High fat intake lowers hepatic fatty acid synthesis and raises fatty acid oxidation in aerobic muscle in Shetland ponies

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(Received 3 August 2000 – Revised 27 November 2000 – Accepted 15 January 2001)

The metabolic effects of feeding soyabean oil instead of an isoenergetic amount of maize starch plus glucose were studied in ponies. Twelve adult Shetland ponies were given a control diet (15 g fat/kg DM) or a high-fat diet (118 g fat/kg DM) according to a parallel design. The diets were fed for 45 d. Plasma triacylglycerol (TAG) concentrations decreased by 55 % following fat supplementation. Fat feeding also reduced glycogen concentrations significantly by up to 65 % in masseter, gluteus and semitendinosus muscles (P<0.05, P<0.01 and P<0.01 respectively). The high-fat diet significantly increased the TAG content of semitendinosus muscle by 80 % (P<0.05). Hepatic acetyl-CoA carboxylase and fatty acid synthase activities were 53 % (P<0.01) and 56 % (P<0.01) lower respectively in the high-fat group, but diacylglycerol acyltransferase activity was unaffected. Although carnitine palmitoyltransferase-I (CPT-I) activity in liver mitochondria was not influenced, fat supplementation did render CPT-I less sensitive to inhibition by malonyl-CoA. There was no significant effect of diet on the activity of phosphofructokinase in the different muscles. The activity of citrate synthase was raised significantly (by 25 %; P<0.05) in the masseter muscle of fat-fed ponies, as was CPT-I activity (by 46 %; P<0.01). We conclude that fat feeding enhances both the transport of fatty acids through the mitochondrial inner membrane and the oxidative capacity of highly-aerobic muscles. The higher oxidative ability together with the depressed rate of de novo fatty acid synthesis in liver may contribute to the dietary fat-induced decrease in plasma TAG concentrations in equines.

Equine: Dietary fat: Hepatic lipogenesis: Muscle fat metabolism: Fatty acid oxidation

High-fat diets have been shown to stimulate fatty acid oxidation by muscle in rats and human subjects. Fat feeding increases the activities of muscle 3-hydroxy-acyl-CoA dehydrogenase (3-HAD) and muscle citrate synthase (CS), key enzymes in the β-oxidation pathway and in Krebs’ cycle, respectively (Miller et al. 1984; Simi et al. 1991; Helge & Kiens’ 1997). Furthermore, a 44 % increase in carnitine palmitoyltransferase-I (CPT-I) activity, the enzyme responsible for the transport of fatty acyl-CoA through the mitochondrial inner membrane, was reported in human subjects fed a high-fat diet (Phinney et al. 1983). Kiens et al. (1987) and Conlee et al. (1990) reported an increase in the concentration of triacylglycerols (TAG) in muscle of human subjects and in rats in response to a high-fat diet. However, Orme et al. (1997) and Geelen et al. (1999) could not confirm these fat-induced changes in horses. It has been reported that in human subjects consuming a high-fat diet muscle glycogen levels decreased (Hultman & Bergstrom, 1967; Bergstrom et al. 1987). In contrast, an increase in resting muscle glycogen concentrations has been found in fat-supplemented horses (Oldham et al. 1990; Jones et al. 1992; Scott et al. 1992), whereas other authors have failed to show such an effect (Hodgson et al. 1986; Greiwe et al. 1989; Essen-Gustavson et al. 1991).

The previously mentioned discrepancy in the effect of fat

Abbreviations: ACC, acetyl-CoA carboxylase; CS, citrate synthase; CPT-I, carnitine palmitoyltransferase-I; DGAT, diacylglycerol acyltransferase; FAS, fatty acid synthase; 3-HAD, 3-hydroxy-acyl-CoA dehydrogenase; PFK, phosphofructokinase; TAG, triacylglycerol.

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feeding on muscle TAG and glycogen concentrations in the different studies could reflect differences in biopsy site which may, at least in part, be attributed to variation in the fibre composition of the biopsy samples. Fibres are most commonly divided into slow-twitch, type I fibres with a high oxidative ability, type II A fibres with an intermediate oxidative ability and fast-twitch, type II B fibres with a low oxidative ability. Type I fibres have high concentrations of mitochondrial enzymes such as 3-HAD and type II B fibres have a high concentration of glycolytic enzymes such as phosphofructokinase (PFK). Type I fibres depend largely on aerobic metabolism of glucose and fatty acids for their energy requirement. The type II fibres derive energy mainly from anaerobic glycolysis with glycogen as the main substrate (Snow, 1983; Vusse & Reneman, 1996). The masseter and the heart are muscles that are composed predominantly of highly-oxidative type I fibres (Kayar et al. 1988; Barrey et al. 1995) and are of interest in the study of the effects of fat supplementation, especially when compared and contrasted with the semitendinosus, a muscle that contains predominantly glycolytic, type II B fibres (Barrey et al. 1995).

In a previous study with horses, a high-fat diet led to a decrease in the concentration of plasma TAG in the fasted state (Geelen et al. 1999). The primary mechanism by which a high-fat diet reduces plasma TAG may include increased removal and/or diminished production of TAG-rich lipoprotein particles. Our study indicated that the decreased concentration of plasma TAG could be attributed to increased removal through an increase in lipoprotein lipase activity. However, decreased esterification of fatty acids, decreased de novo fatty acid synthesis and enhanced fatty acid oxidation within hepatocytes could contribute to the observed decrease in plasma TAG in fast-fed equines. In terms of enzyme activities, these changes would be associated with stimulation of CPT-I and reduction of diacylglycerol acyltransferase (DGAT), acetyl-CoA carboxylase (ACC) and fatty acid synthase (FAS) activities.

The aim of the present study was to investigate the effect of dietary fat supplementation on fatty acid esterification, de novo fatty acid synthesis and fatty acid oxidation in equines. Specifically, the experiment aimed to: (1) determine the muscle TAG and glycogen concentrations and the activities of key oxidative and glycolytic enzymes in different muscles; (2) measure the CPT-I activity in different tissues; and (3) measure the activities of FAS, DGAT and ACC in liver.

Methods

Animal, diets and experimental design

The experimental design was approved by the animal experiments committee of the Utrecht Faculty of Veterinary Medicine. Twelve Shetland ponies (all stallions) weighing 120–220 kg were fed a high-fat or a control diet according to a parallel design. The animals were aged 3–13 years (5·8 (SD 3·9) and 6·4 (SD 4·7) for high-fat and control groups respectively). During a 3-week pre-experimental period the ponies had free access to hay. The ponies were then allocated to two groups of six ponies; one group was fed a fat-rich diet and the other a control diet. Pairs of a control and a test pony entered the experiment at intervals of 1–5 d. The experimental period lasted 45 d for each pair. The diets consisted of hay and either a control or high-fat concentrate; at 10.00 h and 22.00 h concentrate as well as hay were provided. The high-fat concentrate was formulated by adding soyabean oil to the control concentrate at the expense of an isoenergetic amount of starch plus glucose (Table 1). The diets were given to the ponies at a level equivalent to the calculated amount of energy needed for maintenance of their initial body weight. On average, the ponies were supplied daily with 0·88 (SD 0·09) kg hay (25 % of the net energy) and 1·41 (SD 0·17) kg test concentrate or 1·62 (SD 0·11) kg control concentrate (75 % of the net energy). The control diet contained 15 g fat/kg DM and the high-fat diet contained 118 g fat/kg DM. The ponies were housed individually in ventilated stables. All animals walked daily for 15 min on a mechanical horse walker at a speed of 80 m/min.

Sampling procedures

At the end of the experiment, at 09.00 h after an overnight fast, blood samples were collected in heparinized tubes by jugular venepuncture. Directly after blood sampling, the ponies were killed by stunning and exsanguination. Tissue samples (2–4 g) were always taken from the same site for each pony to minimize sampling error. Samples were taken from heart, musculus masseter, musculus semitendinosus, musculus gluteus medius and left liver lobulus. Muscle samples were quickly trimmed of visible fat and connective tissue. Then, samples of muscle or liver were frozen in less than 10 min post-exsanguination in liquid N2 and stored at −80°C for subsequent analyses. One part of the liver sample was homogenized immediately with a loose-fitting Dounce homogenizer (five strokes) in a medium containing (mmol/l): 50 Heps (pH 7·5), 0·25 mannitol, 4·0 citrate, 6·16 EDTA, 5 β-mercaptoethanol. The crude homogenate was centrifuged at 12 000 g for 5 min and the supernatant was frozen quickly in liquid N2 and stored at −80°C until analysis for the activity of FAS and ACC and for mass measurements of ACC. A second part of the liver sample was homogenized at 4°C in a medium containing (mmol/l): 50 Heps (pH 7·5), 0·25 mannitol, 4·0 citrate, 6·16 EDTA, 5 β-mercaptoethanol. The crude homogenate was centrifuged at 12 000 g for 5 min and the supernatant was frozen quickly in liquid N2 and stored at −80°C until analysis for the activity of FAS and ACC and for mass measurements of ACC.

Table 1. Composition of the experimental concentrates (g)

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Control concentrate</th>
<th>High-fat concentrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize starch</td>
<td>193</td>
<td>–</td>
</tr>
<tr>
<td>Glucose</td>
<td>140</td>
<td>–</td>
</tr>
<tr>
<td>Soyabean oil</td>
<td>–</td>
<td>150</td>
</tr>
<tr>
<td>Constant components*</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Total</td>
<td>1183</td>
<td>1000</td>
</tr>
</tbody>
</table>

* The constant components consisted of the following (g): lucerne (Medicago sativa) meal, dehydrated, 342·4; maize starch, 150; glucose, 150; soyabean oil, extracted, 100; molasses, beet, 50; linsed expeller, 20; Ca3(PO4)2, 15; NaCl, 15; MgO, 3·4; CaCO3, 1·7; premix, 2·5. The premix consisted of the following (kg/kg): CoSO4·7H2O 0·66, Na2SeO3·H2O 0·76, KIO3 0·32, MnSO4·H2O 172·4, CuSO4·H2O 27·2, ZnSO4·H2O 192·4, Vitamin A, 12·0 (500 000 IU/g), Cholecalciferol 5·2 (100 000 IU/g), Vitamin E 240·0 (500 IU/g), thiamin, 1·8 (purity 100 %), riboflavin 1·8 (purity 100%), vitamin B6 1·8 (purity 0·1 %), biotin 0·4 (purity 100 %), maize starch (carrier) 343·26.
with five strokes of a glass–Teflon Potter-Elvehjem tissue homogenizer in 4 vol. of a buffer containing 0·25 mol sucrose/l, 20 mmol Tris hydrochloride (pH 7·4)/l and 1 mmol EDTA/l. The homogenate was centrifuged at 600 g for 5 min. The supernatant was recentrifuged at 10 000 g for 15 min. From the supernatant a microsomal pellet was obtained by centrifugation at 105 000 g for 65 min. The final supernatant was termed cytosol.

Assay procedures

Whole-plasma TAG concentration was measured enzymically with an autoanalyser (COBAS-BIO; Hoffmann-La Roche, Mijdrecht, The Netherlands) and a test combination purchased from Boehringer (Mannheim, Germany).

The muscle samples were homogenized with the IKAUltra Turrax ΣT5-FU tissue homogenizer (Janke and Kunkel GmbH and Co. KG, Staufen, Germany) in 9 vol. of a buffer (pH 8·0) containing 25 mmol Hepes/l and 5 mmol β-mercaptoethanol/l. Aliquots of this homogenate were used to measure the levels of TAG (Sundler et al. 1974) and glycogen (Hassid & Abraham, 1957). To ensure full release of mitochondrial enzymes in the remaining homogenate, Triton X-100 (final concentration 0·5 % (v/v)) was added to the strong hypotonic preparation. The activities of the enzymes measured in the present study were not affected by the concentration of detergent used. The Triton X-100-treated homogenate was centrifuged at 48 000 g for 30 min. The supernatant was snap frozen in liquid N2 and stored at −80°C until analysed a few days later for enzyme activities. The activities of CS, 3-HAD, and PFK were determined spectrophotometrically as described by Stitt, (1983), by Passonneau & Lowry (1974) and by Ishikawa et al. (1990) respectively.

Measurement of ACC, FAS and DGAT was performed as described previously (Guzmán & Geelen, 1992). Mitochondria were isolated (Guzmán et al. 1995) for the measurement of activity as described previously (Guzmán & Geelen, 1992).

Mass measurement of ACC was performed by avidin-based ELISA using as the probing antibody a primary antiserum against rat liver ACC, as described previously (Geelen et al. 1997).

Statistical analysis

Statistical analysis was performed by using the Student’s t test. The level of statistical significance was preset at P < 0·05. Values are means and standard deviations.

Results

Feed intake and body weight

The ponies consumed all feed supplied, except for two ponies given the high-fat diet; these animals occasionally refused some concentrate, but the amount was not substantial. The daily feed intake (g/kg body weight) was 5·52 (SD 0·40) hay and 8·89 (SD 0·84) test concentrate or 5·46 (SD 0·52) hay and 10·14 (SD 0·58) control concentrate. The carbohydrate intake (g/kg body weight) was 4·81 (SD 0·40) and 6·07 (SD 0·42) for the test group and control group respectively and the values for fat intake (g/kg body weight) were 1·30 (SD 0·11) and 0·20 (SD 0·01) for the test group and the control group respectively. The ponies maintained their body weight throughout the study: initial and final body weights were respectively 158 (SD 18) kg and 162 (SD 19) kg for the control group and 165 (SD 30) kg and 162 (SD 30) kg for the test group.

Enzyme activities in liver

The influence of 45 d fat feeding on the activity of a number of key enzymes of lipid metabolism in the liver is presented in Table 2. The specific activity of DGAT was unaffected, but the activities of ACC and FAS were diminished significantly in fat-fed animals (P < 0·01 and

### Table 2. Activities (nmol/min per mg protein) of acetyl-CoA carboxylase (ACC), fatty acid synthase (FAS), diacylglycerol acyltransferase (DGAT) and carnitine palmitoyltransferase-I (CPT-I) in liver of ponies fed a low-fat or a high-fat diet†

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Control diet</th>
<th>High-fat diet</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>0·015</td>
<td>0·003</td>
<td>0·007</td>
<td></td>
<td>0·002**</td>
<td></td>
</tr>
<tr>
<td>FAS</td>
<td>0·192</td>
<td>0·024</td>
<td>0·084</td>
<td></td>
<td>0·019***</td>
<td></td>
</tr>
<tr>
<td>DGAT</td>
<td>0·163</td>
<td>0·021</td>
<td>0·158</td>
<td></td>
<td>0·068</td>
<td></td>
</tr>
<tr>
<td>CPT-I</td>
<td>8·01</td>
<td>1·77</td>
<td>6·26</td>
<td></td>
<td>1·56</td>
<td></td>
</tr>
</tbody>
</table>

Mean values were significantly different from those for the control diet **P < 0·01, ***P < 0·001.
† For details of diets and procedures see Table 1 and p. 32.
activity of PFK as an indicator of glycolytic flux and the activities of CS and 3-HAD as indicators of the capacity for fatty acid oxidation were determined. The activity of PFK was higher in the muscles with a high glycolytic capacity and those of 3-HAD and CS were highest in the aerobic muscles. There were no significant effects of diet on the activities of PFK and 3-HAD (Table 3). The activity of CS was enhanced significantly in the masseter muscle of ponies fed the high-fat diet ($P < 0.05$). The activity of CPT-I, a regulatory enzyme of fatty acid oxidation, was significantly higher in mitochondria of the masseter muscle from fat-fed ponies ($P < 0.001$).

**Triacylglycerol and glycogen concentrations in muscle**

There was no significant effect of diet on the TAG concentration in the heart, masseter or the gluteus muscle. However, dietary fat induced a significantly higher TAG concentration in the semitendinosus muscle ($P < 0.05$). The glycogen concentration was lower in all four muscles of the fat-fed ponies and this effect reached statistical significance in the masseter ($P < 0.05$), gluteus ($P < 0.01$) and semitendinosus muscle ($P < 0.001$; Table 4).

**Discussion**

Consistent with previous observations (Duren et al. 1987; Orme et al. 1997; Geelen et al. 1999), ponies fed the high-fat diet had lower plasma concentrations of TAG than did their counterparts fed the control diet. On day 45 of the experiment, the values were 123 (SD 70) and 274 (SD 107) mmol/l respectively ($P < 0.016$). The present study indicates that the fat-induced reduction of plasma TAG was caused, at least in part, by a decrease in de novo fatty acid synthesis, as shown by the decreased activities of ACC and FAS in the liver. Rates of hepatic de novo fatty acid synthesis are associated with rates of secretion of TAG-rich VLDL (Beynen et al. 1981). Thus, we conclude that the decreased plasma levels of TAG reported in fat-supplemented equines is due not only to increased removal of lipoprotein particles (Geelen et al. 1999) but also to lower production rates.

The activity of CPT-I plays a central role in the control of hepatic fatty acid oxidation (McGarry & Brown, 1997). Its activity is potently inhibited by malonyl-CoA, which is the product of the reaction catalysed by ACC. The hepatic concentration of malonyl-CoA is related directly to the rate

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**Table 3. Activities (nmol/min per mg protein) of phosphofructokinase (PFK), 3-hydroxy-acyl-CoA dehydrogenase (3-HAD), citrate synthase (CS) and carnitine palmitoyltransferase-I (CPT-I) in different muscle types of ponies fed a low-fat or a high-fat diet†** (Mean values and standard deviations for six ponies, except CPT-I control values in semitendinosus where values are for five ponies)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Control diet</th>
<th></th>
<th></th>
<th>High-fat diet</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Heart PFK</td>
<td>1009 (260)</td>
<td>1007 (137)</td>
<td>3-HAD CS</td>
<td>343 (50)</td>
<td>355 (31)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Masseter PFK</td>
<td>701 (175)</td>
<td>682 (109)</td>
<td>3-HAD CS</td>
<td>148 (24)</td>
<td>186 (25)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Gluteus PFK</td>
<td>2231 (307)</td>
<td>2478 (608)</td>
<td>3-HAD CS</td>
<td>85 (19)</td>
<td>65 (10)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Semitendinosus PFK</td>
<td>1918 (381)</td>
<td>1846 (450)</td>
<td>3-HAD CS</td>
<td>71 (12)</td>
<td>65 (11)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Heart CS</td>
<td>148 (24)</td>
<td>186 (25)</td>
<td>3-HAD CS</td>
<td>85 (19)</td>
<td>65 (10)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Masseter CS</td>
<td>304 (92)</td>
<td>253 (48)</td>
<td>3-HAD CS</td>
<td>85 (19)</td>
<td>65 (10)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Gluteus CS</td>
<td>343 (50)</td>
<td>355 (31)</td>
<td>3-HAD CS</td>
<td>148 (24)</td>
<td>186 (25)</td>
<td>3-HAD CS</td>
</tr>
<tr>
<td>Semitendinosus CS</td>
<td>71 (12)</td>
<td>65 (11)</td>
<td>3-HAD CS</td>
<td>71 (12)</td>
<td>65 (11)</td>
<td>3-HAD CS</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those for the control diet *$P < 0.05$*, **$P < 0.001$**.

† For details of diets and procedures, see Table 1 and p. 32.

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**Table 4. Triacylglycerol (TAG) and glycogen contents (nmol/mg protein) in different muscle tissues of ponies fed a low-fat or a high-fat diet†** (Mean values and standard deviation for six ponies)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Control diet</th>
<th></th>
<th></th>
<th>High-fat diet</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Heart TAG</td>
<td>24.9 (15.9)</td>
<td>295 (98.1)</td>
<td>Glycogen</td>
<td>218.6 (66.1)</td>
<td></td>
<td>285.8 (65.1)</td>
</tr>
<tr>
<td>Masseter TAG</td>
<td>34.7 (15.2)</td>
<td>161.7 (89.4)</td>
<td>Glycogen</td>
<td>218.6 (66.1)</td>
<td></td>
<td>285.8 (65.1)</td>
</tr>
<tr>
<td>Gluteus TAG</td>
<td>156.3 (62.3)</td>
<td>583.8 (218.6)</td>
<td>Glycogen</td>
<td>218.6 (66.1)</td>
<td></td>
<td>285.8 (65.1)</td>
</tr>
<tr>
<td>Semitendinosus TAG</td>
<td>74.2 (26.3)</td>
<td>978.4 (376.0)</td>
<td>Glycogen</td>
<td>218.6 (66.1)</td>
<td></td>
<td>285.8 (65.1)</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those for the control diet *$P < 0.05$*, **$P < 0.001$**.

† For details of diets and procedures, see Table 1 and p. 32.
of de novo fatty acid synthesis (Beynen et al. 1979). Thus, the concentration control of fatty acid oxidation and fatty acid synthesis. Although CPT-I activity in the liver was not significantly different between groups, the sensitivity of CPT-I for inhibition by malonyl-CoA was lower after fat feeding. In addition, the fat-induced decrease in the activity of hepatic ACC will lower the concentration of malonyl-CoA. Thus, in fat-supplemented animals the effect of a decrease in hepatic malonyl-CoA is amplified through the desensitization of CPT-I to inhibition, thereby allowing an increased rate of oxidation of fatty acids as a source of energy for hepatic requirement. This reasoning would imply that the in situ activity of CPT-I was higher in the ponies fed the high-fat diet.

A new finding of the present study is the 46 % increase in CPT-I activity in the masseter, a muscle with a high aerobic energy metabolism, as a result of the extra dietary fat. This finding is in good agreement with that reported by Phinney et al. (1983) for human subjects and Boyadjiev, (1996) for rats fed a high-fat diet, and indicates a substantial enhancement of the capacity for fatty acid oxidation in this muscle. Comparison of the specific activities of 3-HAD, CS and CPT-I shows that the activities of 3-HAD and CS are in large excess and that an increase in the activity of the enzyme that shuttles fatty acids into mitochondria, CPT-I, will be most effective in upregulating the capacity for fatty acid oxidation and thus of energy production. In agreement with previous results (Orme et al. 1997; Geelen et al. 2000) dietary fat induced an increase in masseter CS activity, where as 3-HAD activity was not significantly affected. This finding may relate to the fact that the activity of 3-HAD is much higher than that of CS and CPT-I, and thus will not limit the oxidative capacity.

In line with observations by Snow (1983), we observed that highly-aerobic muscles (heart and masseter) contain less glycogen than muscles of low aerobic capacity (semitendinosus). In all four muscle types dietary fat reduced the glycogen content markedly; the reduction was less glycogen than muscles of low aerobic capacity (semitendinosus). In all four muscle types dietary fat reduced the glycogen content markedly; the reduction was more, fat supplementation rendered hepatic CPT-I less sensitive to inhibition by malonyl-CoA, which could result in an increased fatty acid oxidation rate, which in turn could contribute to the plasma TAG-lowering effect of high fat intake. In addition, metabolic adaptation to fat supplementation could be demonstrated in a highly-oxidative muscle, the masseter muscle, which showed enhancement of CPT-I and CS activity. If these changes extend to other highly-oxidative muscles, there would be an increase in the capacity for fatty acid oxidation which may be advantageous to exercising horses and may explain why Webb et al. (1987) observed that extra dietary fat provided more energy for work in the cutting horse.

Acknowledgements

We are most grateful to Walter Jansen for logistics and to Ine Geelen-van Eeden, Astrid Herder, Andries Klarenbeek and Marjory Pollak for excellent technical assistance.

References


