Ingested Fat Oxidation Contributes 8% of 24-h Total Energy Expenditure in Moderately Obese Subjects

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ABSTRACT The role of ingested fat in the etiology of obesity is controversial. The aims of this study were to determine the contributions of ingested fat oxidation to: 1) 24-h total energy expenditure (TEE), and 2) substrate oxidation during acute stationary cycle exercises in adult humans. Healthy, moderately obese (n = 18; BMI = 31 ± 1 kg/m²) subjects (8 men; 10 women) were each studied in a whole-room calorimeter for 24 h. They were fed mixed meals (55%, 30%, and 15% as energy from carbohydrate, fat, and protein, respectively) to maintain energy balance. Each subject performed 1255-kJ cycle exercises at 50% VO₂max in the calorimeter. Study test meal fat was labeled with carbon-13 (13C). Ingested fat oxidation was estimated from breath 13CO₂ excretion and the subject's chamber CO₂ production. Total fat and carbohydrate oxidations were estimated from nonprotein respiratory quotient (NP-RQ) values. Endogenous fat oxidation was estimated as the difference between total fat and ingested fat oxidations. TEE was estimated from gas exchanges; 28 ± 3% of ingested fat was oxidized and it provided 8 ± 1% of 24-h TEE. During exercise, ingested fat provided 50% of total fat oxidized and 13.0 ± 2% of energy expended. Endogenous fat oxidation contributed 10.4 ± 3% of energy expenditure during cycle exercises. This study extended to 24-h observations of previous studies that lasted 6–9 h on ingested fat oxidation in humans. Understanding the factors that promote ingested fat oxidation could lead to more effective obesity intervention programs.


KEY WORDS: • fat • oxidation • mixed-meals • obesity

Obesity is a major health problem in the United States and in many parts of the world (1). In 2000, 19.8% of the U.S. adult population was obese, which represented an increase of 61% above 1991 estimates (2). The association of obesity with many chronic diseases such as diabetes, hypertension, and some forms of cancer makes it management expensive (3).

Genetic predisposition, physical inactivity, and habitual consumption of high-energy dense foods are risk factors for obesity (4). Some epidemiologic studies showed a strong correlation between the incidence of obesity and fat intake (5–7). However, there is some debate about the association between dietary fat intake and the high incidence of obesity in the United States (8,9). It has been argued, for example, that although fat consumption by the U.S. population is decreasing, the incidence of obesity is on the increase (10). However, the validity of the data on which the latter conclusion was based has been questioned (11). These divergent views about the role that macronutrients play in the development of obesity further demonstrate the controversial nature of this topic (12–14).

Energy storage in the body is determined in part by the amount and type of macronutrients consumed. Therefore, understanding in vivo macronutrient interactions and the effect these have on nutrient storage in the postprandial period could enhance our knowledge about the etiology of obesity.

Previous studies that investigated the oxidation of ingested fat in humans (15–17) concluded that it was mainly stored and not oxidized. One limitation with these studies, however, was the sole use of indirect calorimetry to estimate ingested fat oxidation. The indirect calorimetry technique is based on gas exchanges in the body [nonprotein respiratory quotient (NP-RQ)] to estimate substrate oxidation (18). However, NP-RQ measurement is insensitive to small changes (scale range = 0.7–1.0) and is inadequate to assess ingested fat oxidation.

Studies that combined indirect calorimetry with isotope labeling techniques reported proportions of ingested fat oxidized ranging from 10 to 25% (19–22). In some of these studies, very little carbohydrate (CHO) was present in the test meal.
meals (19,20). Therefore, under such conditions, the normal physiologic response to mixed meals in the postprandial period may not have been fully realized. Most of the studies cited above were of short duration (6–9 h) and their data could not be extrapolated to 24 h.

Furthermore, the effect of physical activity on ingested fat oxidation is not well established. Votruba et al. (23) showed that prior exercise could selectively alter the partitioning of dietary fatty acids between storage and oxidation, but it is not clear whether this is the case when a mixed fatty acid meal is consumed.

Therefore, the primary objective of this study was to determine the contribution of ingested fat consumed as normal mixed meals to 24-h total energy expenditure (TEE) and substrate oxidation in moderately obese subjects. A secondary objective of the study was to examine the same variables during acute moderate stationary cycle exercise.

SUBJECTS AND METHODS

Subjects. Moderately obese adults (n = 18; 8 men/10 women; BMI = 31 ± 1 kg/m²) participated in the study (Table 1). The subjects were a subset of participants recruited to take part in a 16-mo exercise intervention study. All potential subjects in the primary study cohort were invited to participate in this subsidiary study and those who expressed interest were recruited. The data presented here were obtained during the baseline period, i.e., before the exercise intervention started. Physical examination and clinical tests conducted on the subjects at the time of the study indicated that they were healthy. The women were neither pregnant nor lactating, and no subjects were taking any medication that might influence macronutrient oxidation.

Ethical approval. The study was approved by the ethical committees of the University of Colorado Health Sciences Center (UCHSC), Denver, CO, and the University of Kansas, Lawrence, KS. Written informed-signed consent was obtained from all subjects before they were allowed to participate in the study.

Study sites. The primary study was conducted at the University of Kansas, Lawrence, where the subjects were recruited. Whole-room indirect calorimetry and stable isotope ratio MS (IRMS) studies were performed at the UCHSC, Denver.

Body composition estimation. Hydrostatic weighing at residual lung volume was used to estimate the percentage of body fat (24). Residual lung volume was measured immediately before body density measurement by the method of Wilmore et al. (25). Body density was calculated using the equation of Goldman and Buskirk (26), and the percentage of body fat was calculated with the equation of Brozek et al. (27).

VO2max. To measure aerobic capacity, each subject walked on a motor-driven treadmill for 5 min to provide acclimation to the treadmill. The subject then sat quietly until the heart rate was within 10 bpm of the resting value. Subsequently, the subjects walked to volitional exhaustion. Maximal oxygen consumption was taken as the highest observed value using a modified Balke protocol with 2-min stages (28). Heart rates were recorded at the end of each stage and at maximal exertion. Expired air was measured for oxygen and CO2 at 20-s intervals using a Sensormedics MMC 2900 Horizon system calibrated before each test according to the specifications of the manufacturer.

Whole-room indirect calorimetry. The General Clinical Research Center’s (GCRC) whole-room indirect calorimeter was used to measure substrate oxidation and 24-h TEE (29). In brief, subjects entered the calorimeter at 0800 h and exited at 0700 h the next morning. The mean energy expenditure and substrate oxidation data collected over this 23-h time window were extrapolated to 24 h by multiplying it by a factor of 1.043, i.e., ratio of 24 h/23 h. Additionally, data for specific activities in the calorimetry were also presented separately.

Oxygen consumption and CO2 production were determined from the flow rates and differences in gas concentrations between air entering and air exiting the calorimeter. Values were corrected for temperature, barometric pressure, and humidity. The calculation of energy expenditure from oxygen consumption and CO2 production was based on equations described by Jequier et al. (30). Protein oxidation was determined from 24-h urinary nitrogen excretion (using the pyrocheluminescent technique), and carbohydrate and fat oxidation were estimated using NP-RQ values (31). Nutrient balance over 24 h was calculated as the difference between the intake and oxidation of each nutrient.

Calorimeter protocol. The subjects were admitted to the GCRC facility the night before the calorimeter study. On the study day, the subject entered the calorimeter at 0800 h, which was considered time zero (T0). Breakfast, lunch, and dinner were given at 0830, 1300, and 1800 h, respectively. All meals were consumed within 30 min after they were served. The subjects went to bed at 2300 h and the protocol ended at 0700 h on d 2 of the study. In the calorimeter, each subject performed 1255 kJ of exercise between 1110 and 1230 at 50% of his/her VO2max using a stationary exercise bike (Lode).

Step/Walk exercise. The objective of these step/walk exercises was to increase the activity and hence energy expenditure of the subject in the calorimeter to about the same level that he/she would normally experience under free-living conditions. The step/walk exercises consisted of a series of sitting, stepping, and walking sessions. Between 1430 and 1630 h on the calorimeter study day, the subject performed 10-min sessions of step and walk exercises. Each activity was followed by 10 min of recovery.

Breath 13CO2 sampling. Two baseline breath CO2 samples were collected from the subject on the calorimeter day stay at 0800 and 0830 h using a straw and vacutainers (Becton Dickson). The mean 13C enrichment of these samples was considered baseline breath 13CO2 for the subject. Additional breath samples (2 at each time point) were collected from the subjects at 1100, 1200, 1430, 1630, 1700, 1730, 1945, 2300, 0500, and 0700 h for determination of 13CO2 from oxidation of the labeled fat ingested in the mixed meal.

Calorimeter diet. The GCRC kitchen provided all food eaten by the subjects during their calorimeter day. In the calorimeter, each subject was fed to attain energy balance. Each subject’s energy intake was estimated using a regression equation that was developed in our laboratory: [372 + (FFM × 23.9)] × 1.3, where FFM is the subject’s fat-free mass and 1.3 is an activity factor. This equation proved reliable in estimating subjects’ energy requirements in the chamber in previous studies (32).

The macronutrient composition of the diet was 30:15:55 as the percentage energy from fat, protein, and carbohydrate, respectively. Approximately 70% of the calorimeter test meal fat came from corn oil, which was naturally enriched in 13C (33). Most Americans have fairly high levels of baseline breath 13C due to high intakes of corn products in their foods (34). To reduce the effect of this high baseline breath 13C excretion on our ability to detect breath 13C enrichment, the ingested fat in our calorimeter test meal was supplemented with artificially enriched 1-13C-palmitic acid (2 mg/kg body weight). According to the manufacturer’s (Isotech) label, this artificial 1-13C-palmitic acid was 99% pure. The labeled palmitic acid was added in proportion to the quantity of corn oil present in the test meals served at breakfast, lunch, and dinner (Table 2).

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**Table 1**

**Physical characteristics of the subjects**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Men</th>
<th>Women</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>24 ± 1</td>
<td>25 ± 2</td>
<td>25 ± 1</td>
</tr>
<tr>
<td>Body weight, kg</td>
<td>92 ± 6</td>
<td>86 ± 5</td>
<td>89 ± 4</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.8 ± 0</td>
<td>1.6 ± 0</td>
<td>1.7 ± 0</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>29 ± 2</td>
<td>32 ± 1</td>
<td>31 ± 1</td>
</tr>
<tr>
<td>Body fat, kg</td>
<td>26 ± 4</td>
<td>36 ± 3*</td>
<td>31 ± 2</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>67 ± 3</td>
<td>52 ± 2*</td>
<td>59 ± 2</td>
</tr>
<tr>
<td>VO2max, mL/(kg · min)</td>
<td>39 ± 1</td>
<td>30 ± 1</td>
<td>34 ± 2</td>
</tr>
</tbody>
</table>

1 Values are means ± SEM, n = 8 men and 10 women. * Different from men, P < 0.05.

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Other food items served in the test meal were selected because of their low \(^{13}\)C content (35). Such low-\(^{13}\)C foods appeared to have little effect on baseline breath \(^{13}\)CO\(_2\) production (35). The subjects in our study were instructed to consume all of the food given to them in the calorimeter and they all complied. An example of a typical day's meals is given in Supplemental Table 1.

Aliquots of the enriched corn oil given in the chamber test meal were set aside and used later to determine meal \(^{13}\)C enrichment. These aliquots were later combusted at high temperatures (500–1000°C) to generate \(^{12}\)CO\(_2\), from which test meal \(^{13}\)C enrichment was measured. Mean test meal \(^{13}\)C enrichment was 2.4 ± 0.14 \(\delta\). This was much higher than that of natural corn oil, which has an enrichment of about ~15 \(\delta\) (35).

Isotope ratio MS. \(^{13}\)C isotopic enrichment of breath \(^{12}\)CO\(_2\) samples was determined using a VG Optima IRMS (Fisons Instruments, VG Isotech). The procedures used in the current study were similar to those reported in an earlier publication (20). In brief, the masses of interest for \(^{13}\)C analysis were 44 and 45 and the ratio of 45 to 44 \((^{13}\text{C}^{16}\text{O}^{16}\text{O} : ^{12}\text{C}^{16}\text{O}^{16}\text{O})\). The instrument's software automatically applied Craig's correction (36) before enrichment values were reported. Enrichment values were expressed as \(\delta\) (per mil) which is given as: 
\[
\delta = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} \right] - 1 \times 10^3
\]
where \(R\) is the isotopic ratio of the sample and reference, respectively (36). The enrichments were corrected for baseline breath \(^{13}\)C production and the data were expressed as \(\delta\) relative to an international standard, Pee Dee Bellemnite, a limestone formation used for standardizing the \(^{13}\)C content of materials (36). 

**Ingested fat oxidation estimation.** Ingested fat oxidation was estimated as reported elsewhere (20). The following equation, which was adapted from Mosora et al. (37), was used in the estimation:
\[
Q_{\text{fat}} = \left[ (\delta_i - \delta_b) + (\delta_{-1} - \delta_b) \right] \times (Q_{\text{CO2}} \times MW) / 2(\delta_i - \delta_b) \times 0.56 \times n
\]
where \(Q_{\text{fat}}\) is the quantity of ingested fat oxidized, \(\delta_b\) is the baseline breath \(^{13}\)CO\(_2\)/mil, \(\delta_i\) is the breath \(^{13}\)CO\(_2\)/mil at time \(t\) postmeal ingestion, \(\delta_{-1}\) is the breath \(^{13}\)CO\(_2\)/mil at any other time after time \(t\), \(\delta_b\) is the \(^{13}\)CO\(_2\)/mil of labeled fat ingested, \(Q_{\text{CO2}}\) is the quantity of moles of \(^{12}\)CO\(_2\); \(MW\) is the average molecular weight (~80 g) of ingested corn oil, 0.56 is the acetate correction factor to account for \(^{13}\)CO\(_2\) remaining in the body's bicarbonate pools (38), and \(n = 55\) is the number of carbon atoms in corn oil (triglyceride) molecule.

**Estimation of energy balance and endogenous fat oxidation.** The 24-h energy balance was calculated as the difference between 24-h energy intake and extrapolated 24-h energy expenditure. Endogenous fat oxidation was estimated as the difference between total fat oxidation and ingested fat oxidation.

**Statistics.** Data are presented as means ± SEM. Regression analysis was performed to determine the effect of gender on 24-h TEE and on substrate oxidation after adjusting for FFM and fat mass (FM). Graphpad Prism Software, version 2.01 (Graphpad Software) was used to perform 2-tailed unpaired \(t\) tests for comparisons of FFM, FM, energy expenditure, NP-RQ, and substrate oxidation between men and women in the study. Differences were considered significant at \(P < 0.05\).

**RESULTS**

**Subject physical characteristics.** When the subjects were grouped according to gender, men and women did not differ for age (24 ± 1 vs. 25 ± 2 y), body weight (92 ± 6 vs. 86 ± 5 kg), or BMI (29 ± 2 vs. 32 ± 1 kg/m\(^2\)) respectively. As expected, there was a significant gender difference for FM 26 ± 4 vs. 36 ± 3 kg (\(P < 0.03\)) and FFM, 67 ± 3 vs. 52 ± 2 kg (\(P < 0.001\)) for men and women, respectively. Regression analysis was performed to determine a possible gender effect on our variables of interest (Table 3). The contributions of sex, FFM, and FM individually and collectively to 5 outcome measures [energy expenditure (MJ), total fat oxidation (g/d), ingested fat oxidation (g/d), carbohydrate oxidation (g/d) and NP-RQ] over 24 h were examined. Being female and the amount of FFM in the body were both significant predictors of 24-h energy expenditure. After combining the contributions of sex, FFM, and FM, only FFM remained as a significant predictor of 24-h energy expenditure (Table 3). The remaining 4 outcome measures (total fat oxidation, ingested fat oxidation, carbohydrate oxidation, and NP-RQ) were not influenced by sex, FFM, or FM either individually or when combined. Therefore, all data were combined into a single group and then analyzed.

**Energy intake.** The daily 24-h energy intake for all subjects was 10.81 ± 0.57 MJ. Men consumed significantly (\(t = 0.67, P < 0.002\)) more energy than women (12.51 ± 0.31 MJ/d vs. 10.63 ± 0.38 MJ/d, respectively).

**Energy expenditure and balance.** The 24-h TEE by the subjects was 12.07 ± 0.49 MJ, suggesting a slight negative energy deficit of ~0.18 ± 0.32 MJ/d. Energy balance over 24 h did not differ between men and women (−0.78 ± 0.47 MJ vs. −0.45 ± 0.34 MJ, respectively). Time zero on the graph corresponded to 0800 h when the subjects entered the calorimeter (Fig. 1A). The baseline energy expenditure rate was 8.3 ± 0.6 kJ/min, which increased to 30.1 ± 1.6 kJ/min at the peak of the cycle exercise. Total energy expended by the subjects during cycle exercise was 1.325 ± 0.04 MJ, and during rest periods it was 10.17 ± 0.45 MJ.

**CO\(_2\) production rate.** CO\(_2\) production rate (L/min) (Fig. 1B) closely matched the energy expenditure profile (Fig. 1A). During cycle exercise, CO\(_2\) production rate increased from 0.31 ± 0.02 L/min to 0.72 ± 0.04 L/min.

**Nonprotein respiratory quotient (NP-RQ).** Baseline NP-RQ for the subjects was 0.75 ± 0.03 (Fig. 1C), which increased to 0.95 ± 0.01 during exercise and then declined to the baseline value during recovery. When the subjects woke up the following morning, NP-RQ was 0.83 ± 0.03.

**Breath \(^{13}\)CO\(_2\) elimination.** Baseline breath \(^{13}\)CO\(_2\) \(\delta\) was −21.01 ± 0.13 \(\delta\) which increased rapidly during cycle exercise (\(T_{220\text{min}} - T_{270\text{min}}\)) (Fig. 2). After cycle exercise, breath

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**Table 2**

Macronutrient composition of test meals given to moderately obese subjects during the indirect calorimeter chamber study day

<table>
<thead>
<tr>
<th>Meal</th>
<th>CHO (g)</th>
<th>Protein (g)</th>
<th>Fat (g)</th>
<th>(^{13})C(^2) (% of meal fat)</th>
<th>Meal corn oil (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakfast</td>
<td>123 ± 4 (2059 ± 67)</td>
<td>21 ± 1 (351 ± 17)</td>
<td>31 ± 1 (1167 ± 38)</td>
<td>0.08 ± 0 (3.0 ± 0)</td>
<td>87 ± 2</td>
</tr>
<tr>
<td>Lunch</td>
<td>93 ± 7 (1556 ± 117)</td>
<td>42 ± 2 (703 ± 33)</td>
<td>21 ± 1 (791 ± 38)</td>
<td>0.05 ± 0 (2.0 ± 0)</td>
<td>49 ± 4</td>
</tr>
<tr>
<td>Dinner</td>
<td>101 ± 6 (16900 ± 100)</td>
<td>49 ± 6 (820 ± 100)</td>
<td>40 ± 1 (1506 ± 38)</td>
<td>0.09 ± 0 (3.0 ± 0)</td>
<td>76 ± 1</td>
</tr>
</tbody>
</table>

\(^1\) Values are means ± SEM, \(n = 18\).

\(^2\) Labeled \(^{1}\)\(^{13}\)C palmitic acid that was given to supplement natural corn oil.
Women 0.041

Table 3
Contribution of sex, FFM, and FM to energy expenditure, total fat oxidation, exogenous fat oxidation, CHO oxidation, and NP-RQ in moderately obese subjects consuming mixed meals in a whole-room calorimeter for 24 h.1,2

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>P-value</th>
<th>R²</th>
<th>Predictor</th>
<th>Coefficient</th>
<th>P-value</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Women</td>
<td>564 ± 203</td>
<td>0.013</td>
<td>0.33</td>
<td>Women</td>
<td>259 ± 303</td>
<td>0.41</td>
<td>0.77</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>42.6 ± 6.0</td>
<td>&lt;0.0001</td>
<td>0.76</td>
<td>FFM, kg</td>
<td>52.2 ± 12.9</td>
<td>0.0012</td>
<td>0.56</td>
</tr>
<tr>
<td>FM, kg</td>
<td>4.0 ± 12.6</td>
<td>0.76</td>
<td>0.006</td>
<td>FM, kg</td>
<td>−6.4 ± 10.8</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>Total fat oxidation, g/d</td>
<td>0.11</td>
<td>0.15</td>
<td>46.2 ± 76.1</td>
<td>0.55</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exogenous fat oxidation, g/d</td>
<td>0.15</td>
<td>0.13</td>
<td>4.32 ± 3.25</td>
<td>0.21</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHO oxidation, g/d</td>
<td>0.20</td>
<td>0.10</td>
<td>−3.75 ± 2.72</td>
<td>0.19</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP-RQ</td>
<td>0.004 ± 0.002</td>
<td>0.13</td>
<td>0.089</td>
<td>NP-RQ</td>
<td>0.004 ± 0.002</td>
<td>0.13</td>
<td>0.089</td>
</tr>
</tbody>
</table>

1 Values are means ± SEM, n = 18.
2 The first 3 columns show contributions of each variable individually; the last 3 columns show contributions of all 3 variables in the same model.

13C2O2 gradually decreased to −20.29 ± 0.12 δ and mean breath 13C2O2 enrichment at 0700 h, the end of the study, was −20.33 ± 0.11 δ.

Substrate oxidation. There was an increase in ingested fat oxidation rate corresponding to both cycle exercise and the step/walk exercise sessions (Fig. 2B). After the step/walk exercise, ingested fat oxidation declined gradually until 0500 h the next day when the subjects woke up. Total ingested fat oxidized over 24 h was 27 ± 3 g. The proportion of ingested fat oxidized by the subjects over 24 h was 28 ± 3%; 24-h total fat oxidation was 130 ± 17 g, which was slightly higher than fat intake, therefore resulting in a negative fat balance for the group (−36 ± 14 g). On the other hand, carbohydrate and protein balances were positive for the group (88 ± 26 and 23 ± 3 g, respectively).

Twenty-four hour whole-room calorimeter total fat and carbohydrate oxidizations were significantly (r = −0.75, P < 0.0003) and inversely correlated (Fig. 3A). Similarly, ingested fat oxidation was significantly and negatively correlated with 24-h carbohydrate oxidation (r = −0.52, P < 0.03) (Fig. 3B). The correlation between ingested and endogenous fat oxidation was positive and significant (r = 0.48, P < 0.04) (graph not shown).

During cycle exercise, total fat oxidized was 8.9 ± 2 g, of which 5.7 ± 1 g originated from consumed fat oxidation. Ingested and endogenous fat oxidation provided 13.0 ± 2 and 10.4 ± 3%, respectively, of TEE during cycle exercise.

Macronutrient contribution to TEE. Total carbohydrate oxidation and total fat oxidation contributed 39 ± 4 and 42 ± 6%, respectively, to 24-h energy expenditure. Protein oxidation contributed 13 ± 1% and ingested fat oxidation contributed 8 ± 1% of 24-h TEE in our subjects.

DISCUSSION

In the current study, 28 ± 3% of ingested fat was oxidized, providing 8 ± 1% of TEE. Ingested fat oxidation during moderate cycle exercise provided 13.0 ± 2% of energy expenditure and 50% of fat oxidation.

There are a number of methodological issues that should be addressed. First, the stable isotope 13C occurs naturally in foods given to our subjects. To minimize the effect of this naturally occurring 13C on breath 13C excretion, the subjects consumed only low-13C foods with the enriched corn oil and corn margarine given in the test meals (Supplemental Table 1). This measure was reported to prevent baseline 13C changes in a previous study (35). This finding is supported by a recently completed study (unpublished data) in which the effect of these low-13C foods on baseline breath 13CO2 excretion was determined in 3 adults. Baseline breath 13C enrichment in these subjects was −24.77 ± 0.53 δ and breath 13C enrichment over 24 h postingestion of the low-13C meals was −24.01 ± 0.43 δ (P = 0.305).

Second, the exercises in our study had the potential to increase the contributions of endogenously mobilized substrates (glycogen and stored fat) to TEE in the subjects. Because these substrates contain naturally occurring 13C, they too could increase breath 13C production, which could lead to an overestimation of ingested fat oxidation in our study. It is unlikely that this was the case in the current study for the following reasons: 1) the proportion of enriched ingested fat in the test meal was large (~30% of total energy intake), and 2) the enrichment (2.4 ± 0.14δ) of the ingested fat was much higher than that found in either endogenous fat or glycogen. Both of these factors would reduce the influence of endogenously produced 13C on breath 13CO2 excretion (39). Furthermore, because the energy deficit in our subjects was small...
any contribution from endogenous fat to this deficit was also likely to be small. This would correspondingly reduce the amount of $^{13}$C that could originate from endogenous fat. Last, we did not independently determine an acetate correction factor to account for unrecovered $^{13}$CO$_2$ in our subjects, but used the value reported by Sidossis et al. (38). The data presented here should therefore be interpreted with the above limitations in mind. The use of a normal mixed meal to investigate in vivo dietary fat oxidation is an important distinction between the current study and previous ones (19–22). The consumption of normal mixed meals allows normal in vivo physiologic interactions between different macronutrients to take place in the postprandial period. Understanding the effects of these macronutrient interactions on substrate oxidation and storage should allow a more accurate assessment of the long-term potential obesity-promoting effect of the different macronutrients.

The results of the current study suggested that >70% of the fat ingested by our subjects was stored in the body. This rate of fat storage in the body over the long term has the potential to promote the development of obesity. However, the long-term effect of high-fat intake on the development of obesity will also depend on a number of factors, such as the type of fat habitually consumed, the length of time the individual is habituated to the fat diet, and his/her physical activity level. How these factors influence the oxidation of ingested fat is not yet fully understood.
Other studies (19,20) reported proportions of ingested fat oxidation that are similar to what we observed in this study. Jensen et al. (40) studied meal free fatty acid oxidation and reported 30% in one study and ~50% in another. The authors explained that the differences in the proportions oxidized between the 2 studies were the result of different levels of physical activity allowed on the protocols. Votruba et al. (23,41) also demonstrated recently that physical activity does significantly increase postexercise ingested fat oxidation. Data from the current study also suggested that physical activity is an important stimulant to ingested fat oxidation. During stationary cycle exercises, ingested fat provided at least 50% of total fat oxidation, which implies that during postprandial aerobic exercise of long duration, ingested fat oxidation may be a major source of energy for the body. If this is correct, it will be interesting to investigate whether the pattern of exercise (e.g., a single continuous exercise bout vs. several intermittent exercise bouts of equivalent energy expenditure) will result in comparable amounts of ingested fat being oxidized.

The outcome of such studies could help us design better exercise intervention programs that could potentially channel ingested fat toward oxidation rather than storage in the body. Furthermore, Schrauwen et al. (42) found that when normal-weight subjects consumed a high-fat diet for 1 wk, and then were studied in a whole-room indirect calorimeter for 24 h, they maintained fat balance. This finding suggested that acclimatization to a high-fat diet increases fat oxidation. Although Schrauwen et al. (42) did not directly measure ingested fat oxidation, it was likely that the increased fat oxidation that occurred in their subjects postacclimatization was also accompanied by increased ingested fat oxidation.

At the end of the cycle exercises (Fig. 2C), the NP-RQ value was significantly reduced. This might have been in part a reflection of CO2 washout from the body’s bicarbonate pools during this period. Alternatively, the low NP-RQ during this period could have resulted from increased fat oxidation during exercise.

One of the data sets in the correlation analysis (Fig. 3A) showed negative CHO oxidation, which probably skewed the regression line. This subject’s data were problematic. His 24-h CHO and fat oxidations were −2.9 g and 294.6 g, respectively. The corresponding NP-RQ for the subject was 0.71. Considering the composition of the test meals given to our subjects, it is possible that this particular data set was an artifact. However, because the observed NP-RQ value was within the acceptable range of 0.7–1.0 normally used for substrate oxidation in indirect calorimetry, it is inappropriate to exclude it. When this data set was excluded from the regression analysis, the correlation between 24-h ingested fat oxidation and CHO oxidation was no longer significant (r = 0.44, P < 0.08). On the other hand, the correlation between CHO oxidation and total fat oxidation remained significant (r = 0.66, P < 0.004).

There are several possible mechanisms through which ingested fat oxidation could be increased. First, high-fat diets are reported to affect gene expression in the body, which has the potential to significantly change fatty acid metabolism and other cellular processes (43). High fat availability, for example, could upregulate pyruvate dehydrogenase kinase, whereas it decreases pyruvate dehydrogenase activity (44). The activities of these enzymes could potentially increase fatty acid oxidation and decrease carbohydrate oxidation (45). Second, a number of membrane transporters for fatty acids have now been identified. These include fatty acid translocase, fatty acid binding protein, and fatty acid transport protein (46). These fatty acid membrane transporters may be important in the efficient transfer of fatty acids into the mitochondria where they could be oxidized. However, it is not yet clear whether these reported membrane transporters increase the oxidation of fatty acids in humans (46). Third, exercise training could increase muscle blood flow and mitochondrial content (47). Both of these factors could increase ingested fat oxidation.

Our data are among an accumulating body of literature that suggests that a substantial amount of fat ingested in a normal mixed diet is oxidized. Whether habitual consumption of a diet containing higher fat will result in the development of obesity in the long term will depend on the nature of the equilibrium attained between the factors that promote positive energy balance when high-fat diets are consumed on one hand, and the in vivo mechanisms that are activated to increase fat oxidation on the other hand. Understanding these competing factors could play an important role in our fight against obesity.

Approximately one-third of the fat ingested in the mixed test meals was oxidized over 24 h, and physical activity, even at moderate levels, appeared to stimulate this process. Further studies in this area should be directed at determining the factors that promote ingested fat oxidation. With such knowledge, it may be possible to design specific intervention programs that could promote ingested fat oxidation and thereby help prevent obesity.

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LITERATURE CITED


