Concurrent exercise prevents high-fat-diet-induced macrovesicular hepatic steatosis

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Gauthier, Marie-Soleil, Karine Couturier, Jean-Gilles Latour, and Jean-Marc Lavoie. Concurrent exercise prevents high-fat-diet-induced macrovesicular hepatic steatosis. J Appl Physiol 94: 2127–2134, 2003. First published January 24, 2003; 10.1152/japplphysiol.01164.2002.—The purpose of the present study was to assess the effect of an exercise training program conducted concurrently with a high-fat (HF)-diet regimen on the induction of hepatic steatosis. Two groups of rats were fed either a standard (SD) or a HF (40% kcal) diet for 8 wk and were additionally assigned either to a sedentary (Sed) or a treadmill-trained (TR) group. Training (5 days/wk) was initiated at the same time as the HF diet and was progressively increased, reaching 60 min at 26 m/min, 10% grade, for the last 4 wk. At the end of the 8-wk period, HF-Sed rats exhibited ~72% higher liver triacylglycerol concentration than SD-Sed rats (means ± SE: 17.15 ± 1.5 vs. 9.98 ± 1.0 mg/g; P < 0.01). Histological quantification of lipid infiltration, with the use of an image analysis computing system, revealed that, although fat was mainly stored as microvesicles (<1 µm²), the HF-diet-induced hepatic steatosis occurred via the accumulation of macrovesicles (>1 µm²). Concurrent exercise training completely prevented the HF-diet-induced hepatic steatosis. The surface area of liver parenchyma infiltrated by lipid vacuoles was similar in HF-TR as in SD-Sed rats (26.4 ± 1.8 vs. 29.3 ± 5.9 × 10³ µm²/200,000 µm² of liver parenchyma, respectively; P > 0.05). The different states of liver lipid infiltration after the HF diet in Sed and TR rats were associated with similar changes in plasma free fatty acids and glycerol, as well as with similar changes in fat pad weights, but not with plasma triacylglycerol levels. It is concluded that, after a HF-diet regimen of 8 wk in rats, hepatic steatosis occurs primarily via the accumulation of lipid as macrovesicles. Exercise training pursued at the same time completely prevents the HF-diet-induced macrovesicular hepatic steatosis.

Address for reprint requests and other correspondence: J.-M. Lavoie, Département de kinésiologie, Université de Montréal, C.P. 6128, Suc. centre-ville, Montréal, Québec, Canada H3C 3J7 (E-mail: jean-marc.lavoie@umontreal.ca).

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the present study was first to reexamine the effects of an exercise training program pursued at the same time as a HF-diet-induced obesity (40% in kcal) on the accumulation of lipids in the liver and the associated metabolic disturbances in plasma lipid profile, visceral and subcutaneous fat accumulation, and the development of insulin resistance. In addition, with the use of a novel image analysis computing system software program that enables precise morphological quantification of liver lipid infiltration, the present study was intended to precisely quantify the HF-diet-induced macrovesicular and/or microvesicular hepatic steatosis in rats and the extent to which exercise training affects this classification.

METHODS

Animal care. Female Sprague-Dawley strain rats (n = 37, Charles River, St-Constant, PQ), weighing 180–200 g (6 wk of age), on their arrival, were housed by pairs and had access to food and tap water ad libitum. Their environment was controlled in terms of light (12:12-h light-dark cycle starting at 6:00 AM), humidity, and room temperature (20–23°C). All experiments described in this report were conducted according to the directives of the Canadian Council on Animal Care.

Diet and exercise protocol. A few days after their arrival, all animals were randomly assigned to a standard (SD) or a HF diet for 8 wk. One-half of the animals in each dietary condition were concurrently exercise trained (TR) for the whole 8-wk period, whereas the other one-half remained sedentary (Sed). Hence, the four experimental groups consisted of SD-fed rats in the Sed (SD-Sed, n = 9) or the TR state (SD-TR, n = 9), or HF-fed rats in the Sed (HF-Sed, n = 9) or the TR state (HF-TR, n = 10). The HF diet consisted of 42% lipid, 36% carbohydrate, and 22% protein (kcal) and was provided in small pellets from ICN Pharmaceuticals (New York, NY). The SD diet (12.5% lipid, 63.2% carbohydrate, and 24.3% protein; kcal) consisted of the usual pellet rat chow (Agribrands Purina Canada, Woodstock, ON). Both diets are described in detail in Table 1.

Exercise training consisted of continuous running on a motor-driven rodent treadmill (Quinton Instruments, Seattle, WA) 5 times/wk for 8 wk. Rats were progressively run from 15 min/day at 15 m/min, 0% slope, up to 60 min/day at 20 m/min, 2% slope. These settings were maintained on a 5-day/wk trapezoidal training schedule (45 s on, 15 s off, 2 min rest). The treadmill was shifted to the right jugular vein and kept patent for the entire duration of the test with a sterile saline heparin solution (5 U/ml). A period of 15 min was allowed between the completion of the surgery and the beginning of the test to standardize the effects of the surgical stress. Blood samples were drawn at time −5 and 0 min to measure glucose in the fasting state in addition to plasma glucose and insulin. The ivGTT consisted of an injection of a glucose bolus (0.5 g/kg of 50% dextrose solution) administered over a period of 10 s at time 0 min. The catheter was rinsed four to six times with the animal’s blood to avoid any residual glucose in the catheter. Blood samples (0.5 ml) were collected in an EDTA-rinsed syringe (15%) at 2.5, 5, 15, 25, 35, and 60 min after the glucose injection, and the plasma collected for subsequent glucose and insulin analyses. Red blood cells from each sampling were resuspended in a Krebs-Heinselot solution resembling plasma composition and reinjected into the animal. At the end of the ivGTT, the jugular catheter was removed, and the vein was closed, as well as the opening on the neck of the animal. Penicillin (penicillin G procain, 40,000 U/kg im) was injected in the right leg of the rat to prevent risks of infection. Animals were returned to their cages and housed individually for the remaining experimental period (2 wk). TR rats were allowed 1 day of recovery before the resumption of their training program.

Blood and tissue sampling. Two weeks after the ivGTT, all animals were killed between 9:00 AM and 12:00 PM. All TR animals were restrained from training 48 h before death. Food was removed from the animals’ cages at least 2 h before death. After complete anesthesia (pentobarbital sodium, 50 mg/kg ip), the abdominal cavity was rapidly opened following the median line of the abdomen. Blood was collected by a single 0.5 ml injection from the abdominal aorta (−4 ml) and the hepatic portal vein (−1.5 ml) into syringes pretreated with EDTA (15%). Blood was centrifuged (3,000 rpm for 8 min, 4°C), and the plasma kept for further analyses. Several organs, muscles, and fat deposits were excised and weighed in the following order: liver, mesenteric fat, right and left limb muscles (plantaris, soleus, medial and lateral gastrocnemius), urogenital fat, retroperitoneal fat, and subcutaneous fat. All tissue samples were frozen in liquid nitrogen immediately after being weighed. The liver median lobe was freeze-clamped and used for glycogen and TAG determinations. For histological analysis of liver lipid infiltration, two cross sections of the large lobes were cut, embedded in histological compound (OCT), and prefrozen in 2-methylbutane brought to liquid nitrogen temperature. Mesenteric fat pad consisted of adipose tissue surrounding the gastrointestinal tract from the gastroesophageal sphincter to the end of the rectum, with special care taken in distinguishing and removing pancreatic cells. Urogenital fat pad included adipose tissue surrounding the kidneys, ureters, and bladder, as well as ovaries, oviducts, and uterus. Retroperitoneal fat pad was taken as the total fat deposit behind each kidney along the lumbar muscles. For subcutane-ous deposit measurement, a rectangular piece of skin was taken on the right side of each animal, from the median line of the abdomen to the spine and the right hip to the first rib, as described by Krotkiewski and Björntorp (13). All plasma

Table 1. Composition of the high-fat and standard diets

<table>
<thead>
<tr>
<th>High-Fat Diet</th>
<th>kg</th>
<th>Standard Diet</th>
<th>kg</th>
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<tbody>
<tr>
<td>Casein purified high</td>
<td>20</td>
<td>Crude protein</td>
<td>18.1</td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn starch</td>
<td>39</td>
<td>Crude fat</td>
<td>4.5</td>
</tr>
<tr>
<td>Corn oil</td>
<td>3.4</td>
<td>Crude fiber</td>
<td>3.4</td>
</tr>
<tr>
<td>Lard</td>
<td>14.6</td>
<td>Ash</td>
<td>6.7</td>
</tr>
<tr>
<td>AIN 76 mineral mix</td>
<td>5</td>
<td>Nitrogen-free extract</td>
<td>57.3</td>
</tr>
<tr>
<td>Alpha cell nonnutritive</td>
<td>16</td>
<td>Humidity</td>
<td>10</td>
</tr>
<tr>
<td>Bulk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VDFM (sheet dextrose)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
<td>100</td>
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</table>

VDFM, vitamin diet fortification mixture.
and tissue samples were stored at −78°C until analyses, except for the liver cross sections, which were stored at −25°C until histochemical treatment and analysis.

Analytic procedures. Plasma glucose concentration was determined with the use of a glucose analyzer (Yellow Springs Instruments 2300, Yellow Springs, OH). Insulin and glucagon concentrations were measured with commercially available radioimmunoassay kits (Medicorp, Montréal, PQ, and ICN Pharmaceuticals). Plasma nonesterified fatty acid (NEFA) levels were measured with a commercially available kit from Roche Diagnostics (Mannheim, Germany), and glycerol, TAG, and β-hydroxybutyrate were measured with kits from Sigma Diagnostics (St. Louis, MO).

Liver TAG concentration was estimated from glycerol released after ethanolic KOH hydrolysis by using a commercial kit (Sigma Diagnostics). Although this method does not discriminate between glycerol from phospholipids or TAG, Frayn and Maycock (8) have shown that omitting phospholipids leads to only a ±2% error in the determination of tissue TAG. Liver glycogen content was determined by use of the phenol-sulfuric acid reaction (15). For histological analysis, OCT-embedded liver sections were cut in a cryostat at 5 μm and mounted on microslide slides at −25°C. The slides were then fixed with formaldehyde (10%) and stained with oil red O. Lipid infiltration was assessed with light microscopy by using an image analysis computing system (Northern Eclipse, Empix Imaging). This system enabled a morphological quantification of liver lipid infiltration in terms of lipid vacuole size and number, as well as the overall surface area of liver parenchyma occupied by lipid vacuoles. Lipid vacuoles with a surface area <1 μm² were considered as microvesicles, whereas lipid vacuoles with a surface area >1 μm² were considered as macrovesicles. To account for discrepancies in sinusoid size between animals, the number and the surface area of the lipid vacuoles are expressed for a standardized surface of liver parenchyma of 200,000 μm².

Statistical analysis. Values are expressed as means ± SE. Statistical analyses were performed by a two-way ANOVA for nonrepeated-measures design, with diet and exercise training as main effects. Fisher’s post hoc test was used in the event of a significant (P < 0.05) F ratio. The area under the curve for plasma glucose and insulin levels during the ivGTT was computed by using a trapezoidal model.

RESULTS

The HF diet resulted in a significant (P < 0.01) increase in body weight in HF-Sed compared with SD-Sed rats (Table 2). Exercise training in rats on the HF diet resulted in a smaller body weight gain (P < 0.06) compared with that in HF-Sed rats, so that, after training, body weight of HF-TR rats was similar to body weight of SD-TR rats. The HF diet in the Sed state was associated with a significantly (P < 0.05) higher mean daily energy intake compared with the SD diet (Table 2). Exercise training increased (P < 0.01) energy intake only in animals fed the SD diet. A lower (P < 0.01) total relative muscle weight was measured after the HF diet in the Sed state, whereas it was only increased (P < 0.01) after exercise training in the HF group (Table 2).

There were no significant (P > 0.05) effects of either the HF diet or exercise training on plasma glucose response during the ivGTT (Fig. 1). However, the glucose-stimulated insulin response was significantly (P < 0.05) higher in HF-fed rats than rats fed the SD diet in both the Sed and the TR state. There was no significant

Table 2. Initial and final body weight, energy intake, and total relative muscle weight in standard- and high-fat-fed rats kept sedentary or exercise trained for 8 wk

<table>
<thead>
<tr>
<th></th>
<th>SD-Sed</th>
<th>SD-TR</th>
<th>HF-Sed</th>
<th>HF-TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Initial body weight, g</td>
<td>183 ± 2.1</td>
<td>186 ± 1.0</td>
<td>187 ± 1.9</td>
<td>184 ± 1.1</td>
</tr>
<tr>
<td>Final body weight, g</td>
<td>284 ± 9.0</td>
<td>306 ± 4.3</td>
<td>330 ± 12.7†</td>
<td>306 ± 7.0</td>
</tr>
<tr>
<td>Total relative muscle weight, g/100 g body wt</td>
<td>0.732 ± 0.01</td>
<td>0.705 ± 0.01</td>
<td>0.646 ± 0.02†</td>
<td>0.721 ± 0.02§</td>
</tr>
<tr>
<td>Energy intake, kcal/day</td>
<td>70.9 ± 1.4</td>
<td>75.8 ± 1.2‡</td>
<td>77.0 ± 2.3*</td>
<td>75.1 ± 1.5</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of animals. SD, standard diet; HF, high-fat diet; Sed, sedentary state; TR, trained state. Total relative muscle weight represents the sum of soleus, plantaris, and gastrocnemius muscle relative weight of the right leg. Energy intake represents the daily mean over the 8-wk protocol. Significantly different from SD counterpart: †P < 0.05, ‡P < 0.01. Significantly different from Sed counterpart: †P < 0.05, §P < 0.01.
(P < 0.05) effect of training on glucose-stimulated insulin response, although a tendency for a decrease (7.5%) can be observed in the HF rats (Fig. 2).

The HF diet in the Sed rats resulted in a significant (P < 0.01) increase in plasma NEFA and glycerol concentrations, whereas plasma TAG and β-hydroxybutyrate concentrations were not affected by the dietary manipulation (Table 3). Exercise training significantly (P < 0.05) reduced plasma NEFA and glycerol concentrations in both dietary conditions, although the values remained higher in rats fed the HF than the SD diet. There was also a tendency (P < 0.07) for plasma TAG to be decreased by training in both dietary groups, whereas β-hydroxybutyrate values were not changed after training (Table 3). Plasma glucose and insulin levels measured in peripheral blood were not affected by either the HF diet or exercise training (Table 3). On the other hand, insulin measured in the portal blood and glucagon measured in the fasting state were all significantly (P < 0.05) increased after the HF diet. Although a substantial reduction in fasting glucagon level of ~30% can be observed after training in the HF rats, there were no statistically significant effects of training on the hormones measured in the present study (Table 3). As expected, the HF diet in the Sed rats resulted in a significant (P < 0.05) increase (from 133 to 228%) in the relative weight of all visceral and subcutaneous fat pads (Fig. 3A). Exercise training resulted in a significant (P < 0.05) decrease in mesenteric and subcutaneous fat deposits, and in the sum of the three visceral and the four measured (including subcutaneous) fat pads in both rats on the SD diet, and even more in rats on the HF diet (Fig. 3B). On the whole, it appears that the HF diet altered most of the variables related to lipid metabolism and that physical training was of significant value in counteracting these deleterious effects.

There were no significant (P > 0.05) effects of either HF diet or exercise training on relative liver weight (Fig. 4A). Liver glycogen content was significantly (P < 0.01) lower after the HF diet in both Sed and TR rats (Fig. 4B). Training resulted in an increase (P < 0.05) in liver glycogen content in both dietary groups (Fig. 4B). The HF diet in the Sed group resulted in a significant (P < 0.01) increase in liver TAG concentrations (Fig. 4C). Exercise training in rats on the HF diet prevented the increase in liver TAG (P < 0.01), so that, after training, liver TAG concentrations were similar in HF-TR and SD-Sed groups (Fig. 4C). The histological assessment of liver lipid infiltration revealed that the total surface area occupied by lipid vacuoles was largely increased (~48%) after the HF diet in the Sed state, although the statistical significance level of this comparison was at P < 0.07 (Fig. 5A). As for the liver TAG levels, the surface area occupied by the lipid

![Fig. 2. Plasma insulin response during the ivGTT test (A: means) and total AUC for insulin concentration (B: means ± SE) in SD-fed rats in the Sed and TR state and in HF-fed rats in the Sed and TR state. n = 9–10 Rats/group. *Significantly different from SD-fed animals, P < 0.05.](image-url)

Table 3. Plasma metabolites and hormone concentrations in standard- and high-fat-fed rats kept sedentary or exercised trained for 8 wk

<table>
<thead>
<tr>
<th></th>
<th>SD-Sed</th>
<th>SD-TR</th>
<th>HF-Sed</th>
<th>HF-TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>NEFA, mM</td>
<td>0.09 ± 0.01</td>
<td>0.05 ± 0.01d</td>
<td>0.21 ± 0.04*</td>
<td>0.13 ± 0.02c,d</td>
</tr>
<tr>
<td>Glycerol, mM</td>
<td>0.12 ± 0.01</td>
<td>0.08 ± 0.01*a</td>
<td>0.18 ± 0.03b</td>
<td>0.11 ± 0.01b,“</td>
</tr>
<tr>
<td>TAG, mM</td>
<td>0.75 ± 0.10</td>
<td>0.60 ± 0.06</td>
<td>0.92 ± 0.22</td>
<td>0.59 ± 0.07</td>
</tr>
<tr>
<td>β-OH, mM</td>
<td>0.10 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>0.09 ± 0.01</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>Glucose, mM</td>
<td>7.66 ± 0.21</td>
<td>8.06 ± 0.21</td>
<td>7.76 ± 0.22</td>
<td>7.60 ± 0.22</td>
</tr>
<tr>
<td>Peripheral insulin, pM</td>
<td>148.7 ± 10.5</td>
<td>170.9 ± 15.7</td>
<td>167.8 ± 16.5</td>
<td>161.2 ± 16.7</td>
</tr>
<tr>
<td>Portal insulin, pM</td>
<td>225.6 ± 17.2</td>
<td>219.3 ± 30.1</td>
<td>265.8 ± 23.5*</td>
<td>277.0 ± 26.8</td>
</tr>
<tr>
<td>Fasting glucagon, pg/l</td>
<td>191.7 ± 9.9</td>
<td>207.3 ± 30.3</td>
<td>345.6 ± 70.6*</td>
<td>247.7 ± 18.2</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of animals. NEFA, nonesterified fatty acids; TAG, triacylglycerol; β-OH, beta-hydroxybutyrate. Note: all variables were measured in a postprandial state (>2 h) except for fasting glucagon. Significantly different from SD-fed counterpart animals: *P < 0.05, bP < 0.01, cP < 0.001. Significantly different from Sed counterpart animals. dP < 0.05, eP < 0.01.
vacuoles was significantly (P < 0.01) reduced by exercise training (Fig. 5A). No statistical differences were found between groups in the total number of lipid vacuoles in the liver (Fig. 5B). There was no statistical difference between all groups in the number of liver lipid vacuoles of surface area <1 µm² (Fig. 6). HF-Sed rats had, however, a significantly (P < 0.05) higher number of lipid vacuoles with surface area between 1 and 10 µm² than did SD-Sed rats. Exercise training significantly (P < 0.05) lowered the number of liver lipid vacuoles in all sizes between 1 and 10 µm² (Fig. 6).

DISCUSSION

The present HF diet regimen in rats resulted in a 72% higher fat accumulation in the liver compared with that of SD-fed animals (Fig. 4C). Histological analyses confirmed these results, with the surface area of liver parenchyma occupied by the lipid vacuoles being ~48% greater in HF- than in SD-fed animals (Fig. 5A). These results are in concordance with those of previous studies in which hepatic steatosis is ro-

dents was induced by HF diets (9, 19, 27). Hepatic steatosis can also be induced by other types of diets, such as high-cholesterol (28), ethanol-containing (29), choline-methionine-deficient (17), and high-sucrose diets (3). In the present study, we used a 40% HF diet in rats (compared with ~12% fat in standard chow, in kcal) over a relatively long period of time (8 wk) for this species, in an attempt to reproduce a common HF diet in humans (~60% kcal as fat in a HF diet vs. 30% in a recommended standard diet). Our results, using biochemical and histological measurements, clearly show that hepatic steatosis can be induced by such a fat-rich diet without any toxin ingestion or alimentary deficiency.

The major finding of the present study is that, when an exercise training program is pursued at the same time as the HF diet, the induction of hepatic steatosis is completely suppressed. At the end of the 8-wk experimental period, HF-TR animals had similar liver fat content as SD-Sed animals. This was observed by using biochemical as well as histological analyses (Figs. 4C and 5A). There is some evidence that ethanol-induced fatty liver can be attenuated by repeated running exercise in rats (29). The evidence that exercise training
reduces liver lipid accumulation induced by fat-rich diets is, however, controversial. In previous studies, an effect (19) and the absence of an effect (28) of exercise training on hepatic steatosis have been reported. Comparison between these two studies reveals that, in the latter study (28), exercise training was started after fatty liver had been induced. It is, therefore, possible that, to be most effective, exercise must be concurrent with the induction of fatty liver. In a recent study, however, Straczkowski et al. (27) failed to show an effect of concurrent exercise training on HF diet-induced hepatic steatosis in rats. In that study, rats were sustained on a 59% fat diet (as kcal), resulting in an 110% increase in liver TAG and a 65% decrease in liver glycogen over a period of 3 wk. Exercise training, over a 4-wk period, consisted of running six times per week at 1–3 km/min, 10% slope. In the present study, liver TAG were increased by 72%, whereas liver glycogen content was decreased by 20%. It is thus possible that, in the study by Straczkowski et al. (27), the metabolic perturbations induced by the HF diet might have been too intense to be compensated by the exercise training program. Although the modalities of application of the exercise regimen seem to play a role, the present results clearly indicate that a 40% HF diet-induced hepatic steatosis can be totally prevented by a concurrent exercise training program.

Hepatic steatosis can be distinguished as macro- or microvesicular, according to the size of the lipid vacuoles (>1 or <1 μm² of surface area, respectively). Macrovesicular steatosis has been reported to be more common (26), whereas microvesicular steatosis is usually described in association with more severe clinical cases (7, 10). It has been recently suggested, however, that microvesicular steatosis is more prevalent than was originally believed and that it can be present without liver dysfunction (7) or hepatotoxicity (24). Thus it seems that the clinical implications of microvesicular vs. macrovesicular steatosis require better characterization. In a first step toward this goal, we, for the first time, used a novel image analysis computing system to quantitatively assess the number and the size of lipid vacuoles accumulated within liver parenchyma. The results obtained with the use of this tool indicate that, although the number of microvesicles in the liver is far greater than the number of macrovesicles, HF-diet-induced hepatic steatosis occurs mainly via an increased number of macrovesicles (Fig.

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**Fig. 5.** Total surface area occupied by the lipid vacuoles (A) and total number of lipid vacuoles (B), both expressed for a standardized surface area (2 × 10⁵ μm²) of liver parenchyma in SD-fed rats in the Sed and TR state and in HF-fed rats in the Sed and TR state. Values were obtained from histochemical quantification by using an image analysis computing system (Northern Eclipse, Empix Imaging). Values are means ± SE; n = 4–8 rats/group. *Significantly different from corresponding SD-fed group, P < 0.07. **Significantly different from corresponding Sed group, P < 0.01.

**Fig. 6.** Number of lipid vacuoles per unit of surface area expressed for a standardized surface area (2 × 10⁵ μm²) of liver parenchyma in SD-fed rats in the Sed and TR state and in HF-fed rats in the Sed and TR state. Values were obtained via histochemical quantification by using an image analysis computing system (Northern Eclipse, Empix Imaging). Values are means ± SE; n = 4–8 rats/group. Significantly different between *HF-Sed and SD-Sed groups and & HF-TR and HF-Sed groups, P < 0.05. Statistical significance was for all vacuole sizes between 1 and 10 μm² (shown within brackets).
The present study also provides the first evidence that prevention of HF-diet-induced hepatic steatosis by exercise training occurs mainly by preventing the accumulation of TAG as macrovesicles, without any apparent changes in the pool of microvesicles. It is not possible, however, to determine from the present data whether lipid macrovesicles are newly synthesized as large vesicles or whether they result from the aggregation of small lipid vesicles into larger vesicles (5), accompanied by an increased synthesis of microvesicles. Nevertheless, the increased number of macrovesicles without any reduction in quantity of microvesicles should have led to an increase in the total number of vesicles after the HF diet. Although a tendency toward an increase in the total number of vesicles after the HF diet and a decrease in the total number of vesicles after exercise training can be observed among HF-fed rats, the differences did not reach statistical significance (Fig. 5B). This could be due to the remarkably greater number of microvesicles compared with macrovesicles and the fact that the number of microvesicles was not affected by the present dietary and exercise manipulations (Fig. 6).

The precise mechanism by which macrovesicular hepatic steatosis can be prevented through exercise training remains speculative. Mechanisms involved in the pathogenesis of HF-diet-induced hepatic steatosis are themselves nebulous. The accumulation of lipids within the liver must be the result of an imbalance among 1) lipid uptake by the liver, 2) lipid oxidation inside the liver, and 3) very-low-density lipoprotein (VLDL)-TAG secretion. In the present experiment, HF diet resulted in more than a twofold increase in plasma NEFA. The increased delivery of fatty acids to the liver should result in a higher uptake by the liver, because NEFA uptake is mostly done in a concentration-dependent manner (5). Although we did not directly measure liver lipid oxidation, plasma β-hydroxybutyrate levels, which can be used as an index of the activation of this metabolic pathway, were not altered by either the HF diet or exercise training. An increase in lipid uptake by the liver should have resulted in an increased output through incorporation of TAG into VLDL. The increased VLDL secretion by the liver should have led to an increased plasma level of TAG (11). In our study, plasma TAG levels were not, however, increased by the HF diet. During increased fat availability, the synthesis and secretion of VLDL have already been reported to be insufficient to ensure the normal lipid cycling between adipocytes and hepatocytes (16, 31). Altogether, the changes in blood lipid profiles after the HF diet suggest that fat accumulation inside the liver was the result of an increased uptake of fatty acids by the organ, leading to an increased TAG synthesis rather than an increased oxidation. Furthermore, it appears that the increased liver TAG synthesis could not be compensated by an increase in VLDL secretion, resulting in fat accumulation within hepatocytes.

Consistent with the above-discussed mechanisms involved in the development of HF-diet-induced hepatic steatosis, there are three possibilities through which exercise training could have prevented liver fat accumulation: 1) a diminished delivery of lipids to the liver, 2) an increased hepatic oxidation, and/or 3) an increased incorporation of TAG into VLDL. Concurrent training in rats receiving the present HF diet resulted in a large decrease in circulating plasma NEFA, no change in plasma β-hydroxybutyrate levels, and a tendency (P < 0.07) for lower plasma TAG levels. Altogether, these results suggest that the preventing effect of exercise training on hepatic fat accumulation is a consequence of a diminished delivery of NEFA to the liver rather than an increased hepatic oxidation or an increased VLDL synthesis.

The reduced NEFA and glycerol plasma concentrations in TR animals are most likely related to the decreased level of adiposity in these rats, most likely due to an increased fat utilization. The interpretation that the decrease in liver lipid accumulation with exercise training is due to a decrease in circulating lipids rather than an increased output from the liver would be consistent with the above-mentioned suggestion that training is more efficient in decreasing hepatic fat accumulation if it is conducted at the same time that fatty liver is induced than if it is conducted after fatty liver has been induced. Another interesting observation is that, similar to the liver, fat accumulation in the mesenteric fat pad, which is drained into the hepatic portal vein, was completely prevented by exercise training. In contrast, HF-diet-induced enlargement of other visceral fat pads (urogenital and retroperitoneal), which are drained into the vena cava, was not completely abolished by exercise training. It has been suggested in a recent review (14) that intracellular TAG storage depot within the liver could act as an internal buffer to temporarily protect the hepatocytes against the potential toxicity of NEFAs when their uptake is greater than their oxidation rate and VLDL secretion. Similarly, it can be postulated that, along with the mesenteric fat pad, the liver could act as a systemic buffer to temporarily lower circulating NEFAs.

A decrease in liver lipid accumulation may have clinical significance. An increase in liver TAG content has been associated with impaired insulin signaling pathway within hepatocytes of fatless mice, resulting in decreased insulin suppression of hepatic glucose production (12). Normal insulin action on hepatic glucose production was reestablished when liver TAG were reduced by redistribution of fat into transplanted adipocytes (12). In our experiment, hepatic insulin sensitivity was not determined. However, the results of the ivGTT revealed that HF-fed rats developed mild systemic insulin resistance, which was only somewhat improved by training (Fig. 2). HF-fed rats also depicted higher portal insulin and fasting glucagon levels than their SD-fed counterpart animals, which was not fully counteracted by training. The rather small effect of training on these insulin-sensitivity-related variables contrasts, however, with the large effect of training observed on hepatic lipid accumulation. Hepatic steatosis also constitutes the first hit in the pathogenesis of nonalcoholic fatty liver, which can progress to stea-
atohepatitis, steatonecrosis, fibrosis, cirrhosis, and even liver failure (2, 20). Exercise training can, therefore, constitute a tool contributing to the protection of the liver against clinical complications of fatty liver.

In summary, the results of the present study indicate that a HF diet administered over a period of 8 wk in rats induced a state of hepatic steatosis, which was primarily attributable to an accumulation of lipids into macrovesicles (>1 μm² of surface area). Exercise training conducted concurrently with the HF diet completely prevented the accumulation of lipids into the liver. The exercise-induced decrease in hepatic fat accumulation was mainly attributed to a reduction in the number of macrovesicles.

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