Obesity is of increasing concern in equid populations because its presence is associated with altered metabolic function and risk for disease. Obesity has been associated with insulin resistance in horses and ponies,1–3 and obesity and insulin resistance have been associated with impaired reproductive function in mares and an increased risk of and a predisposition for developing pasture-associated laminitis.4–7 In addition to insulin resistance, other obesity-associated factors have been implicated in increasing risk for pasture-associated laminitis, including hyperinsulinemia and hyperleptinemia.8 Therefore, developing management strategies that mitigate the extent of obesity and insulin resistance is important for lessening disease risk in obese horses.

Effects of exercise training on adiposity, insulin sensitivity, and plasma hormone and lipid concentrations in overweight or obese, insulin-resistant horses

Rebecca A. Carter, PhD; L. Jill McCutcheon, DVM, PhD; Emanuela Valle, DMV, PhD; Elaine N. Meilahn, PhD; Raymond J. Geor, BVSc, PhD

Objective—To determine effects of exercise training without dietary restriction on adiposity, basal hormone and lipid concentrations and glucose and insulin dynamics in overweight or obese, insulin-resistant horses.

Animals—12 overweight or obese (body condition score ≥ 7), insulin-resistant (insulin sensitivity ≤ 1.2 X 10–4 L/min/mU) geldings.

Procedures—4 horses remained sedentary, and 8 horses were exercised for 4 weeks at low intensity and 4 weeks at higher intensity, followed by 2 weeks of detraining. Prior to and after each training period, frequently sampled IV glucose tolerance tests with minimal model analysis were performed and baseline plasma insulin, glucose, triglycerides, non-esterified fatty acids, and leptin concentrations were analyzed. Adiposity was assessed by use of morphometrics, ultrasonic subcutaneous fat thickness, and estimation of fat mass from total body water (deuterium dilution method).

Results—Body weight and fat mass decreased by 4% (mean ± SD, 20 ± 8 kg) and 34% (32 ± 9 kg), respectively, compared with pre-exercise values, with similar losses during low- and higher-intensity training. There was no effect of exercise training on subcutaneous fat thickness, plasma hormone and lipid concentrations, or minimal model parameters of glucose and insulin dynamics.

Conclusions and Clinical Relevance—Results suggested that moderate exercise training without concurrent dietary restriction does not mitigate insulin resistance in overweight or obese horses. A more pronounced reduction in adiposity or higher volume or intensity of exercise may be necessary for improvement in insulin sensitivity in such horses. (Am J Vet Res 2010;71:314–321)

Obesity is of increasing concern in equid populations because its presence is associated with altered metabolic function and risk for disease. Obesity has been associated with insulin resistance in horses and ponies,1–3 and obesity and insulin resistance have been associated with impaired reproductive function in mares and an increased risk of and a predisposition for developing pasture-associated laminitis.4–7 In addition to insulin resistance, other obesity-associated factors have been implicated in increasing risk for pasture-associated laminitis, including hyperinsulinemia and hyperleptinemia.8 Therefore, developing management strategies that mitigate the extent of obesity and insulin resistance is important for lessening disease risk in obese horses.

Abbreviations

<table>
<thead>
<tr>
<th>ABR</th>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AIRg</td>
<td>Acute insulin response to glucose</td>
<td></td>
</tr>
<tr>
<td>BCS</td>
<td>Body condition score</td>
<td></td>
</tr>
<tr>
<td>DE</td>
<td>Digestible energy</td>
<td></td>
</tr>
<tr>
<td>FFM</td>
<td>Fat-free mass</td>
<td></td>
</tr>
<tr>
<td>FM</td>
<td>Fat mass</td>
<td></td>
</tr>
<tr>
<td>FSIGTT</td>
<td>Frequently sampled IV glucose tolerance test</td>
<td></td>
</tr>
<tr>
<td>NEFA</td>
<td>Nonesterified fatty acid</td>
<td></td>
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<tr>
<td>Sg</td>
<td>Glucose effectiveness</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>Insulin sensitivity</td>
<td></td>
</tr>
<tr>
<td>TBW</td>
<td>Total body water</td>
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</table>

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In humans, regular exercise is recommended for weight reduction and management of metabolic disease, and research has helped to elucidate the amount and intensity of exercise necessary for desired effects. Studies in humans and rodents suggest that improvements in SI with exercise training may be induced by increased glucose transporter 4 content in skeletal muscle and increased expression or activity of proteins involved in signal transduction, including insulin receptor substrate 1 and phosphatidylinositol 3-kinase. Additionally, exercise training in obese subjects may improve SI through mechanisms involving weight reduction.

Previous studies in horses support a role of short-term (7-day) exercise training for increasing SI, although sustained effects lasting > 1 day after the last exercise session are inconsistent. Additionally, in obese, insulin-resistant ponies, decreased adiposity through controlled feed intake increases SI to a similar degree as exercise training alone. However, it is unknown whether longer-term exercise training without feed restriction would induce a sustained increase in SI or reduction in adiposity in obese, insulin-resistant horses. It is also of interest to determine whether alterations in obesity and metabolism are dependent on intensity level of exercise training.

The present study was designed to test the hypothesis that exercise training in overweight or obese, insulin-resistant horses mitigates risk factors for metabolic disease and laminitis, that high-intensity exercise is more effective at altering these risk factors, and that these alterations will be present up to 2 weeks after the cessation of exercise training. The specific objectives of this study were to identify changes in measurements of adiposity, minimal model parameters of glucose and insulin dynamics, and circulating concentrations of insulin, glucose, NEFAs, triglycerides, and leptin in obese, insulin-resistant horses in response to low-intensity and higher-intensity exercise training without dietary restriction, and to determine whether these changes persist for a 2-week sedentary detraining period.

Materials and Methods

Horses—Twelve Arabian or Arabian cross gendings (age, 9 to 21 years) from the Virginia Tech Middleburg Agricultural Research and Extension Center research herd were evaluated during the study period (August to November 2007). The study spanned summer and autumn seasons, with typical daily low and high ambient temperatures of 16°C to 30°C at the beginning of the study and 0°C to 14°C at the end of the study. Horses were used as a model of diet-induced obesity in a previous study that concluded 6 months prior to the initiation of the present study; therefore, horses had been maintained at a high body condition (BCS ≥ 7, scale 1 to 9) for ≥ 7 months, and there was no difference in mean SI values between the last measurement of the previous study and the first measurement of the present study (P = 0.13 [paired t test]). At study initiation, horses were overweight or obese (BCS ≥ 7; n = 11) and insulin resistant (SI ≤ 1.2 × 10⁻⁴ L/min/mU), with SI values in the lowest (7; 0.14 to 0.78 × 10⁻⁴ L/min/mU) or second to lowest (4; 0.79 to 1.50 × 10⁻⁴ L/min/mU) reference quintiles for clinically normal horses. One horse was insulin resistant but not overweight or obese (control group), and a separate horse was overweight but not insulin resistant (exercise group). Horses were allocated into 2 groups (n = 4 and 8) to achieve similar mean values between groups for body weight, BCS, cresty neck score, and previously obtained values of SI.

Horses were maintained as separate groups on adjacent drylots beginning 2 weeks prior to and for the duration of the study. Mixed alfalfa and grass hay was fed at 2.4% of body weight daily (12 kg/horse). Before study initiation, feeding requirements were determined by adjusting hay intake until a stable body weight was maintained for each group with minimal hay wastage. Each horse also received 1 kg of concentrate feed/d to supplement vitamins and minerals and was provided access to fresh water and a salt block at all times. The overall nutrient profile of the diet was 18% crude protein, 4% crude fat, 10% nonstructural carbohydrate, 30% acid detergent fiber, 43% neutral detergent fiber, and 10% ash, on a dry matter basis. Total DE intake was estimated at 23 Mcal/d, accounting for an estimated 15% hay wastage. On the basis of mean body weights for each group at each time point, energy intake was estimated as 133% of maintenance DE requirements for the control group throughout the study.

For the exercise group, energy intake was estimated as 137% of maintenance DE requirements at initiation of the study, 117% of DE requirements during low-intensity training according to requirements for light work, 102% of DE requirements during higher intensity according to requirements for moderate work, and 141% of maintenance DE requirements during detraining. The experimental protocol was approved by the Virginia Tech Institutional Animal Care and Use Committee.

Experimental design—In a longitudinal study lasting 14 weeks, the 2 groups of horses either were allocated to an exercise training protocol (n = 8) or remained sedentary (4). Horses in the exercise group were exercised for 4 weeks at low intensity followed by 4 weeks at higher intensity and then underwent 2 weeks with no structured exercise (detraining). Low-intensity exercise consisted of 10 minutes of walking (1.1 m/s) and 30 minutes of trotting (2.5 m/s) on an automated horse exerciser 4 times/wk. High-intensity exercise consisted of 10 minutes of walking (1.1 m/s) and 30 minutes of trotting (3.0 m/s) on an automated horse exerciser for 2 d/wk, and 10 minutes of walking (1.3 m/s), 10 minutes of trotting (3.7 ± 0.3 m/s, 3° incline) at a target heart rate of 130 beats/min, and 20 minutes of cantering (6.2 ± 0.8 m/s, 3° incline) at a target heart rate of 160 beats/min on a treadmill for 2 d/wk. Heart rate was monitored with a commercial digital heart rate monitor.

The low-intensity exercise regimen was chosen to represent a training program with the potential to have a high compliance if recommended for use in obese equids. Each exercise session was estimated to have a mean energy expenditure of 2.3 Mcal for a 500-kg horse. The higher-intensity exercise regimen was chosen to be comparable to current recommendations for obese humans. Each of the treadmill sessions was estimated to have an energy expenditure of 4.8 Mcal for a 500-kg horse.
Testing procedures consisted of measurements of adiposity, FSIGTT, and deuterium oxide dilutions. Testing procedures were performed in all horses during a 4-day period during the weeks prior to low-intensity exercise, between low- and higher-intensity exercise, between higher-intensity exercise and detraining, and after detraining. Deuterium oxide dilutions were not performed after detraining. For testing procedures, horses were allocated into 3 groups (n = 1 or 2 control horses and 2 or 3 exercised horses) and each group underwent tests on consecutive days. On day 1 of the testing procedures, catheters were inserted into a jugular vein and the deuterium oxide infusion protocol was performed, starting between 10:00 AM and 12:00 PM. On day 2 of testing procedures, FSIGTT were performed in the morning, starting between 8:00 AM and 8:30 AM, followed by measurements of adiposity. Deuterium oxide infusions and FSIGTT were performed on horses in the exercise group approximately 24 and 48 hours, respectively, after their last exercise session.

Morphometrics, condition scores, and subcutaneous fat thickness—Body weight, girth and abdominal circumferences, and neck circumference at 0.25, 0.50, and 0.75 of neck length were measured as described. Mean neck circumference was calculated as the mean of the measurements taken at 0.25, 0.50, and 0.75 of neck length. Intra-assay coefficients of variation for morphometric measurements were < 3%, determined by use of triplicate measurements in each of 3 horses. Three evaluators graded BCS on a scale from 1 to 9 and neck crest adiposity from 0 to 5. The mean of the 3 scores for each horse was used for data analysis. Intraclass correlation coefficients for the reliability of the mean scores were 0.93 for BCS and 0.92 for neck adiposity score. Measurements of subcutaneous fat thickness were performed by use of B-mode ultrasonography over the rump, back, rib, and shoulder regions, as described. Intra- and interassay coefficients of variation for ultrasonographic measurements were < 6%, determined by use of triplicate measurements in each of 3 horses.

Deuterium oxide dilution—After catheter placement into a jugular vein, baseline blood samples were drawn and placed into 10-mL evacuated tubes containing sodium heparin as an anticoagulant and kept on ice until centrifugation. Deuterium oxide solution was then infused at a rate of 0.2 g/kg of body weight as rapidly as possible (< 2 minutes). Actual weight of infused deuterium oxide solution was calculated from syringe weights before and after infusion. Blood samples were taken 180 minutes after completion of deuterium oxide infusion.

FSIGTT—On the days of FSIGTT procedures, horses were removed from the drylot at 7:00 AM and placed in stalls for the duration of the testing procedure. No feed or hay was offered prior to or during the testing procedure on FSIGTT days; however, horses had continual access to water. Extension sets were attached to catheters already in place from the previous day, and the insulin-modified FSIGTT procedure was initiated as described. Briefly, a glucose bolus (30% [wt/vol] dextrose solution) of 0.3 g/kg of body weight was administered rapidly (within 2 minutes) through the catheter, followed 20 minutes later by rapid administration (within 10 seconds) of an insulin bolus of 20 mU/kg of body weight. Blood samples were collected at ~20 (between 8:00 AM and 8:30 AM), ~3, 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 14, 16, 19, 22, 23, 24, 25, 27, 30, 35, 40, 50, 60, 70, 80, 100, 120, 130, 180, 210, and 240 minutes with respect to completion of glucose administration. Samples were immediately placed into 10-mL evacuated tubes containing sodium heparin as an anticoagulant and kept on ice until centrifugation. Additional blood was collected during the ~5-minute sampling time into tubes containing potassium EDTA as an anticoagulant.

Analysis of samples—Plasma was separated by centrifugation (3,000 × g) within 30 minutes of sample collection and stored at −80°C until analysis. Plasma glucose and insulin (in heparin) concentrations were measured in all FSIGTT samples. Plasma triglyceride, NEFA, and leptin (in EDTA) concentrations were measured in the −5-minute blood samples. Plasma glucose, triglycerides, and NEFA concentrations were assayed enzymatically by use of commercial kits and an automated analyzer. Plasma insulin and leptin concentrations were measured by use of commercial radioimmunoassays validated for use in equine plasma. All analyses were performed in duplicate. Intra-assay coefficients of variation were 0.9%, 3.0%, 3.8%, 5.2%, and 5.6% for glucose, triglycerides, NEFAs, insulin, and leptin, respectively. Interassay coefficients of variation were 1.1% and 6.4% for glucose and insulin, respectively. All other analyses were performed in a single assay for each analysis.

Deuterium oxide analysis was performed in a commercial laboratory as described. Briefly, the deuterium oxide concentration of plasma was measured via zinc reduction at 490°C to produce deuterium gas that was measured with an isotope ratio mass spectrometer. Data were determined as delta (δ) deuterium per milliliter relative to Vienna standard mean ocean water.

The TBW content (mol) was calculated by use of the following equation:

\[
TBW (\text{mol}) = \frac{(WA/18.02a) \times ((\delta_{\text{post}} - \delta_{\text{pre}})/(\delta_{\text{post}} - \delta_{\text{pre}}))/1.04}
\]

where \( W \) is the weight (g) of the dilution water, \( A \) is the weight (g) of the deuterium oxide dose administered, \( \delta_{\text{pre}} \) and \( \delta_{\text{post}} \) are the delta deuterium values determined for the predose (0 minutes) and postdose (180 minutes) samples, \( \delta_{\text{dil}} \) is the measured deuterium content of the diluted dose, and \( \delta_{\text{ww}} \) is the measured deuterium content of dilution water. To correct for the nonexchange of deuterium in the body with acidic amino acids and other binding sites, TBW (mol) was adjusted by 4% by dividing by 1.04.

Total body water (mol) was converted into kilograms by use of the following equation:

\[
\text{TBW (kg)} = \text{TBW (mol)} \times 18.02 \ (\text{g/mol})/1,000 \ (\text{g/kg})
\]

The FFM (kg) was calculated as TBW (kg)/0.73 by use of a hydration factor of 73% for FFM.
FM (kg) was calculated as body weight (kg) minus FFM (kg).

The minimal model of glucose and insulin dynamics was applied to glucose and insulin curves for each FSIGTT by use of commercially available software and reported methods. The model was used to calculate values for SI, Sg, AIRg, and disposition index.

Statistical analysis—The Shapiro-Wilk test was used to test for normality of variables within each group. The Grubbs test (α = 0.01) was used to determine outliers, which were subsequently removed from analysis. Data points removed from analysis included 2 high insulin concentrations (1 control horse and 1 exercised horse during detraining) and 1 high glucose concentration (exercised horse during detraining). The effect of group and time point on variables was assessed by use of repeated-measures ANOVA with horse nested within group and by use of the Huynh-Feldt ε correction factor to adjust for sphericity. When a significant value for the F ratio was obtained, Fisher-Hayter pairwise comparisons were made between groups or time points. Values of P < 0.05 were considered significant. Values are reported as mean ± SD unless stated otherwise. Statistical analyses were conducted by use of a computer software program.

Results

Morphometrics, condition scores, and subcutaneous fat thickness—There was no effect of exercise group on any measurements of morphometrics, condition scores, or subcutaneous fat thickness. There was no effect of group, time point, or their interaction on measurements of neck adiposity score or shoulder fat thickness. Only an effect of time point was present in measurements of girth (P = 0.006), mean neck circumference (P = 0.001), back fat thickness (P = 0.002), and rib fat thickness (P = 0.026), indicating that they changed similarly in both groups during the study. There were group × time point effects for body weight (P < 0.001), abdominal circumference (P = 0.036), and BCS (P = 0.013), indicating a decrease in these adiposity measurements in the exercised group, compared with those in the control group (Table 1). In the exercise group, body weight decreased by 10 ± 4 kg (2.0 ± 0.8%) after low-intensity exercise, decreased by 20 ± 8 kg (4.0 ± 1.5%) after higher-intensity exercise, and remained lower by 12 ± 6 kg (2.3 ± 1.2%) after detraining, com-

Table 1—Mean ± SD values for adiposity measurements in 4 control (CON) and 8 exercised (EX) horses.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Before exercise</th>
<th>Low intensity</th>
<th>Higher intensity</th>
<th>Detraining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (kg)</td>
<td>CON</td>
<td>513 ± 90*</td>
<td>518 ± 94**</td>
<td>520 ± 91**</td>
<td>526 ± 94**</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>503 ± 29</td>
<td>492 ± 26</td>
<td>483 ± 28</td>
<td>491 ± 29</td>
</tr>
<tr>
<td>BCS</td>
<td>CON</td>
<td>8.0 ± 1.2</td>
<td>8.0 ± 1.3</td>
<td>8.0 ± 1.1</td>
<td>8.1 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>7.9 ± 0.5</td>
<td>7.4 ± 0.7</td>
<td>7.3 ± 0.6</td>
<td>7.5 ± 0.7</td>
</tr>
<tr>
<td>Abdominal circumference (cm)</td>
<td>CON</td>
<td>213 ± 15</td>
<td>217 ± 13</td>
<td>214 ± 14</td>
<td>215 ± 14</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>211 ± 3</td>
<td>212 ± 5</td>
<td>207 ± 5</td>
<td>212 ± 5</td>
</tr>
<tr>
<td>Girth circumference (cm)</td>
<td>ALL</td>
<td>190 ± 8</td>
<td>191 ± 9</td>
<td>190 ± 8</td>
<td>193 ± 9</td>
</tr>
<tr>
<td>Neck adiposity score</td>
<td>ALL</td>
<td>3.2 ± 0.6</td>
<td>3.0 ± 0.7</td>
<td>2.9 ± 0.7</td>
<td>2.9 ± 0.6</td>
</tr>
<tr>
<td>Mean neck circumference (cm)</td>
<td>ALL</td>
<td>96.4 ± 4.8</td>
<td>95.1 ± 4.9</td>
<td>95.8 ± 4.7</td>
<td>97.3 ± 4.9</td>
</tr>
<tr>
<td>Rump fat (cm)</td>
<td>CON</td>
<td>2.64 ± 1.04</td>
<td>2.98 ± 1.24</td>
<td>2.95 ± 1.19</td>
<td>3.07 ± 1.19</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>2.57 ± 0.70</td>
<td>2.45 ± 0.66</td>
<td>2.49 ± 0.66</td>
<td>2.52 ± 0.65</td>
</tr>
<tr>
<td>Back fat (cm)</td>
<td>ALL</td>
<td>0.87 ± 0.29</td>
<td>0.80 ± 0.30</td>
<td>0.93 ± 0.32</td>
<td>0.96 ± 0.34</td>
</tr>
<tr>
<td>Rib fat (cm)</td>
<td>ALL</td>
<td>0.89 ± 0.17</td>
<td>0.96 ± 0.14</td>
<td>0.95 ± 0.15</td>
<td>0.96 ± 0.15</td>
</tr>
<tr>
<td>Shoulder fat (cm)</td>
<td>ALL</td>
<td>0.87 ± 0.11</td>
<td>0.90 ± 0.10</td>
<td>0.91 ± 0.10</td>
<td>0.93 ± 0.10</td>
</tr>
</tbody>
</table>

*Within a variable, means with different superscript letters differ significantly (P < 0.05).

If no group or group × time point effect was observed, groups were combined (ALL). Measurements were performed with respect to the exercise protocol before exercise training, after 4 weeks of low-intensity exercise, after 4 weeks of higher-intensity exercise, and after 2 weeks of detraining.
pared with pre-exercise measurements. A group \( \times \) time point effect \( (P = 0.003) \) indicated an increase in rump fat thickness in the control group throughout the study, compared with baseline (pre-exercise) measurements.

TBW—There was no effect of exercise group, time point, or their interaction on TBW or FFM. There was a group \( \times \) time point effect \( (P < 0.001) \) on FM, which decreased \( (P < 0.05) \) in the exercise group by \( 20 \pm 7 \) kg \( (21 \pm 6\%) \) after low-intensity exercise and \( 32 \pm 9 \) kg \( (34 \pm 9\%) \) after high-intensity exercise, compared with pre-exercise values (Table 2). Similarly, percentage body fat calculated by FM and body weight decreased \( (P < 0.001) \) with exercise training.

FSIGTT—Baseline circulating concentrations of insulin, glucose, NEFAs, triglycerides, and leptin did not differ between groups, with no group \( \times \) time point interactions. However, there was an effect of time point on insulin \( (P = 0.013) \), glucose \( (P = 0.003) \), NEFA \( (P = 0.004) \), and triglyceride \( (P = 0.001) \) concentrations, indicating that they changed similarly in both groups during the study (Figures 1 and 2).

A time point effect was detected for AIRg \( (P = 0.001) \), with values of both groups measured after higher-intensity exercise and detraining higher \( (P < 0.05) \) than pre-exercise values (Table 3). No other group, time point, or group \( \times \) time point effects were observed for AIRg, SI, Sg, or disposition index.

### Discussion

Four weeks of low-intensity exercise training was associated with a 2% reduction in body weight and 21% reduction in FM, and a further 4 weeks of higher-intensity exercise training reduced body weight by 4% and FM by 34%, compared with pre-exercise values. However, there were no changes in subcutaneous fat thickness over the rump, shoulder, back, or rib areas with exercise training. Additionally, metabolic changes resulting from exercise training were not observed because baseline blood variable concentrations and minimal model parameters changed similarly between control and exercise groups over time.

Because metabolic variables did not differ between control and exercise groups throughout the study, there was no measured benefit of higher-intensity exercise training or effect of detraining for these variables. Furthermore, the magnitude of the decreases in body weight and estimated FM did not differ between the low- and high-intensity exercise periods. Although FM was not measured during the detraining time point, approximately half of the body weight that was lost during exercise training was regained during 2 weeks without structured exercise.

The present study revealed that in overweight or obese, insulin-resistant horses, 8 weeks of low- to moderate-intensity exercise training without dietary restriction did not result in sustained increases in SI. Conversely, previous studies in horses have detected improvements in SI with exercise training in the presence of weight loss or when dietary factors, such as a high-nonstructural carbohydrate diet, contributed to the insulin resistance. Short-term (7-day) exercise training increases SI in lean and obese horses, as indicated by an approximately 2-times increase in glucose disposal rate measured by use of the euglycemic-hyperinsulinemic clamp test performed 24 hours after the final exercise session.\(^{14,15}\)

Insulin sensitivity remained higher than pre-exercise values 3 days after the last exercise session.
when there was a decrease in body weight with exercise in lean horses,\textsuperscript{13,14} but returned to pre-exercise values by 9 days after the last exercise session when there was no decrease in body weight with exercise training in obese horses.\textsuperscript{14} Insulin sensitivity increased after 7 weeks of training when body weight remained constant; however, this occurred only in horses adapted to a high–nonstructural carbohydrate feed and not in horses adapted to a high-fat feed.\textsuperscript{29} In obese, hyperinsulinemic ponies, SI improved after 6 weeks of training and remained higher after 2 weeks of detraining.\textsuperscript{16} However, similar changes were observed in the control group, including decreased body weight and increased SI; therefore, exercise resulted in no additional improvements beyond those associated with controlled feed intake.

Previous studies\textsuperscript{14,15} have determined exercise training effects by measuring SI < 48 hours after completion of the last exercise session. Results may be confounded by the effects of acute exercise, or a single exercise session, on SI. Insulin sensitivity increases dramatically during moderate-intensity exercise in horses.\textsuperscript{30} Although short-term increases in SI within 24 hours after exercise have not been detected in horses,\textsuperscript{31} there is substantial data in humans suggesting an increase in SI as long as 2 days after an exercise bout.\textsuperscript{32} Therefore, the present study assessed SI 48 hours after the last exercise session to determine the effects of exercise training independent of the effects of a single exercise session.

Previous studies\textsuperscript{13,14} in horses and humans reveal improvements in SI through exercise-induced weight loss. Additionally, studies\textsuperscript{13,33} in human subjects reveal that exercise training improves SI independent of any change in body weight or fat distribution. Conversely, in the present study, although there was a decrease in body weight and FM in exercised horses, there was no associated improvement in SI. It is possible that a higher volume, frequency, or intensity of exercise training is required to enhance SI in overweight or obese, insulin-resistant horses.

Although significant changes occurred in metabolic variables between time points, these changes were similar between control and exercise groups. Overall, there was an increase in AIRg and insulin and triglyceride concentrations and a decrease in NEFA concentrations as the study progressed. Collectively, these data indicated either an increase in insulin secretion or a decrease in clearance, leading to an increase of circulating insulin concentrations and subsequent inhibition of lipolysis. Because there were no changes in dietary intake or composition, the most likely explanation for changes in metabolic variables is an influence of other environmental factors, such as weather or day length. Seasonal changes in SI may occur through changes in secretion of hormones such as ACTH or melatonin. In ponies and horses, ACTH concentration was higher in September than in January and May.\textsuperscript{35} An increase in ACTH stimulation may increase the effects of cortisol to decrease SI.

In exercised horses, abdominal circumference decreased after higher-intensity exercise and FM decreased after both low- and higher-intensity exercise training. However, there were no changes in subcutaneous fat thickness at the 4 measured body sites, suggesting a decrease in adipose depots other than subcutaneous adipose. Although not directly measured in the present study, changes in visceral or intramuscular adipose depots may decrease with exercise training. In humans, visceral adipose tissue decreases to a greater degree with weight loss than does total FM.\textsuperscript{36} Visceral adipocytes are hypothesized to have a higher fat turn-over rate than subcutaneous adipocytes because in vitro studies have revealed visceral adipocytes to be more lipolytically active.\textsuperscript{37} Additionally, fat stored in or around muscle fibers could decrease with exercise. Intramyocellular triglycerides are an important substrate source during exercise for endurance-trained human athletes\textsuperscript{38} and decrease in obese subjects with weight loss.\textsuperscript{39}

In the present study, TBW ranged from 59 ± 2% of body weight in both groups at the pre-exercise sampling to 64 ± 2% in the exercise group after higher-intensity exercise, which was within the range of 56% to 68% observed in a previous study\textsuperscript{26} that used the deuterium dilution method for TBW measurements in horses. Body condition was not indicated in previous studies, but calculation of percentage body fat from TBW provides a range from 7% to 23% FM; at the initiation of the present study, horses had 19 ± 3% FM.

It cannot be excluded that changes in hydration status or gastrointestinal tract content partially contributed to the observed changes in FM. When calculating FFM from TBW, it is assumed that FFM is 73% water content,\textsuperscript{4,35} water does not equilibrate into FM, and hydration status is similar during each infusion (before exercise, after low-intensity exercise, and after higher-intensity exercise). Deuterium oxide dilution protocols were performed in horses at least 24 hours after the

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Table 3—Mean ± SD values for minimal model parameters obtained from FSIGTT glucose and insulin curves in the same horses as in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Pre-exercise</th>
<th>Low intensity</th>
<th>Higher intensity</th>
<th>Detraining</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI (× 10⁻³ L/min/mU)</td>
<td>CON</td>
<td>0.52 ± 0.48</td>
<td>0.98 ± 1.26</td>
<td>0.37 ± 0.20</td>
<td>0.42 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>0.93 ± 0.87</td>
<td>1.49 ± 1.58</td>
<td>0.89 ± 0.93</td>
<td>1.46 ± 1.72</td>
</tr>
<tr>
<td></td>
<td>CON</td>
<td>1.06 ± 0.14</td>
<td>1.20 ± 0.29</td>
<td>0.90 ± 0.72</td>
<td>1.36 ± 0.47</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>0.92 ± 0.64</td>
<td>0.97 ± 0.64</td>
<td>0.72 ± 0.66</td>
<td>1.20 ± 0.84</td>
</tr>
<tr>
<td>AIRg (mU × min/L)</td>
<td>CON</td>
<td>560 ± 191</td>
<td>720 ± 286 \textsuperscript{29}</td>
<td>862 ± 408 \textsuperscript{29}</td>
<td>1,215 ± 602 \textsuperscript{29}</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>424 ± 162 \textsuperscript{33}</td>
<td>591 ± 204 \textsuperscript{29}</td>
<td>786 ± 302 \textsuperscript{29}</td>
<td>865 ± 602 \textsuperscript{29}</td>
</tr>
<tr>
<td>Disposition index (× 10⁻³)</td>
<td>CON</td>
<td>2.40 ± 1.70</td>
<td>5.34 ± 5.01</td>
<td>2.89 ± 1.28</td>
<td>4.36 ± 1.39</td>
</tr>
<tr>
<td></td>
<td>EX</td>
<td>3.59 ± 2.68</td>
<td>7.92 ± 5.87</td>
<td>5.63 ± 2.94</td>
<td>7.47 ± 7.52</td>
</tr>
</tbody>
</table>

\textsuperscript{29} For variables with a significant (P < 0.05) time point effect, mean values with different superscript letters differ significantly (P < 0.05). See Table 1 for remainder of key.
last exercise session to minimize effects of exercise on hydration because it has been reported that TBW re-equilibrates to pre-exercise values within 24 hours after an exercise session. Additionally, differences in transeellular fluid, including intraluminal gastrointestinal tract water and urine, and timing of urination and defecation with respect to body weight determination and deuterium oxide infusion could potentially influence calculations of TBW, FFM, and FM. In rabbits, intraluminal gastrointestinal tract water accounted for 12% of measured TBW, and 0.1% to 0.6% of injected deuterium oxide was excreted in urine.

During the entire training period (low- and higher-intensity exercise), estimated total energy expenditure was approximately 100 Mcal. With an estimated 1.6-Mcal energy expenditure necessary for each kilogram of body weight loss, mean weight loss was predicted to be approximately 13 kg. Therefore, the observed 20-kg decrease in body weight after higher-intensity exercise was actually more than expected, and the 12-kg loss maintained after detraining was similar to what was expected.

Considering the management effort necessary for modest decreases in body weight, it may be discouraging for horse owners to implement an exercise training program to reduce obesity in their horses. However, exercise training in combination with dietary restriction would be expected to have an additive effect on weight reduction. Additionally, exercise may have beneficial effects that dietary restriction alone would not provide. In humans, exercise training with weight reduction maintains or increases FFM (primarily muscle mass), whereas dietary restriction alone may decrease FFM with weight reduction. Similar occurrences in horses are supported by the present study because exercised horses had a nonsignificant 13-kg increase in FFM after exercise training. Additionally, in humans, maintenance of weight loss is more likely to succeed if exercise is part of the daily routine.

In the present study, 8 weeks of low- to moderate-intensity exercise modestly decreased adiposity (body weight and FM) without concurrent changes in glucose and insulin dynamics or basal metabolic blood variables. Results suggested that moderate exercise training without concurrent dietary restriction did not mitigate insulin resistance in the presence of overweight or obese body condition. A higher intensity or volume of exercise that induces greater loss of body weight and FM may be required for improvement in SI in overweight or obese, insulin-resistant horses.

References