Exercise-Induced Changes in the Concentration of Individual Fatty Acids and Triacylglycerols of Human Plasma

Vassilis Mougios, Christos Kotzamanidis, Christine Koutsari, and Sotiris Atsopardis

Nineteen male handball players played for two 30-minute periods with a 10-minute interval. Blood samples were drawn at rest, at halftime, and at the end of the game. A biopsy of subcutaneous fat was also taken from 14 participants. Mean plasma lactate concentration was not greater than 4 mmol/L at the end of either half. The concentration of nonesterified fatty acids (NEFA) in plasma increased gradually but not uniformly throughout the game. In effect, the percentages of the major NEFA were significantly different at the three time points of sampling: palmitate (16:0) and stearate (18:0) decreased and oleate (18:1) and linoleate (18:2) increased, resulting in an increase of the ratio of unsaturated to saturated fatty acids (U/S) from 1.1 at rest to 1.6 at the end. The concentration of plasma triacylglycerols (TG) declined during the game, but nine of 19 subjects showed increases during one or both halves, implying a stimulation of TG release from the liver during exercise, which can, at times, overcome the increased hydrolysis of TG in muscle capillaries. Changes in the acyl-group distribution of plasma TG were minor but also in favor of unsaturated fatty acids. Changes in NEFA composition tended toward the composition of adipose tissue, in which TG had a U/S ratio of 3.2. Linear regression between changes in the total concentration of plasma NEFA during each half of the game and corresponding changes in the concentration of individual NEFA showed that the contributions (slopes) of myristate (14:0), palmitoleate (16:1), 16:0, and 18:2 were not significantly different from their fractions in adipose tissue TG. In contrast, the contributions of 16:0 and 18:1 were, respectively, higher and lower than their fractions in adipose tissue TG, suggesting that the rates of release were, respectively, higher and lower than the rates of uptake. The observed shift toward unsaturated NEFA and TG may contribute to the favorable modifications of the plasma lipoprotein profile associated with aerobic exercise and with a diet rich in unsaturated fatty acids.

SUBJECTS AND METHODS

Our research was conducted among selected handball players at the level of the Greek national junior team. The study group consisted of 19 healthy male volunteers aged 15 to 17 who had been training for the previous 4 to 6 years. They averaged 1.84 m in height and 76 kg in mass. Each subject participated in one of four handball matches played between 5 and 10 pm and had eaten a light meal 3 to 4 hours before the start of his game. The rules were modified to ensure continuous 30-minute play in each half, ie, no time-out, no substitution of players, and no suspension from playing was allowed.

Three blood samples were taken from the antecubital veins of each player: one at rest (15 to 20 minutes before playing), one during the 10-minute halftime (2 to 6 minutes after the end of the first half), and one 2 to 6 minutes after the end of the game. Then a biopsy of subcutaneous adipose tissue was taken by needle aspiration from the right buttock of 14 participants as previously described. EDTA plasma was prepared from each blood sample and stored at −20°C along with the biopsies. Analyses were performed within 1 month.

Plasma lactate, glucose, and glycerol were determined by enzymatic spectrophotometric methods using reagent kits from Boehringer (Mannheim, Germany). Analysis of plasma NEFA and TG was initiated by the addition of appropriate amounts of heptadecanoic acid and triheptadecanoin (Sigma, St Louis, MO) as internal standards. Lipids were extracted as previously described and separated by thin-layer chromatography on silica gel plates. The developer was petroleum ether:diethyl ether-acetic acid 87:13:1 (vol/vol/vol). Lipid spots were located under UV light after spraying with dichlorofluorescein in solution, and spots corresponding to NEFA and TG were excised and incubated in methanol.

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sulfuric acid 96:4 (vol/vol) at 60°C overnight. The methyl esters produced were separated by gas chromatography in a Hewlett-Packard 5890 Series II chromatograph (Walldronn, Germany) equipped with a 30-m long Carbowax capillary column from Alltech (Deerfield, IL). The column temperature was programmed from 180° to 215°C at 4°C/min and from 215° to 260°C at 10°C/min. The carrier gas was helium at a flow rate of 1.5 mL/min. Methyl esters of the samples were quantified by comparing the area under their peaks in the chromatogram with that of methyl heptadecanoate. Similarly, adipose tissue lipids were extracted and separated by thin-layer chromatography, and the percent molar distribution of the TG acyl groups was determined by gas chromatography.

Values are expressed as the mean ± SEM. Statistical comparisons of means at the three time points were performed using ANOVA. Comparisons involving two-sample means or two estimates of regression coefficients were made by applying Student’s t test. The level of significance (P) was set at .05.

RESULTS

Table 1 lists plasma concentrations of lactate, glucose, and glycerol before, after the first half, and after the end of a handball game. Lactate increased from a mean resting value of 1.78 to 3.75 mmol/L at halftime and declined to 2.54 mmol/L at the end. Likewise, glucose exhibited the lowest concentration at rest (4.20 mmol/L) and the highest at 30 minutes of play (5.92 mmol/L). Glycerol, on the other hand, had a progressive increase from 0.060 at rest to 0.148 mmol/L at the end (2.5-fold). Mean values for each of these parameters at the three time points were significantly different. Moreover, the change in lactate concentration during the first half was significantly different from the change during the second half. This was also the case for changes in glucose concentration. In contrast, changes in glycerol concentration during each half were not significantly different.

The effect of exercise on plasma NEFA levels is shown in Table 2. Being significantly different at the three time points of sampling, the concentrations of individual NEFA underwent successive increases during the game, resulting in an increase of the mean total concentration from 0.189 at rest to 0.623 mmol/L at 60 minutes (3.3-fold). The change during the first half (0.261 ± 0.043 mmol/L) was not significantly different from the change during the second half (0.173 ± 0.030).

The relative change in the mean concentration of individual NEFA throughout the game was not uniform. At one extreme was linoleate (18:2) with a 4.5-fold increase, and at the other, stearate (18:0) with a mere twofold increase. As a result, molar percentages of individual NEFA changed during the game (Table 2). These changes were significant for the four major plasma NEFA. Percentages of the saturated fatty acids palmitate (16:0) and 18:0 decreased gradually, whereas those of the unsaturated fatty acids oleate (18:1) and 18:2 increased. As a consequence, the mean ratios of unsaturated to saturated fatty acids (U/S) were significantly different at the three time points, increasing from 1.08 at rest to 1.61 at the end of the game.

Table 3 lists mean concentrations of the acyl groups of plasma TG. All concentrations decreased progressively, resulting in a decrease of the mean total TG concentration from 0.907 at rest to 0.708 mmol/L at 60 minutes. However, differences at the three time points did not reach statistical significance for any of the individual acyl groups or for the total TG. This lack of significance reflects the lack of uniform changes during the game. More precisely, although most (10) subjects exhibited the pattern imprinted in the mean values (ie, decrease during the first half and further decrease during the second half), all other possible patterns were also observed: decrease and then increase (five subjects), increase and then decrease (two subjects), and even sequential increases (two subjects). It should be noted that, with the exception of arachidonate (20:4), mean levels of each TG acyl group at rest and at the end of the game were significantly different. This was also the case for total TG concentrations.

In accordance with the absolute concentrations, the relative amounts of each TG acyl group were not significantly different at the three time points of sampling (Table 3). However, molar percentages of certain acyl groups underwent changes in the same direction during the two halves of the game, which resulted in significant differences between the resting and 60-minute values. These were, on one side, myristate (14:0) and 16:0, the percentages of which increased, and, on the other side, palmitoleate (16:1), 18:1, and 20:4, the percentages of which decreased. (The percentages of 18:2 showed sequential increases, too, but the mean postexercise values were not significantly different.) Likewise, the mean U/S ratio increased slightly with exercise, and the ratio at 60 minutes was significantly different from that at rest.

In an attempt to correlate changes in the profile of plasma NEFA with the profile of their major source, ie, TG of adipose tissue, we obtained biopsies from 14 participants and determined the acyl-group composition of their TG. These data are listed in Table 4 along with the plasma NEFA distribution at rest, 30 minutes, and 60 minutes of exercise for these individuals. Approximately half the acyl groups in adipose tissue TG belonged to 18:1, with 18:2 and 16:0 competing for second place. Two observations are striking, considering the relationship between the composition of plasma NEFA and adipose tissue TG: First, at all three time points, mean percentages of each of the four

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Table 1. Plasma Lactate, Glucose, and Glycerol Concentrations (mmol/L) at Rest, After 30 Minutes, and After 60 Minutes of Handball Playing, and Changes During Each Half (mean ± SEM, N = 19)

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>30 Minutes</th>
<th>60 Minutes</th>
<th>ANOVA 30 Minutes - Rest</th>
<th>60 Minutes - 30 Minutes</th>
<th>t Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactate</td>
<td>1.78 ± 0.11</td>
<td>3.75 ± 0.38</td>
<td>2.54 ± 0.28</td>
<td>P &lt; .001</td>
<td>-1.20 ± 0.39</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>Glucose</td>
<td>4.20 ± 0.13</td>
<td>5.92 ± 0.33</td>
<td>5.27 ± 0.48</td>
<td>P &lt; .01</td>
<td>1.72 ± 0.33</td>
<td>P &lt; .01</td>
</tr>
<tr>
<td>Glycerol</td>
<td>0.086 ± 0.010</td>
<td>0.127 ± 0.016</td>
<td>0.148 ± 0.016</td>
<td>P &lt; .001</td>
<td>0.067 ± 0.021</td>
<td>0.022 ± 0.021</td>
</tr>
</tbody>
</table>
EXERCISE AND INDIVIDUAL PLASMA NEFA AND TG

Table 2. Concentration and Percent Molar Distribution of Individual Plasma NEFA at Rest, After 30 Minutes, and After 60 Minutes of Handball Playing (mean ± SEM, N = 19)

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Concentration (µmol/L)</th>
<th>Percent Molar Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest 30 Minutes 60 Minutes ANOVA</td>
<td>Rest 30 Minutes 60 Minutes ANOVA</td>
</tr>
<tr>
<td>14:0</td>
<td>3.0 ± 0.6 8.0 ± 1.1 9.2 ± 1.4 P &lt; .001</td>
<td>1.5 ± 0.3 1.8 ± 0.2 1.4 ± 0.2 NS</td>
</tr>
<tr>
<td>16:0</td>
<td>59.0 ± 4.3 126.8 ± 11.6 166.8 ± 15.6 P &lt; .001</td>
<td>31.6 ± 0.8 28.9 ± 0.6 27.0 ± 0.5 P &lt; .001</td>
</tr>
<tr>
<td>16:1</td>
<td>6.6 ± 1.0 15.2 ± 2.1 20.4 ± 2.1 P &lt; .001</td>
<td>3.7 ± 0.5 3.4 ± 0.3 3.3 ± 0.1 NS</td>
</tr>
<tr>
<td>18:0</td>
<td>28.3 ± 2.2 481.3 ± 36 57.7 ± 3.5 P &lt; .001</td>
<td>15.7 ± 1.0 11.7 ± 0.7 10.4 ± 0.8 P &lt; .001</td>
</tr>
<tr>
<td>18:1</td>
<td>67.6 ± 6.6 181.5 ± 21.6 260.8 ± 26.3 P &lt; .001</td>
<td>35.1 ± 1.1 39.3 ± 1.1 41.6 ± 0.8 P &lt; .001</td>
</tr>
<tr>
<td>18:2</td>
<td>23.1 ± 3.1 66.9 ± 9.5 102.9 ± 14.2 P &lt; .001</td>
<td>11.5 ± 0.8 14.2 ± 0.8 15.4 ± 1.0 P &lt; .01</td>
</tr>
<tr>
<td>18:3</td>
<td>0.4 ± 0.3 0.8 ± 0.3 1.7 ± 0.6 P &lt; .05</td>
<td>0.2 ± 0.1 0.1 ± 0.0 0.2 ± 0.0 NS</td>
</tr>
<tr>
<td>20:4</td>
<td>1.0 ± 0.3 2.5 ± 0.4 3.4 ± 0.5 P &lt; .001</td>
<td>0.7 ± 0.2 0.6 ± 0.1 0.7 ± 0.1 NS</td>
</tr>
<tr>
<td>Total</td>
<td>189.2 ± 14.8 449.7 ± 46.0 623.0 ± 59.5 P &lt; .001</td>
<td>100.0 100.0 100.0</td>
</tr>
<tr>
<td>U/S</td>
<td>1.08 ± 0.06 1.40 ± 0.07 1.61 ± 0.07 P &lt; .001</td>
<td></td>
</tr>
</tbody>
</table>

plasma NEFA that underwent significant changes during exercise (16:0, 18:0, 18:1, and 18:2) are significantly different from the percentage of the same fatty acid in adipose tissue TG. The same holds true for the mean U/S ratios. Second, changes in the percentages of these NEFA in plasma are in the direction of the adipose tissue percentages, ie, decrease where the percentage in plasma at rest was higher than the percentage in adipose tissue (16:0 and 18:0), and increase where the percentage in plasma at rest was less than the percentage in adipose tissue (18:1 and 18:2). Accordingly, U/S ratios of plasma NEFA moved toward the U/S ratio of adipose tissue TG during the game. These trends are depicted schematically in Fig 1. The mean percent convergence of the plasma-NEFA to adipose-tissue percentage for 16:0, 18:0, 18:1, and 18:2 after 60 minutes of exercise was, respectively, 39, 54, 37, and 62. Likewise, the convergence in U/S ratios was 29%.

If the composition of adipose tissue TG determines the changes in the distribution of plasma NEFA during exercise (as the data of Table 4 imply), then the contribution of each fatty acid to the increase in the concentration of plasma NEFA should be proportional to its fraction in adipose tissue TG. To test this hypothesis, we examined the correlation between changes in the total concentration of plasma NEFA and changes in the concentration of each NEFA during the same period. Significant correlations were found for the six major fatty acids (14:0, 16:0, 16:1, 18:0, 18:1, and 18:2), with correlation coefficients ranging from .62 (P < .05) to an impressive .98 (P < .001).

Linear regression showed that for each of these fatty acids, the regression coefficient (slope) related to the changes during the first half was not significantly different from the one related to the changes during the second half. This suggested, in statistical terms, that the two coefficients were estimates of a common slope or, in physiologic terms, that the dependence of the individual changes on the total changes was uniform during the two halves. This, in turn, allowed us to simplify the picture by pooling the data from the two halves for each fatty acid. Table 3 lists the characteristics of these correlations and lines. As with the data from the individual halves, the combined data showed significant correlations between changes in the total concentration of plasma NEFA and changes in the concentration of each of the six major NEFA, with correlation coefficients now ranging from .67 to .97.

None of the Y intercepts of the lines describing these correlations were significantly different from 0. However,
the effect of exercise on the percent distribution of plasma
in adipose tissue) is well documented, little is known about
All rest, halftime, and end values are significantly different from
NEFA. Plasma TG, on the other hand, are considered to
increase in the concentration of NEFA in blood
though an increase in the concentration of NEFA in blood
during prolonged efforts (as a result of augmented lipolysis
to aerobic catabolism in working muscles plays an important
role during prolonged exercise of moderate intensity. Al-
though an increase in the concentration of NEFA in blood
during prolonged efforts (as a result of augmented lipolysis
in adipose tissue) is well documented, little is known about
the effect of exercise on the percent distribution of plasma
NEFA. Plasma TG, on the other hand, are considered to
the most interesting information lay in the slopes: Compari-
sion to the fractions of the same fatty acids in adipose tissue
TG showed that most differences were not significant, with
two remarkable exceptions, 16:0 and 18:1. The slope for
16:0 was higher than its fraction in adipose tissue TG, whereas the slope for 18:1 was lower than its fraction in
adipose tissue TG. It is noteworthy that these two fatty
acids had the highest correlation coefficients. The sum of
the slopes for the six fatty acids was 1.000, very close to the
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two fatty acids had the highest correlation coefficients. The sum of
adipose tissue value.

**DISCUSSION**

Utilization of blood-borne NEFA as a substrate for
aerobic catabolism in working muscles plays an important
role during prolonged exercise of moderate intensity. Al-
though an increase in the concentration of NEFA in blood
during prolonged efforts (as a result of augmented lipolysis
in adipose tissue) is well documented, little is known about
the effect of exercise on the percent distribution of plasma
NEFA. Plasma TG, on the other hand, are considered to
contribute little to energy provision during physical activ-
it. It is probably because of this that acute changes in TG
concentration have received less attention than the long-
term effects of exercise.

We have examined a number of biochemical changes,
with an emphasis on aspects of lipid metabolism, during
exercise of variable intensity (handball playing). The two
indices of carbohydrate utilization examined, ie, plasma
lactate and glucose concentrations, showed similar changes
during the game: increase at 30 minutes of exercise and
decline to values above resting levels at 60 minutes (Table
1). Lactate values were less than 4 mmol/L, which is
considered to mark the anaerobic threshold,21 pointing to a
predominance of aerobic metabolism in muscle. The lower
lactate concentration after 60 minutes of play as compared
with the 30-minute value indicates reduced utilization of
carbohydrates during the second half. Taking this into
account, the glucose values suggest that output from the
liver was reduced during the second half.

Plasma glycerol and all NEFA, on the other hand, exhibited a different pattern, ie, sequential increases at the
two halves of the game (Tables 1 and 2). This is typical of
prolonged efforts,1,2 and indicates a continuous stimulation
of lipolysis throughout the game.

Physical activity caused significant changes in the relative
amounts of plasma NEFA (Table 2). Our data afford a
clear distinction between the major saturated fatty acids
16:0 and 18:0, whose percentages decreased, and the major
unsaturated fatty acids 18:1 and 18:2, whose percentages
increased. We have been able to trace only two relevant
reports in the literature. Horstman et al3 found a decrease in the percentage of 18:1 and an increase in the percentage
of 18:2 with heavy exercise, which caused the total plasma
NEFA concentration to decrease, and the opposite effect
with moderate exercise, which caused the NEFA concentra-
tion to increase. Vihko et al4 reported decreased percent-
ages of 16:0, 18:0, and 18:2 and increased percentages of
16:1 and 18:1 after intermittent exercise of variable inten-
sity, which elevated the total plasma NEFA concentration.
The consensus of these results and our own is that, with the
exception of 18:2, the relative amounts of saturated plasma
NEFA decrease and those of unsaturated NEFA increase
when exercise conditions favor an increase in the total
plasma NEFA concentration. A possible explanation for the
discrepancy regarding 18:2 will be presented later.

The response of plasma TG concentration to exercise
was not as clear as that of NEFA (Table 3). Although the
predominant change was a decrease, interestingly enough,
nine of 19 athletes exhibited increases in total TG concen-
tration during one or both halves of the game. Several other
studies have found an exercise-induced increase in blood
glyceraldehyde concentration,10-18 although the methodology used in a
total of them casts doubt on the validity of the relevant
data. As already pointed out,14 the usual enzymatic assays
for TG measure the level of glycerol produced after total
TG hydrolysis. Since prolonged exercise elevates blood
glycerol concentration, TG values will be falsely elevated
unless the glycerol naturally present in a sample is deter-
deoxon, as well. Correction for free glycerol has indeed been

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**Table 4. Percent Molar Distribution of Acyl Groups in Adipose Tissue**

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Adipose Tissue TG</th>
<th>Rest</th>
<th>30 Minutes</th>
<th>60 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:0</td>
<td>1.8 ± 0.4</td>
<td>1.4 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>18:0</td>
<td>18.8 ± 1.5</td>
<td>32.4 ± 0.7*</td>
<td>29.2 ± 0.6*</td>
<td>27.4 ± 0.6*</td>
</tr>
<tr>
<td>18:1</td>
<td>3.7 ± 0.4</td>
<td>3.5 ± 0.4</td>
<td>3.6 ± 0.4</td>
<td>3.4 ± 0.1</td>
</tr>
<tr>
<td>18:2</td>
<td>4.9 ± 0.3</td>
<td>14.3 ± 0.9*</td>
<td>11.1 ± 0.8*</td>
<td>9.3 ± 0.7*</td>
</tr>
<tr>
<td>16:0</td>
<td>18.8 ± 1.9</td>
<td>35.7 ± 1.1*</td>
<td>39.3 ± 1.3*</td>
<td>41.2 ± 0.9*</td>
</tr>
<tr>
<td>18:1</td>
<td>19.3 ± 0.9</td>
<td>12.1 ± 0.9*</td>
<td>14.3 ± 0.9*</td>
<td>16.4 ± 1.1*</td>
</tr>
<tr>
<td>18:2</td>
<td>0.6 ± 0.1</td>
<td>0.2 ± 0.2</td>
<td>0.1 ± 0.1*</td>
<td>0.3 ± 0.1*</td>
</tr>
<tr>
<td>20:4</td>
<td>0</td>
<td>0.4 ± 0.27</td>
<td>0.5 ± 0.11</td>
<td>0.5 ± 0.1*</td>
</tr>
</tbody>
</table>

U/S 3.18 ± 0.31

*P < .001, tP < .05, sP < .01: Significantly different from the adipose tissue value.

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**Fig 1.** Mean molar percentages of the four major fatty acids (16:0, 18:0, 18:1, and 18:2) and the U/S ratio in plasma NEFA of 14 handball players at rest, at halftime, and at the end of a game, as well as in the acyl groups of their adipose tissue TG. Error bars represent the SEM. All rest, halftime, and end values are significantly different from adipose tissue values (P < .001).
Researchers who observed an elevation of plasma TG with exercise have offered the explanation of increased synthesis by the liver as a result of increased secretion of NEFA from adipose tissue into the bloodstream, whereas the increases in TG concentration seen in some other studies are probably too great to be exclusively due to increased glycerol production.

Changes in the concentration of 14:0 (●), 16:0 (■), 16:1 (▲), 18:0 (▲), 18:1 (○), and 18:2 (▲) in the plasma of 14 handball players during each half of a game (pooled data, N = 28) as a function of corresponding changes in the total concentration of plasma NEFA.

Changes in the distribution of acyl groups in plasma TG (Table 3) were not as large as those in plasma NEFA, reaching statistical significance only after the end of the game. Had the changes in the concentration of TG been more uniform, we might have seen clearer changes in the percentages of acyl groups. At present, it is interesting to note the similarity between NEFA and TG: in both, there was a decrease in the percentages of saturated fatty acids and an increase in the percentages of unsaturated fatty acids.

The changes we observed in the profile of plasma NEFA made in a few of the studies cited above whereas the increases in TG concentration seen in some other studies are probably too great to be exclusively due to increased glycerol production.

We believe we are faced with the challenging possibility of an as-yet-unidentified process in the liver that is stimulated during exercise and supplements the well-established release of glucose with lipid fuel in the form of TG. We are currently investigating the precise conditions of activation of the process and the reason for the considerable individual variation observed in this and other studies. For the moment, there appears to be a competition between increased output by the liver and increased hydrolysis by lipoprotein lipase, with the latter factor winning in the majority of cases.

Changes in the concentration of 14:0 (●), 16:0 (■), 16:1 (▲), 18:0 (▲), 18:1 (○), and 18:2 (▲) in the plasma of 14 handball players during each half of a game (pooled data, N = 28) as a function of corresponding changes in the total concentration of plasma NEFA.
during exercise have to be explained by the fact that either NEFA release into the bloodstream or NEFA uptake into the tissues or both were at proportions different from the ones at rest. As for the first possibility, the predominant source of plasma NEFA are the TG of adipose tissue. A further contribution is made by fatty acids, which are not removed immediately from the capillaries once they are produced through hydrolysis of circulating TG by lipoprotein lipase. The latter source is unlikely to have caused the changes in NEFA distribution because, in that case, the changes in acyl-group distribution of the remaining plasma TG could not have been in the same direction, ie, downward for 16:0 and 18:0 and upward for 18:1 and 18:2. However, this is exactly what happened: as shown in Table 5 and as mentioned earlier, the percentage of 16:0 in plasma TG decreased, whereas that of 18:1 increased, with the changes being significant after 60 minutes of exercise.

Our data favor the hypothesis that the major determinant of changes in the distribution of plasma NEFA observed with exercise is the acyl-group composition of adipose tissue TG. This is supported by two lines of evidence: First, the significant changes in the percentages of individual NEFA, ie, 16:0, 18:0, 18:1, and 18:2, are in the direction of the corresponding percentages in adipose tissue TG (Table 4 and Fig 1), confirming an older proposal. It is evident that the composition of plasma NEFA changes during exercise because of the increased mobilization of adipose tissue TG, which have a different acyl-group composition. The difference between the profiles of adipose tissue TG and plasma NEFA at rest is remarkable, and only part of it is bridged after 60 minutes of exercise. This leaves open the possibility of more dramatic changes with efforts of longer duration.

The finding that percentages of the major plasma NEFA move toward the corresponding percentages in adipose tissue TG during exercise may explain the discrepancy between our results and those of the investigators who found a decrease in the percentage of 18:2 with exercise. The composition of adipose tissue was not determined in those studies, but it is possible that, due to metabolic and/or dietary particularities of the study groups, the percentage of 18:2 in plasma NEFA at rest was higher than that in adipose tissue TG. It is probably no coincidence that this disagreement arose with regard to an essential fatty acid, the concentrations of which in tissues depend on their fractions in adipose tissue TG. The simplest conclusion that can be drawn from this is that the rates of release of these fatty acids are proportional to their percentages in adipose tissue TG. Alternatively, the rates could be different but counterbalanced by rates of uptake from plasma equal to the corresponding rates of release.

While attesting to the prevalence of adipose tissue composition in determining changes in the profile of plasma NEFA during exercise, the results listed in Table 5 raise the question as to what determines the contribution of the two most abundant fatty acids, 16:0 and 18:1, to the increase of plasma NEFA. Since the regression coefficient between changes in the total concentration of plasma NEFA and changes in the concentration of 16:0 (.271) is higher than its fraction in adipose tissue TG (0.188), one has to accept that its rate of release is higher than its rate of uptake, owing to either a preferential release from adipose tissue or a diminished uptake from the other tissues (or both). Conversely, since the regression coefficient between changes in the total concentration of plasma NEFA and changes in the concentration of 18:1 (.405) is lower than its fraction in adipose tissue TG (0.509), one has to assume that its rate of release is lower than its rate of uptake, due to either a diminished release or a preferential uptake (or both). Our data do not allow a distinction between the two possibilities for 16:0 and 18:1, and the available literature is confusing. Evidence has been presented for preferential mobilization of both fatty acids from adipose tissue, preferential mobilization of 18:1 and retention of 16:0 equal or not significantly different fractional uptakes of the two fatty acids by skeletal muscle and liver at rest, as well as by the liver during exercise, and preferential uptake of 18:1 as compared with 16:0 by the exercising muscles. Of all these reports, only the latter accommodates our findings. We therefore tend to favor the differential uptake of 16:0 and 18:1 by the exercising muscles over the differential release from adipose tissue as the reason for the observed differences between their fractions in adipose tissue TG and their contribution to the increase of plasma NEFA.

It is noteworthy that the percentage of 16:0 in plasma NEFA is bridged after 60 minutes of exercise, confirming an older proposal. It is evident that the composition of plasma NEFA changes during exercise because of the increased mobilization of adipose tissue TG, which have a different acyl-group composition. The difference between the profiles of adipose tissue TG and plasma NEFA at rest is remarkable, and only part of it is bridged after 60 minutes of exercise. This leaves open the possibility of more dramatic changes with efforts of longer duration.

The finding that percentages of the major plasma NEFA move toward the corresponding percentages in adipose tissue TG during exercise may explain the discrepancy between our results and those of the investigators who found a decrease in the percentage of 18:2 with exercise. The composition of adipose tissue was not determined in those studies, but it is possible that, due to metabolic and/or dietary particularities of the study groups, the percentage of 18:2 in plasma NEFA at rest was higher than that in adipose tissue TG. It is probably no coincidence that this disagreement arose with regard to an essential fatty acid, the concentrations of which in tissues depend on their fractions in adipose tissue TG. The simplest conclusion that can be drawn from this is that the rates of release of these fatty acids are proportional to their percentages in adipose tissue TG. Alternatively, the rates could be different but counterbalanced by rates of uptake from plasma equal to the corresponding rates of release.

While attesting to the prevalence of adipose tissue composition in determining changes in the profile of plasma NEFA during exercise, the results listed in Table 5 raise the question as to what determines the contribution of the two most abundant fatty acids, 16:0 and 18:1, to the increase of plasma NEFA. Since the regression coefficient between changes in the total concentration of plasma NEFA and changes in the concentration of 16:0 (.271) is higher than its fraction in adipose tissue TG (0.188), one has to accept that its rate of release is higher than its rate of uptake, owing to either a preferential release from adipose tissue or a diminished uptake from the other tissues (or both). Conversely, since the regression coefficient between changes in the total concentration of plasma NEFA and changes in the concentration of 18:1 (.405) is lower than its fraction in adipose tissue TG (0.509), one has to assume that its rate of release is lower than its rate of uptake, due to either a diminished release or a preferential uptake (or both). Our data do not allow a distinction between the two possibilities for 16:0 and 18:1, and the available literature is confusing. Evidence has been presented for preferential mobilization of both fatty acids from adipose tissue, preferential mobilization of 18:1 and retention of 16:0 equal or not significantly different fractional uptakes of the two fatty acids by skeletal muscle and liver at rest, as well as by the liver during exercise, and preferential uptake of 18:1 as compared with 16:0 by the exercising muscles. Of all these reports, only the latter accommodates our findings. We therefore tend to favor the differential uptake of 16:0 and 18:1 by the exercising muscles over the differential release from adipose tissue as the reason for the observed differences between their fractions in adipose tissue TG and their contribution to the increase of plasma NEFA.

It is noteworthy that the percentage of 16:0 in plasma

<p>| Table 5. Linear Regression (y = a + bx) Between Changes in Total Concentration of Plasma NEFA (x) and Changes in Concentration of Individual NEFA (y) During Each Half of a Handball Game for 14 Players Who Provided Adipose Tissue Specimens (N = 28) |
|---------------------------------|-----------------|--------|-------|----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Correlation Coefficient</th>
<th>Significance (P)</th>
<th>a (mmol/L)</th>
<th>Standard Error</th>
<th>t Test (a = 0)</th>
<th>b</th>
<th>Standard Error</th>
<th>Fraction in Adipose Tissue TG (f)</th>
<th>t Test (b = f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:0</td>
<td>.70</td>
<td>&lt;.001</td>
<td>-2.7</td>
<td>1.5</td>
<td>NS</td>
<td>0.027</td>
<td>0.005</td>
<td>0.018</td>
<td>NS</td>
</tr>
<tr>
<td>16:0</td>
<td>.97</td>
<td>&lt;.001</td>
<td>-4.5</td>
<td>3.5</td>
<td>NS</td>
<td>0.271</td>
<td>0.012</td>
<td>0.188</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>16:1</td>
<td>.75</td>
<td>&lt;.001</td>
<td>-4.1</td>
<td>2.5</td>
<td>NS</td>
<td>0.051</td>
<td>0.009</td>
<td>0.037</td>
<td>NS</td>
</tr>
<tr>
<td>18:0</td>
<td>.67</td>
<td>&lt;.001</td>
<td>-1.9</td>
<td>4.6</td>
<td>NS</td>
<td>0.075</td>
<td>0.016</td>
<td>0.049</td>
<td>NS</td>
</tr>
<tr>
<td>18:1</td>
<td>.95</td>
<td>&lt;.001</td>
<td>7.6</td>
<td>7.1</td>
<td>NS</td>
<td>0.405</td>
<td>0.026</td>
<td>0.509</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>18:2</td>
<td>.80</td>
<td>&lt;.001</td>
<td>3.8</td>
<td>7.1</td>
<td>NS</td>
<td>0.171</td>
<td>0.025</td>
<td>0.193</td>
<td>NS</td>
</tr>
</tbody>
</table>

*Data from Table 4.*
Low-density lipoprotein production has been directly related to intake of saturated fatty acids, whereas low-density lipoprotein catabolism has been directly related to intake of monounsaturated fatty acids. Polyunsaturated fatty acids have also been implicated, since an increased intake decreased plasma cholesterol. It is reasonable to assume that the effect of each of these categories of fatty acids is determined by its proportion relative to the other fatty acids in blood either directly or through uptake by tissues involved in lipoprotein metabolism. In this sense, it is impressive that the shifts in the distribution of plasma NEFA and TG caused by exercise (downward for saturated and upward for monounsaturated and polyunsaturated fatty acids) are totally consistent with a protective role against atherosclerosis. We believe that our results can establish a link between diet and exercise in the prevention of cardiovascular disease. It remains to be seen how long after cessation of exercise these changes last.

In conclusion, the main findings of our research are as follows: (1) Aerobic exercise of variable intensity for a total of 1 hour caused decreases in the percentages of the major saturated plasma NEFA, 16:0 and 18:0, and increases in the percentages of the major unsaturated NEFA, 18:1 and 18:2, such that the U/S ratio increased by almost 50%; (2) Changes in the profile of plasma TG were in the same direction, but not as impressive. The increase in the total concentration of plasma TG observed in many individuals suggests the existence of a pathway for elevated TG output from the liver in response to an exercise-associated stimulus, which competes with increased TG clearance from the bloodstream; (3) The percentages of 16:0, 18:0, 18:1, and 18:2 in plasma NEFA tend toward the percentages in adipose tissue TG as exercise progresses; (4) It appears that the rate of release of 16:0 from adipose tissue is higher than the rate of uptake from plasma, and the reverse is probably true for 18:1; and (5) The increase in the U/S ratio of plasma NEFA and TG may be part of a common mechanism underlying the beneficial effects of aerobic exercise and a diet rich in unsaturated fatty acids on the profile of plasma lipoproteins and the risk of cardiovascular disease.

REFERENCES


