 1 or 2 cups/day is reached in 2–3 weeks. Similarly, a fat-added feed or fat supplement should be introduced in small increments (~25% of the desired feeding rate) every 3 or 4 days. When initiating a fat feeding program, horses should be closely observed for signs of digestive upset and the rate of fat introduction adjusted accordingly. If the horse's feces are greasy, grayish in color, more abundant, or too loose, the introduction of fat may have been too rapid. These signs are usually preceded by sheen on well-formed fecal balls, a sign of some fat escaping digestion (Kronfeld et al 2004). In such cases, the amount of fat should be temporarily reduced until the feces return to normal, followed by reintroduction of fat at a slower rate.

Impact of fat-added diets on antioxidant requirements

Fatty acids, particularly unsaturated fatty acids, are prone to oxidation. As a result, it is often recommended that additional antioxidants be added to the diet. Unfortunately, there has been limited study on the impact of high fat diets on antioxidant requirements in horses. Vitamin E status was not negatively affected in horses fed diets with 64 g fat/kg DM (~20% of DE intake) from added soybean oil and 80 IU vitamin E/kg DM (Siciliano & Wood 1993). Vitamin E status was similarly unaffected in ponies fed a diet with 10% of DE intake from corn oil; however, plasma thiobarbituric acid reactive substances (TBARS) and breath pentane were elevated during exercise, especially in ponies with lower plasma vitamin E concentrations (McMeniman & Hintz 1992). Although TBARS and breath pentane are non-specific markers of oxidative stress, this finding indicates that additional vitamin E may be needed in the diet of horses with increased oxidative loads, even when including only moderate levels of fat. The level and type of endogenous tocopherols present in vegetable oils varies between different sources (Table 7-4), which may explain the discrepancy between these two studies. In addition, at least a portion of the naturally occurring tocopherols in oil may be used in defense of lipid peroxidation during storage and are thus unavailable to aid in meeting the vitamin E requirements of the horse. Functional and synergistic relationships between different antioxidant nutrients (e.g., selenium, vitamin C, carotenoids) and their level in the diet could further impact the need for additional supplementation; however, these relationships have not been investigated in the horse.

A general recommendation for the prevention of peroxidative damage is to provide a minimum of 100 IU of vitamin E per 100 ml of vegetable oil (Harris 1999, Stratton-Phelps et al 2003). This recommendation is based on research in rodents that concluded that 0.6 mg α-tocopherol equivalents per gram of linoleic acid was suitable for preventing excessive lipid peroxidation, and that some of the endogenous tocopherols in oil may be applied towards meeting this

Table 7-4 α- and γ-Tocopherol Content and Vitamin E Activity (as α-Tocopherol Equivalents) in Various Oils and Fats[a]

Fat source	α-tocopherol (mg/100 g)	γ-tocopherol (mg/100 g)	Vitamin E activity (mg/100 g)
Canola oil	21.0	4.2	21.5
Coconut oil	0.5	–[b]	0.7
Corn oil	11.2	60.2	19.8
Cottonseed oil	38.9	38.7	42.8
Olive oil	11.9	–	12.0
Palm oil	25.6	31.6	33.5
Peanut oil	13.0	21.4	15.2
Safflower oil	34.2	7.1	34.9
Soybean oil	7.5	79.7	17.1
Sunflower oil	48.7	5.1	49.2
Wheat germ oil	133.0	26.0	173.6
Cod liver oil	22.0	–	22.0
Herring oil	9.2	–	9.2
Menhaden fish oil	7.5	–	7.5
Lard	1.2	–	1.5
Tallow	2.7	–	2.7

[a]Data modified from Sheppard et al 1993.
[b]Dashes denote no value or trace.

additional tocopherol requirement (Valk & Hornstra 2000). Although research findings have been inconsistent, there is evidence in other species that supplementation with highly unsaturated fatty acids (e.g., EPA and DHA), even if coupled with lower total fat intakes, would require higher levels of vitamin E supplementation (Valk & Hornstra 2000). However, supplementation of yearling horses with high levels of EPA and DHA (6 g/100 kg BW) from encapsulated fish oil had no negative effects on plasma vitamin E or lipid-specific measures of peroxidative damage (e.g., lipid hydroperoxides, F2-isoprostanes) when diets contained adequate levels of vitamin E and a relatively low total fat content (4.2% DM) (White et al 2007). Further research on the impact of various fat sources on antioxidant requirements is needed, particularly in horses under increased oxidative stress (e.g., performance horses).

Product stability

Due to potential for oxidation, inclusion of fat in the concentrate can reduce the shelf life of the product compared to a non fat-added feed (e.g., by 1 to 2 weeks in hot and humid climates). Most feed manufacturers attempt to counteract the deterioration of fats by adding natural and/or artificial antioxidants to their products. Nonetheless, the risk of rancidity is still a concern if feeds are stocked for long periods in a warehouse or with distributors before being purchased or if owners fail to store products appropriately or utilize them in a timely manner. Fat with a high content of unsaturated fatty acids is particularly susceptible to oxidation, resulting in deterioration of fatty acids and the development of a number of components (e.g., hydroxyperoxides and aldehydes) which may have negative local and systemic effects on the horse if consumed. Rancid feeds should not be fed to horses.

Owners should regularly inspect fat-added feeds and supplements. Feeds that have gone rancid tend to have a sweet, alcohol-like smell and are generally, but not always unpalatable to horses. Fat-added feeds, supplements and oils should be stored in a cool, dry location and be purchased in quantities that can be fed in 2 to 4 weeks, depending on season and/or climate.

Potential contraindications for feeding fat to horses

Increasing the fat content of the diet can benefit many horses; however, there are a few scenarios in which this practice would be contraindicated. First and most obvious are horses or ponies that are already overweight or obese. Dietary fat is the most calorie-dense component that can be added to the diet; thus, adding fat to the diet of an animal that is overweight is not only unnecessary, it can contribute to diseases associated with obesity (e.g., insulin resistance) by promoting weight gain. Similarly, fat should not be added to the diet of ponies or horses prone to or experiencing hyperlipemia. Finally, added fat should not be a part of the initial refeeding program for starved or severely malnourished horses, as many of these horses have compromised gastrointestinal and organ function (Kronfeld 1993, Witham & Stull 1998).

Key Points

- Fat should be introduced into the diet gradually to avoid digestive problems.
- Be attentive to nutrient imbalances when top-dressing oil onto an existing ration.
- Commercial fat-added feeds are available and typically contain 5–14% crude fat.
- The level of fat to include in equine diets will depend on the feeding goals and desired outcome.
- Fat should not be added to equine diets indiscriminately and should be avoided in overweight horses.
- Inclusion of high levels of fat in the diet may precipitate a higher need for antioxidants such as vitamin E.

Conclusion

In today's equine industry, the inclusion of fat sources in horse rations has become commonplace even though this concept was considered fairly novel as little as 20 years ago. It could be argued that the widespread use of vegetable oils and the availability of fat-added rations, particularly those with higher fiber and lower starch, is perhaps the biggest change to horse feeding to occur in the last 20 or so years. Furthermore, this shift in feeding practice was driven by scientific research. Oils and other fat-rich feedstuffs offer a means to dramatically alter calorie intake in horses, not only in quantity but also in quality, enabling the formulation of safe and effective diets for healthy and special needs horses. Although great inroads have been made, there is still much to learn about how the horse utilizes fat, as well as the biological and physiological benefits that can be harnessed from different fat sources.

References

Berbert, A.A., Kondo, C.R., Almendra, C.L., et al., 2005. Supplementation of fish oil and olive oil in patients with rheumatoid arthritis. Nutrition 21, 131–136.

Borgia, L.A., Valberg, S.J., McCue, M.E., et al., 2010. Effect of dietary fats with odd or even numbers of carbon atoms on metabolic response and muscle damage with exercise in Quarter Horse-type horses with type 1 polysaccharide storage myopathy. Am J Vet Res 71, 326–336.

Boufaïed, H., Chouinard, P.Y., Tremblay, G.F., et al., 2003. Fatty acids in forages. I. Factors affecting concentrations. Can J Anim Sci 83, 501–511.

Bowman, V.A., Fontenot, J.P., Meacham, T.N., et al., 1979. Acceptability and digestibility of animal, vegetable and blended fats by equine. In: Proc 6th Equine Nutr Physiol Symp, College Station, TX. Equine Nutrition and Physiology Society, Savoy, IL, p. 74.

Brinsko, S.P., Varner, D.D., Love, C.C., et al., 2005. Effect of feeding a DHA-enriched nutraceutical on the quality of fresh, cooled and frozen stallion semen. Theriogenology 63, 1519–1527.

Bush, J.A., Freeman, D.E., Kline, K.H., et al., 2001. Dietary fat supplementation effects on in vitro nutrient disappearance and in vivo nutrient intake and total tract digestibility by horses. J Anim Sci 79, 232–239.

Byers, F.M., Schelling, G.T., 1988. Lipids in ruminant nutrition. The Ruminant Animal, Digestive Physiology and Nutrition. In: Church, D.C. (Ed.), Prospect Heights. Waveland Press, Inc, Illinois, pp. 298–312.

Calder, P.C., 2006. Polyunsaturated fatty acids and inflammation. Prostaglandins Leukotr Essent Fatty Acids 75, 197–202.

Calder, P.C., Grimble, R.F., 2002. Polyunsaturated fatty acids, inflammation and immunity. Eur J Clin Nutr 56 (suppl. 3), S14–S19.

Cargile, J.L., Burrow, J.A., Kim, I., et al., 2004. Effect of dietary corn oil supplementation on equine gastric fluid acid, sodium, and prostaglandin E2 content before and during pentagastrin infusion. J Vet Intern Med 8, 545–549.

Cleland, L.G., French, J.K., Betts, W.H., et al., 1998. Clinical and biochemical effects of dietary fish oil supplements in rheumatoid arthritis. J Rheumatol 15, 1471–1475.

Coenen, M., 1986. Verdaulichkeit und praecaecale passage einer suspendierfähigen diät in abhängigkeit von der applikationsform (spontane futteraufnahme bzw. Flüssig per sonde). J Anim Physiol Anim Nutr 56, 104–117.

Davison, K.E., Potter, G.D., Greene, L.W., et al., 1991. Lactation and reproductive performance of mares fed added dietary fat during late gestation and early lactation. J Equine Vet Sci 11, 111–115.

Delobel, A., Fabry, C., Schoonheere, N., et al., 2008. Linseed oil supplementation in diet for horses: Effects on palatability and digestibility. Livestock Sci 116, 15–21.

Domingo, J.L., Bocio, A., Falco, G., et al., 2007. Benefits and risks of fish consumption I. A quantitative analysis of the intake of omega-3 fatty acids and chemical contaminants. Toxicology 230, 219–226.

Dunnett, C.E., Marlin, D.J., Harris, R.C., 2002. Effect of dietary lipid on response to exercise: Relationship to metabolic adaptation. Equine Vet J 34 (Suppl), 75–80.

Duvaux-Ponter, C., Tournie, M., Detrimont, L., et al., 2004. Effect of a supplement rich in linolenic acid added to the diet of mares on fatty acid composition of mammary secretions and the acquisition of passive immunity in the foal. Anim Sci 78, 399–407.

Eaton, M.D., Hodgson, D.R., Evans, D.L., et al., 1995. Effect of a diet containing supplementary fat on the capacity for high intensity exercise. Equine Vet J 18 (Suppl), 353–356.

Essen-Gustavsson, B., Blomstrand, E., Karlstrom, K., et al., 1991. Influence of diet on substrate metabolism during exercise. In: Persson, S.G.B., Lindholm, A., Jeffcott, L.B. (Eds.), Equine Exercise Physiology 3. ICEEP Publications, Stockholm, Sweden, pp. 288–298.

Fahy, E., Subramaniam, S., Brown, H.A., et al., 2005. A comprehensive classification system for lipids. J Lipid Res 46, 839–861.

Fayt, J., Dotreppe, O., Hornick, J.L., et al., 2008. Spelt, an ancient cereal and first pressure linseed oil as ingredients of compound feedstuffs for modern horse feeding. J Anim Physiol Anim Nutr 92, 303–309.

Fedor, D., Kelley, D.S., 2009. Prevention of insulin resistance by n-3 polyunsaturated fatty acids. Curr Opin Clin Nutr Metab Care 12, 138–146.

Firshman, A.M., Valberg, S.J., Bender, J.B., et al., 2003. Epidemiologic characteristics and management of polysaccharide storage myopathy in Quarter Horses. Am J Vet Res 64, 1319–1327.

Frank, N., Sojka, J.E., Latour, M.A., 2004. Effect of hypothyroidism on the blood lipid response to higher dietary fat intake in mares. J Anim Sci 82, 2640–2646.

Frank, N., Andrews, F.M., Elliott, S.B., et al., 2005. Effects of dietary oils on the development of gastric ulcers in mares. Am J Vet Res 66, 2006–2011.

French, S.J., Murray, B., Rumsey, R.D., et al., 1995. Adaptation to high-fat diets: effects on eating behaviour and plasma cholecystokinin. Br J Nutr 73, 179–189.

Friberg, C.A., Logas, D., 1999. Treatment of culicoides hypersensitive horses with high-dose n-3 fatty acids: A double-blinded crossover study. Vet Derm 10, 117–122.

Fonnesbeck, P.V., Lydman, R.K., Vander Noot, G.W., et al., 1967. Digestibility of the proximate nutrients of forage by horses. J Anim Sci 26, 1039–1044.

Gatta, D., Casini, L., Liponi, G.B., et al., 2005. Effect of oils administration on diets digestibility and haematic fatty acids profile in exercising horses. Ital J Anim Sci 4 (Suppl 2), 415–417.

Geelen, S.N.J., Sloet van Oldruitenborgh-Oosterbaan, M.M., Beynen, A.C., 1999. Dietary fat supplementation and equine plasma lipid metabolism. Equine Vet J 30 (Suppl), 475–478.

Geelen, S.N.J., Jansen, W.L., Geelen, M.M., et al., 2000. Lipid metabolism in equines fed a fat-rich diet. Int J Vitam Nutr Res 70, 148–152.

Geelen, S.N.J., Blazquez, C., Geelen, M.J.H., et al., 2001. High fat intake lowers fatty acid synthesis and raises fatty acid oxidation in aerobic muscle in Shetland ponies. Br J Nutr 86, 31–36.

Geor, R.J., Harris, P.A., Hoekstra, K.E., et al., 2001. Effect of corn oil on solid-phase gastric emptying in horses. (Abstr.) Proc. 19th ACVIM. p. 853.

Godoi, F.N., Almeida, F.Q., Saliba, E.O.S., et al., 2009. Intake, digestive kinetics and nutrient digestibility in athletic horses fed diets with soybean oil. R Bras Zootec, online version, vol 38, doi: 10.1590/S1516–35982009001000011.

Goyens, P.L.L., Spiker, M.E., Zock, P.L., et al., 2006. Conversion of α-linolenic acid in humans is influenced by the absolute amounts of α-linolenic acid and linoleic acid in the diet and not by the ratio. Am J Clin Nutr 84, 44–53.

Greeve, J., Altkemper, I., Dieterich, J.H., et al., 1993. Apolipoprotein B mRNA editing in 12 different mammalian species: hepatic expression is reflected in low concentrations of apoB-containing plasma lipoproteins. J Lipid Res 34, 1367–1383.

Gurr, M.I., Harwood, J.L., Frayn, K.N., 2002. Lipid Biochemistry: an Introduction. fifth ed. Blackwell Science Ltd., Oxford, UK.

Hall, J.A., Van Saun, R.J., Tornquist, S.J., et al., 2004a. Effect of type of dietary polyunsaturated fatty acid supplement (corn oil or fish oil) on immune responses in healthy horses. J Vet Intern Med 18, 880–886.

Hall, J.A., Van Saun, R.J., Wander, R.C., 2004b. Dietary (n-3) fatty acids from menhaden fish oil alter plasma fatty acids and leukotriene b synthesis in healthy horses. J Vet Intern Med 18, 871–879.

Hallebeek, J.M., Beynen, A.C., 2002. The plasma level of triacylglycerols in horses fed high-fat diets containing either soybean oil or palm oil. J Anim Physiol Anim Nutr 86, 111–116.

Hargin, K.D., Morrison, W.R., 1980. The distribution of acyl lipids in the germ, aleurone, starch and non-starch endosperm of four wheat varieties. J Sci Food Agric 31, 877–888.

Harkins, J.D., Morris, G.S., Tulley, R.T., et al., 1992. Effect of added dietary fat on racing performance in Thoroughbred horses. J Equine Vet Sci 12, 123–129.

Harwood, J.L., 1996. Recent advances in the biosynthesis of plant fatty acids. Biochim Biophys Acta 1301, 7–56.

Harris, M.A., Baumgard, L.H., Arns, M.J., et al., 2005. Stallion spermatozoa membrane phospholipid dynamics following dietary n-3 supplementation. Anim Reprod Sci 89, 234–237.

Harris, P.A., 1999. Feeding and management advice for tying up. Proceedings of the BEVA Specialist meeting on Nutrition and Behaviour 100–104.

Hess, B.W., Moss, G.E., Rule, D.C., 2008. A decade of developments in the area of fat supplementation research with beef cattle and sheep. J Anim Sci 86 (E. Suppl.), E188–E204.

Henry, M.M., Moore, J.N., Feldman, E.B., et al., 1990. Effect of dietary alpha-linolenic acid on equine monocyte procoagulant activity and eicosanoid synthesis. Circ Shock 32, 173–188.

Henry, M.M., Moore, J.N., Fischer, J.K., 1991. Influence of an omega-3 fatty acid-enriched ration on in vivo responses of horses to endotoxin. Am J Vet Res 52, 523–527.

Hintz, H.F., Schryver, F.F., 1989. Digestibility of various sources of fat by horses. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. Syracuse, NY, pp. 44–48.

Hoffman, R.M., Lawrence, L.A., Kronfeld, D.S., et al., 1999. Dietary carbohydrates and fat influence radiographic bone mineral content of growing horses. J Anim Sci 77, 3330–3338.

Hoffman, R.M., Wilson, J.A., Lawrence, L.A., et al., 2001. Supplemental calcium does not influence radiographic bone mineral content of growing foals fed pasture and a fat and fiber supplement. In: Proceedings of Equine Nutrition and Physiology Society Symposium, Lexington, KY. Equine Nutrition and Physiology Society, Savoy, IL, pp. 122–123.

Hoffman, R.M., Boston, R.C., Stefanovski, D., et al., 2003. Obesity and diet affect glucose dynamics and insulin sensitivity in Thoroughbred geldings. J Anim Sci 81, 2333–2342.

Holland, J.L., Kronfeld, D.S., Meacham, T.N., 1996. Behavior of horses is affected by soy lecithin and corn oil in the diet. J Anim Sci 74, 1252–1255.

Holland, J.L., Kronfeld, D.S., Rich, G.A., 1998. Acceptance of fat and lecithin containing diets by horses. Appl Anim Behav Sci 56, 91–96.

Hotwagner, K., Iben, C., 2007. Evacuation of sand from the equine intestine with mineral oil, with and without psyllium. J Anim Physiol Anim Nutr 92, 86–91.

Hughes, S.J., Potter, G.D., Greene, L.W., et al., 1995. Adaptation of Thoroughbred horses in training to a fat supplemented diet. Equine Vet J 18 (Suppl), 349–352.

Hussein, N.E., Ah-Sing, P., Wilkinson, C., et al., 2005. Long-chain conversion of [^{13}C]linoleic acid and alpha-linolenic acid in response to marked changes in their dietary intake in men. J Lipid Res 46, 269–280.

Hyyppa, S., Saastamoinen, M., Poso, A.R., 1999. Effect of a post exercise fat-supplemented diet on muscle glycogen repletion. Equine Vet J 30 (Suppl), 493–498.

Iqbal, J., Hussain, M.M., 2009. Intestinal lipid absorption. Am J Physiol Endocrinol Metab 296, E1183–E1194.

IUPAC-IUB (International Union of Pure & Applied Chemistry-International Union of Biochemistry), 1976. The nomenclature of lipids. IUPAC-IUB Commission on Biochemical Nomenclature. J Lipid Res 19, 114–128.

James, M.J., Gibson, R.A., Cleland, L.G., 2000. Dietary polyunsaturated fatty acids and inflammatory mediator production. Am J Clin Nutr 71, 343S-348S.

Jansen, W.L., van der Kuilen, J., Geelen, S.N.J., et al., 2000. The effect of replacing nonstructural carbohydrates with soybean oil on the digestibility of fibre in trotting horses. Equine Vet J 32, 27–30.

Jansen, W.L., van der Kuilen, J., Geelen, S.N.J., et al., 2001. The apparent digestibility of fibre in trotters when dietary soybean oil is substituted for an iso-energetic amount of glucose. Arch Anim Nutr 54, 297–304.

Jansen, W.L., Geelen, S.N.J., van der Kuilen, J., et al., 2002. Dietary soybean oil depresses the apparent digestibility of fibre in trotters when substituted for an iso-energetic amount of corn starch or glucose. Equine Vet J 34, 302–305.

Jansen, W.L., Sloet van Oldruitenborgh-Oosterbaan, M.M., Cone, J.W., et al., 2007. Studies on the mechanism by which a high intake of soybean oil depresses the apparent digestibility of fibre in horses. Anim Feed Sci Tech 138, 298–308.

Jenkins, T.C., 1993. Lipid metabolism in the rumen. J Dairy Sci 76, 3851–3863.

Kane, E., Baker, J.P., Bull, L.S., 1979. Utilization of a corn oil supplemented diet by the pony. J Anim Sci 48, 1379–1384.

Khol-Parisini, A., van den Hoven, R., Leinker, S., et al., 2007. Effects of feeding sunflower oil or seal blubber oil to horses with recurrent airway obstruction. Can J Vet Res 71, 59–65.

King, S.S., Abughazaleh, A.A., Webel, S.K., et al., 2008. Circulating fatty acid profiles in response to three levels of dietary omega-3 fatty acid supplementation in horses. J Anim Sci 86, 1114–1123.

Kronfeld, D.S., 1993. Starvation and malnutrition: recognition and treatment. J Equine Vet Sci 13, 298–303.

Kronfeld, D.S., 1996. Dietary fat affects heat production and other variables of equine performance, under hot and humid conditions. Equine Vet J 22 (Suppl), 24–34.

Kronfeld, D.S., Harris, P.A., 2003. Equine grain-associated disorders. Comp Contin Educ Pract Vet 25, 974–983.

Kronfeld, D.S., Custalow, S.E., Ferrante, P.L., et al., 1998. Acid-base responses of fat-adapted horses: relevance to hard work in the heat. Appl Anim Behav 59, 61–72.

Kronfeld, D.S., Holland, J.L., Rich, G.A., et al., 2004. Fat digestibility in *Equus caballus* follows increasing first-order kinetics. J Anim Sci 82, 1773–1780.

Lau, C.S., Morley, K.D., Belch, J.J., 1993. Effects of fish oil supplementation on non-steroidal anti-inflammatory drug requirement in patients with mild rheumatoid arthritis – a double-blind placebo controlled study. Br J Rheumatol 32, 982–989.

Lindberg, J.E., Karlsson, C.P., 2001. Effect of partial replacement of oats with sugar beet pulp and maize oil on nutrient utilisation in horses. Equine Vet J 33, 585–590.

Lorenzo-Figueras, M., Preston, T., Ott, E.A., et al., 2005. Meal-induced gastric relaxation and emptying in horses after ingestion of high-fat versus high-carbohydrate diets. Am J Vet Res 66, 897–906.

Lorenzo-Figueras, M., Morisset, S.M., Morisset, J., et al., 2007. Digestive enzyme concentrations and activities in healthy pancreatic tissues of horses. Am J Vet Res 68, 1070–1072.

Manco, M., Calvani, M., Mingrone, G., 2004. Effects of dietary fatty acids on insulin sensitivity and secretion. Diabetes, Obesity and Metabolism 6, 402–413.

Manhart, D.R., Scott, B.D., Gibbs, P.G., et al., 2009. Markers of inflammation in arthritic horses fed omega-3 fatty acids. Prof Anim Sci 25, 155–160.

Mansbach, C.M., Gorelick, F., 2007. Development and physiological regulation of intestinal lipid absorption. II. Dietary lipid absorption, complex lipid synthesis, and the intracellular packing and secretion of chylomicrons. Am J Physiol Gastrointest Liver Physiol 293, G645–G650.

Marchello, E.V., Shurg, W.A., Marchello, J.A., et al., 2000. Changes in lipoprotein composition in horses fed a fat-supplemented diet. J Equine Vet Sci 20, 453–458.

McCann, J.S., Meacham, T.N., Fontenot, J.P., 1987. Energy utilization and blood traits of ponies fed fat-supplemented diets. J Anim Sci 65, 1019–1026.

McKenzie, E.C., Valberg, S.J., Godden, S.M., et al., 2003. Effect of dietary starch, fat, and bicarbonate content on exercise responses and serum creatine kinase activity in equine recurrent exertional rhabdomyolysis. J Vet Intern Med 17, 693–701.

McMeniman, N.P., Hintz, H.F., 1992. Effect of vitamin E status on lipid peroxidation in exercised horses. Equine Vet J 24, 482–484.

Meyer, H., Flothow, C., Radicke, S., 1997. Preileal digestibility of coconut fat and soybean oil in horses and their influence on metabolites of microbial origin of the proximal digestive tract. Arch Anim Nutr 50, 63–74.

Meyer, J.H., Mayer, E.A., Jehn, D., et al., 1986. Gastric processing and emptying of fat. Gastrotenterology 90, 1176–1187.

Meyers, M.C., Potter, G.D., Evans, J.W., et al., 1989. Physiologic and metabolic response of exercising horses to added dietary fat. J Equine Vet Sci 9, 218–223.

Morgado, E.S., Almeida, F.Q., Godoi, F.N., et al., 2009. Carbohydrate digestion in horses fed diets composed by roughages or roughages supplemented with concentrate and/or soybean oil. Arquivo Brasileiro de Medicina Veterinaria e Zootecnia 61, 1112–1119.

Morris, D.D., Henry, M.M., Moore, J.N., et al., 1991. Effect of dietary alpha-linolenic acid on endotoxin-induced production of tumor necrosis factor by peritoneal macrophages in horses. Am J Vet Res 52, 528–532.

Moreau, H., Gargouri, Y., Lecat, D., et al., 1988. Screening of lipases in several mammals. Biochim Biophys Acta 959, 247–252.

Munsterman, A.S., Bertone, A.L., Zachos, T.A., et al., 2005. Effects of the omega-3 fatty acid, alpha-linolenic acid, on lipopolysaccharide-challenged synovial explants from horses. Am J Vet Res 66, 1503–1508.

Nicol, C., Badnell-Waters, A., Bice, R., et al., 2005. The effects of diet and weaning method on the behaviour of young horses. Appl Anim Behav Sci 95, 205–221.

Nieto, J.E., Aldridge, B.M., Beldomenico, P.M., et al., 2005. Characterization of equine intestinal fatty acid binding protein and its use in managing horses with colic. Am J Vet Res 66, 223–232.

NRC, 2005. Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids (macronutrients). The National Academies Press, Washington, DC.

NRC, 2007. Nutrient requirements of horses, sixth Rev ed. The National Academies Press, Washington, DC.

Oldham, S.L., Potter, G.D., Evans, J.W., et al., 1990. Storage and mobilization of muscle glycogen in exercising horses fed a fat-supplemented diet. J Equine Vet Sci 10, 353–359.

O'Neill, W., McKee, S., Clarke, A.F., 2002. Flaxseed (*Linum usitatissimum*) supplementation associated with reduced skin test lesional area in horses with culicoides hypersensitivity. Can J Vet Res 66, 272–277.

Oomah, B.D., Mazza, G., Kenaschuk, E.O., 1992. Cyanogenic compounds in flaxseed. J Agr Food Chem 40, 1346–1348.

Orme, C.E., Harris, R.C., Marlin, D.J., et al., 1997. Metabolic adaptation to a fat-supplemented diet by the Thoroughbred horse. Br J Nutr 97, 443–458.

Pagan, J.D., Essen-Gustavsson, B., Lindholm, A., et al., 1987. The effect of dietary energy source on exercise performance in Standardbred horses. In: Gillespie, J.R., Robinson, N.E. (Eds.), Equine Exercise Physiology 2. ICEEP Publications, Davis, CA, pp. 686–700.

Pagan, J.D., Harris, P.A., Kennedy, M.A.P., et al., 1999. Feed type and intake affects glycemic response in Thoroughbred horses. In: Proc 16th Equine Nutr Physiol Symp, Raleigh, NC. Equine Nutrition and Physiology Society, Savoy, IL, pp. 149–150.

Pagan, J.D., Geor, R.J., Harris, P.A., et al., 2002. Effects of fat adaptation on glucose kinetics and substrate oxidation during low intensity exercise. Equine Vet J 34 (Suppl), 33–38.

Palmquist, D.L., 1988. The feeding value of fats. In: Ørskov, E.R. (Ed.), World Animal Science. B. Disciplinary Approach. 4. Feed Science. Elsevier, Amsterdam, pp. 293–311.

Potter, G.D., Hughes, S.L., Julen, T.R., et al., 1992. A review of research on digestion and utilization of fat by the equine. Pferdeheilkunde: Sonderausgabe. 1. Europäische Konferenz über die Ernährung des Pferdes 119–123.

Quinn, R.W., Burk, A.O., Hartsock, T.G., et al., 2008. Insulin sensitivity in Thoroughbred geldings: effect of weight gain, diet, and exercise on insulin sensitivity in Thoroughbred geldings. J Equine Vet Sci 28, 728–738.

Redondo, A.J., Carranza, J., Trigo, P., 2009. Fat diet reduces stress and intensity of startle reaction in horses. Appl Anim Behav Sci 118, 69–75.

Ribeiro,, W.P., Valberg, S.J., Pagan, J.D., et al., 2004. The effect of varying dietary starch and fat content on serum creatine kinase activity and substrate availability in equine polysaccharide storage myopathy. J Vet Intern Med 18, 887–894.

Rich, G.A., Fontenot, J.P., Meacham, T.N., 1981. Digestibility of animal, vegetable and blended fats by equine. In: Proc 7th Equine Nutr Physiol Symp, Warrenton, VA. Equine Nutrition and Physiology Society, Savoy, IL, pp. 30–36.

Risérus, U., Willett, W.C., Hu, F.B., 2009. Dietary fats and prevention of type 2 diabetes. Prog Lipid Res 48, 44–51.

Sales, J., Homolka, P., 2011. A meta-analysis of the effects of supplemental dietary fat on protein and fibre digestibility in the horse. Livestock Sci 136, 55–63.

Sallmann, H.P., Kienzle, E., Fuhrmann, H., et al., 1991. Metabolic consequences of feeding ponies with marginal amounts of fat. In: Proc 12th Equine Nutr Physiol Symp, Calgary, Alberta. Equine Nutrition and Physiology Society, Savoy, IL, pp. 81–82.

Schumacher, J., DeGraves, F.J., Spano, J.S., 1997. Clinical and clinicopathologic effects of large doses of raw linseed oil as compared to mineral oil in healthy horses. J Vet Intern Med 11, 296–299.

Scott, B.D., Potter, G.D., Greene, L.W., et al., 1992. Efficacy of a fat-supplemented diet on muscle glycogen concentrations in exercising Thoroughbred horses maintained in varying body conditions. J Equine Vet Sci 12, 105–109.
Sheppard, A.J., Pennington, A.T., Welbrauch, J.L., 1993. Analysis and distribution of vitamin E in vegetable oils and foods. In: Packer, L., Fuchs, J. (Eds.), Vitamin E in Health and Disease. Marcel Dekker, Inc., New York, New York.
Siciliano, P.D., Wood, C.H., 1993. The effect of added dietary soybean oil on vitamin E status of the horse. J Anim Sci 71, 3399–3402.
Singer, E.R., Smith, M.A., 2002. Examination of the horse with colic: is it medical or surgical? Equine Vet Educ. 34, 87–96.
Sprecher, H., 2000. Metabolism of highly unsaturated n-3 and n-6 fatty acids. Biochim Biophys Acta 1486, 219–231.
Sprecher, H., Luthria, D.L., Mohammed, B.S., et al., 1995. Reevaluation of the pathways for the biosynthesis of polyunsaturated fatty acids. J Lipid Res 36, 2471–2477.
Staniar, W.B., Kronfeld, D.S., Akers, R.M., et al., 2007. Insulin-like growth factor I in growing Thoroughbreds. J Anim Physiol Anim Nutr 91, 390–399.
Stelzleni, E.L., Warren, L.K., Kivipelto, J., 2006. Effect of dietary n-3 fatty acid supplementation on plasma and milk composition and immune status of mares and foals. J Anim Sci 84 (Suppl. 1), 392–393.
Stratton-Phelps, M., Fascetti, A.J., Geor, R.J., 2003. Nutritional support in selected metabolic, hepatic, urinary, and musculoskeletal conditions. In: Robinson, N.E. (Ed.), Current Therapy in Equine Medicine 5. Elsevier Science, Philadelphia, PA, pp. 715–722.
Sturgeon, L.S., Baker, L.A., Pipkin, J.L., et al., 2000. The digestibility and mineral availability of matua, bermuda grass, and alfalfa hay in mature horses. J Equine Vet Sci 20, 45–48.
Swinney, D.L., Potter, G.D., Greene, L.W., et al., 1995. Digestion of fat in the equine small and large intestine. In: Proc 14th Equine Nutr Physiol Symp, Ontario, CA. Equine Nutrition and Physiology Society, Savoy, IL, pp. 30–35.
Topliff, D.R., Potter, G.D., Dutson, T.R., et al., 1983. Diet manipulation and muscle glycogen in the equine. In: Proc. 8th Equine Nutr Physiol Soc Symp, Lexington, KY. Equine Nutrition and Physiology Society, Savoy, IL, pp. 119–124.
Treiber, K.H., Boston, K.C., Kronfeld, D.S., et al., 2005. Insulin resistance and compensation in Thoroughbred weanlings adapted to high-glycemic meals. J Anim Sci 83, 2357–2364.
Treiber, K.H., Geor, R.J., Boston, R.C., et al., 2008. Dietary energy source affects glucose kinetics in trained Arabian geldings at rest and during endurance exercise. J Nutr 138, 964–970.
USDA-ARS (United States Department of Agriculture, Agricultural Research Service), 2010. USDA National Nutrient Database for Standard Reference, Release 23. Nutrient Data Laboratory. (http://www.ars.usda.gov/ba/bhnrc/ndl) accessed February 2011.
Valberg, S.J., 2010. Review of muscle diseases in sport horses. In: Proceedings of the Veterinary Sport Horse Symposium. Amer Assoc Equine Prac, Lexington, KY, pp. 107–120.
Valk, E.E., Hornstra, G., 2000. Relationship between vitamin E requirement and polyunsaturated fatty acid intake in man: a review. Int J Vitam Nutr Res 70, 31–42.
van Dijk, S., Wensing, T., 1989. Comparison of the lipoprotein pattern of the horse, the pony and the lactating and non-lactating cow obtained by a combination of an ultracentrifugation and a precipitation technique. Comp. Biochem. Physiol. B. 94, 735–738.
Vervuert, I., Klein, S., Coenen, M., 2010. Short-term effects of a moderate fish oil or soybean oil supplementation on postprandial glucose and insulin responses in healthy horses. Vet J 184, 162–166.
Vineyard, K.R., Warren, L.K., Kivipelto, J., 2007. Effect of fish oil supplementation on neutrophil function and antibody production in yearling horses. In: Proc 20th Equine Sci Soc Symp, Hunt Valley, MD. Equine Nutrition and Physiology Society, Savoy, IL, pp. 13–14.
Vineyard, K.R., Warren, L.K., Kivipelto, J., 2008. Effect of high fat diets and fat source on immune function in yearling horses. J Anim Sci 86 (E-suppl. 2), 376.
Vineyard, K.R., Warren, L.K., Kivipelto, J., 2010. Effect of dietary omega-3 fatty acid source on plasma and red blood cell membrane composition and immune function in yearling horses. J Anim Sci 88, 248–257.
Warren, L.K., Kivipelto, J., 2007a. Fatty acid content of grass and legume hays commonly fed to horses. J Anim Sci 85 (Suppl 1), 140–141.
Warren, L.K., Kivipelto., 2007b. Effect of season, forage maturity and grazing on the fatty acid composition of bahiagrass pasture. J Anim Sci 85 (Suppl 1), 141.
Warren, L.K., Kivipelto., 2008. Seasonal effects of diet on the omega-6 and omega-3 fatty acid composition of plasma and red blood cells in grazing horses. J Anim Sci 86 (E-Suppl. 2), 376.
Warren, L.K., Kivipelto, J., Gettinger, E., 2010. Evaluation of the capacity for maternal transfer and foal synthesis of long-chain polyunsaturated fatty acids. J Anim Sci 88 (E-Suppl. 2), 203.
Watson, T.D.G., Packard, C.J., Shepherd, J., 1993. Plasma lipid transport in the horse (Equus caballus). Comp. Biochem. Physiol. Part B Biochem. Mol. Biol. 106, 27–34.
Webb, S.P., Potter, G.D., Evans, J.W., 1987. Physiologic and metabolic response of race and cutting horses to added dietary fat. In: Proc 10th Equine Nutr Physiol Soc Symp, Fort Collins, CO. Equine Nutrition and Physiology Society, Savoy, IL, p. 115.
White, S., Warren, L.K., Vineyard, K.R., et al., 2007. Effect of dietary omega-3 fatty acid supplementation on vitamin E status and lipid peroxidation in growing horses. In: Proc. 20th Equine Science Society Symposium, Hunt Valley, MD, Equine Nutrition and Physiology Society, Savoy, IL, pp. 60–61.
Williams, C.A., Kronfeld, D.S., Staniar, W.B., et al., 2001. Plasma glucose and insulin responses of thoroughbred mares fed a meal high in starch and sugar or fat and fiber. J Anim Sci 79, 2196–2201.
Wilson, K.R., Potter, G.D., Michael, E.M., et al., 2003. Alteration in the inflammatory response in athletic horses fed diets containing omega-3 polyunsaturated fatty acids. In: Proc 18th Equine Nutr Physiol Symp, East Lansing, MI, Equine Nutrition and Physiology Society, Savoy, IL, pp. 20–23.
Witham, C.L., Stull, C.L., 1998. Metabolic responses of chronically starved horses to refeeding with three isoenergetic diets. J Am Vet Med Assoc 212, 691–696.
Woodward, A.D., Nielsen, B.D., O'Connor, C.I., et al., 2007. Supplementation of dietary long-chain polyunsaturated omega-3 fatty acids high in docosahexaenoic acid (DHA) increases plasma DHA concentration and may increase trot stride lengths in horses. Eq Comp Ex Physiol 4, 71–78.
Wyse,, C.A., Murphy, D.M., Preston, T., et al., 2001. The 13C-octanoic acid breath test for detection of effects of meal composition on the rate of solid-phase gastric emptying in ponies. Res Vet Sci 71, 81–83.
Zeyner, A.C., Hoffmeister, A., Einspanier, J., et al., 2006. Glycaemic and insulinaemic response of quarter horses to concentrates high in fat and low in soluble carbohydrates. Equine Vet J 36 (Suppl), 643–647.
Zhou, M., Robards, K., Glennie-Holmes, M., et al., 1999. Oat lipids. J Amer Oil Chem Soc 76, 159–169.