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The effect of dietary oleic, linoleic, and linolenic acids on fat oxidation and energy expenditure in healthy men

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Abstract

Studies have shown that the long chain fatty acid composition of a dietary fat influences whether it will be partitioned for either energy or storage. The objective of this study was to compare the effects of 3 oils differing in fatty acid composition on postprandial energy expenditure and macronutrient oxidation in healthy normal-weight men. Using a randomized crossover design, 15 subjects consumed breakfast meals containing 60% of energy as fat. The principal source of fat was (*a*) olive oil rich in oleic acid (18:1n-9), (*b*) sunflower oil rich in linoleic acid (18:2n-6), or (*c*) flaxseed oil rich in linolenic acid (18:3n-3). Measurements of resting metabolic rate, thermic effect of food, and postprandial energy expenditure were conducted with indirect calorimetry that recorded O_2 consumed and CO_2 produced one-half hour before meal consumption and 6 hours after meal consumption. Fat and carbohydrate oxidation rates were calculated from nonprotein gaseous exchange. Olive oil feeding showed a significant overall increase in energy expenditure compared with flaxseed oil ($P < .0006$) and a trend to increased energy expenditure compared with sunflower oil ($P < .06$). None of the 3 treatments exhibited significant effects on fat or carbohydrate oxidation. In conclusion, diets rich in oleic acid derived from olive oil may offer increased oxidation translating into increased energy expenditure postprandially.

1. Introduction

Over the past decade, obesity rates have increased dramatically [1]. Overconsumption of high-energy–dense foods and increased portion sizes are among the contributors to positive energy balance [1]. A reduction in dietary energy from fat is associated with weight loss [2]. On the other hand, research is suggesting that the type of fat consumed influences the partitioning of dietary fat for either energy or storage [3-7]. In particular, the degree of long chain fatty acid unsaturation is proposed to influence the channeling of dietary fat toward either immediate oxidation or storage. Therefore, the quality of fat consumed may become an important aspect to consider in long-term weight management.

Animal [8] and human [3,4] studies have revealed a pattern of selective oxidation of long chain unsaturated fatty acids over long chain saturated fatty acids. However, differences between the various unsaturated fatty acids are less clear. Some animal studies [9-12], but not others [8,13], suggest that oleic acid is more rapidly diverted for energy use compared with linoleic acid. Similarly, the data from human studies using isotopic tracer methodologies have revealed inconsistent observations. Some studies have shown a greater oxidation rate of oleic acid compared with linoleic or linolenic acids [14,15]. However, when fatty acid tracers were introduced directly into the bloodstream, the oxidation rate determined by cumulative $^{14}CO_2$ production was higher for linoleic acid than it was for oleic acid [16]. DeLany et al [7] gave human subjects labeled fatty acid in a blended meal and found that the oxidation of linolenate was higher than that of linoleate and oleate, which had similar rates of oxidation. On the contrary, a recent study by McCloy et al [6] showed that ^{13}C-linoleate oxidation was lower than those for oleate and linolenate.

Thus, human studies show inconsistent evidence regarding whether unsaturated fatty acids respond differently in their partitioning of fatty acid storage and oxidation on the

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basis of fatty acid structure. An explanation for this inconsistency may be related to the method used to measure fatty acid oxidation in the previous studies. The use of isotope-labeled fatty acid to quantify fatty acid oxidation underestimates fat oxidation, as some of the labeled carbon liberated during oxidation is sequestered into other metabolic pathways; and therefore, an acetate recovery factor must be applied [17]. However, the acetate recovery factor has high interindividual variability and should be determined in every subject [18]. Moreover, data obtained using isotope-labeled fatty acid do not reflect the change in total fat oxidation in terms of total dietary fatty acids used [5]. Alternatively, indirect calorimetry techniques can be used to measure energy expenditure as well as net substrate oxidation. The use of indirect calorimetry provides an accurate estimate of substrate balance over a given time [19]. Therefore, to better describe how the human body handles different unsaturated fatty acids, a short-term study was conducted to examine whether the degree of unsaturation of an 18-carbon fatty acid chain influences postprandial energy expenditure, fat oxidation, and carbohydrate oxidation in healthy men. Three dietary fatty acids with the same carbon length but with different levels of unsaturation were provided in equal quantities to test human whole-body capacity for oxidation of dietary oleic (18:1n-9), linoleic (18:2n-6), and linolenic (18:3n-3) fatty acids.

2. Subjects and methods

2.1. Subjects

Fifteen healthy male university students were recruited by advertisement from the Macdonald Campus of McGill University, Montreal, Québec, Canada. No individual was an elite athlete. An initial screening process conducted by personal interview accepted subjects if they reported no more than moderate physical activity and absence of chronic diseases including diabetes, heart disease, hypothyroidism, and disorders of fat metabolism. A second set of screening procedures allowed subjects to enter the study on the basis of a fasting blood sample of triglycerides (TG) <3.5 mmol/L, total cholesterol (TC) <5.2 mmol/L, glucose <4 mmol/L, and body mass index between 20 and 25 kg/m^2. Screening blood samples were obtained if subjects declared having fasted for 12 hours and abstained from alcohol for 48 hours.

Subjects were instructed to engage in a minimal amount of activity before arriving to the Mary Emily Clinical Nutrition Research Unit at McGill University in the morning. Moreover, they were asked not to change their regular lifestyles and physical activity levels between test days. Informed consent was obtained from all subjects before commencement of the study, and the McGill University Human Ethics Committee approved all procedures.

2.2. Study design

After an overnight fast of 16 hours and a minimal level of activity on the test morning, the subjects consumed one of the 3 test oils (olive, sunflower, or flaxseed) as part of a standardized breakfast meal. Each subject returned to the research unit 2 more times, for a total of 3 test meals. The order in which the oils were given to the study subjects was randomized in single-blind fashion. Each meal was separated by 1 week of regular food intake and physical activity.

2.3. Test meals

The meals were identical in composition except for the type of test oil. Olive, sunflower, and flaxseed oils were chosen for their high contributions of oleic (18:1n-9), linoleic (18:2n-6), and linolenic (18:3n-3) acids, respectively, which allowed for hypothesis testing regarding saturation level and metabolism. The breakfast meal consisted of 60%, 30%, and 10% of energy as fat, carbohydrate, and protein, respectively. Each test morning, meals were prepared at the Mary Emily Clinical Nutrition Research Unit. Food ingredients were weighed to the nearest 0.1 g. The meal included a vegetable omelet, fried potatoes, a glass of milk, and the test oil poured over an English muffin. Analysis of the macronutrient profile of the meal was performed using the computerized nutrient composition program Food Processor (Version 7, Windows, Salem, OR). The meal represented one third of assessed daily caloric needs for weight maintenance for each subject as determined by the equation of Mifflin et al [20], which accounts for weight, height, age, and activity of the individual. Activity level was set at 1.6, reflecting a medium level of physical activity in each subject. Because the amount of test oil fed in the test meal was tailored to each subject's energy needs, there was no fixed amount of test oil given. The average amount of test oil given to subjects was 50.4 g, with a range of 43.6 to 59.3 g.

2.4. Laboratory measurements

Total cholesterol, TG, and glucose blood levels were analyzed in triplicate with enzymatic kits, standardized reagents, and standards using a VP Autoanalyzer (Abbott Laboratories, North Chicago, IL). Fatty acid composition of each treatment oil was determined using a gas-liquid chromatograph (model 5890; Hewlett Packard, Palo Alto, CA) following previously outlined procedures of lipid extraction [21] and boron trifluoride methylation [22]. The gas chromatograph was equipped with an autosampler and flame ionization detectors. Separation was made possible with an SP2330 30-m × 0.2-mm capillary column. Running conditions were as follows: initial temperature of 120°C with a ramp of 4°C/min until 160°C, which was held for 10 minutes, followed by a ramp of 4°C/min until 220°C/min, which was held for 5 minutes, followed by a decrease of 50°C/min until 120°C was reached. Helium was used as a carrier gas with a rate of 1 mL/min. Fatty acid methyl ester chromatographic peaks were identified by comparison of retention data with those of authentic standards and quantified by area integration.

2.5. Respiratory gas exchange measurements

Measurements of resting metabolic rate (RMR), thermic effect of food (TEF), and postprandial energy expenditure were conducted with indirect calorimetry using a Deltatrac Metabolic Monitor (Sensormedics, Anaheim, CA), which recorded the amount of O_2 consumed and CO_2 produced one-half hour before meal consumption and 6 hours after meal consumption. Upon arrival to the unit, subjects were asked to relax for 30 minutes before RMR measures. The RMR was measured for 30 minutes before consumption of each meal. Subjects were allowed 15 minutes to eat breakfast while remaining in bed under supervision. No additional foods were permitted for the following 6 hours, during which time TEF was measured. For all measurements, subjects remained in a supine position in an adjustable bed with their head placed under a transparent ventilated hood connected to the Deltatrac monitor by Collins tubing. Subjects were allowed to quietly watch movies or television, or read under constant supervision. In the postprandial period, washroom breaks were allowed as needed.

Accuracy of the Deltatrac was verified using the combustion of ethanol within the respiratory hood. Each day, subsequent to a 30-minute warm-up period, the machine was calibrated using daily atmospheric pressure readings from Environment Canada and reference gas standards of 4% carbon dioxide and 96% oxygen. All values of O_2 consumption and CO_2 production recorded by the Deltatrac were entered manually into a spreadsheet. Data were analyzed using equations that relate O_2 consumption, CO_2 production, and protein utilization to metabolic rate. Substrate oxidation rate was calculated based on the assumption of a constant nitrogen excretion of 0.14 g nitrogen per kilogram per day [3]. The O_2 and CO_2 values corresponding to nitrogen excretion were subtracted from O_2 and CO_2 output values to obtain values for carbohydrate and fat utilization. Assuming that RMR was constant throughout the daily session, TEF was measured by integrating the cumulative 6-hour postprandial energy expenditure relative to basal energy expenditure.

2.6. Statistics

All statistical analyses were performed using the Statistical Analysis Software (SAS, version 6.04; SAS Institute, Cary, NC) computer program. Analysis of variance was used to test significance of differences between treatments, with subsequent Tukey tests for mean comparisons. Results are expressed as means ± SEM. Differences with $P < .05$ were considered to be significant.

3. Results

Fifteen male subjects completed the study protocol. The subjects' characteristics at baseline are reported in Table 1. All subjects showed tolerance to the meals and consumed all the food that was provided to them. All subjects reported no change in their physical activity and dietary habits through the 3 phases of the trial. No subjective changes in body weight were observed. Subjects took one of 3 modes of transportation to arrive at the center in the morning: two used a public bus, one drove, one was driven, and 11 subjects walked no more than 10 minutes.

Table 1
Subject baseline characteristics (N = 15)

Characteristic	Average ± SD	Range
Age (y)	28.6 ± 6.2	21-40
Weight (kg)	73.7 ± 10.2	57.5-85.9
Height (m)	1.77 ± 0.06	1.68-1.89
BMI (kg/m^2)	23 ± 1.9	20-25
Serum TC (mmol/L)	3.96 ± 0.61	3.18-5.20
Serum TG (mmol/L)	0.90 ± 0.28	0.52-1.45
Serum glucose (mmol/L)	4.38 ± 0.44	4.03-5.21

For serum TC: to convert to milligrams per deciliter, multiply by 38.66. For serum TG: to convert to milligrams per deciliter, multiply by 88.57. For serum glucose: to convert to milligrams per deciliter, multiply by 18.01. BMI indicates body mass index.

Gas chromatography analysis of the dietary oils used in the study revealed 71.3% 18:1(n-9) in olive oil, 69.7% 18:2 (n-6) in sunflower oil, and 58.8% 18:3(n-3) in flaxseed oil. These results demonstrate significant amounts of test fatty acids across the various test diets.

Overall, olive oil significantly increased total energy expenditure when compared with flaxseed oil ($P < .0006$) and tended to increase energy expenditure when compared with sunflower oil ($P < .06$) (Fig. 1). In addition, sunflower oil tended to increase energy expenditure when compared with flaxseed oil ($P < .07$). No significant differences were established for rates of fat or carbohydrate oxidation between any of the 3 oils tested (Fig. 1).

The differences in energy expenditure were most significantly established during hours 2 and 3 after consumption of the test meals (Fig. 2). At hour 2, both olive oil and sunflower oil tended to have increased energy expenditure when compared with flaxseed oil ($P < .09$). Again during hour 3, energy expenditure tended to increase when subjects consumed olive oil compared with flaxseed oil ($P < .09$), but did not differ from sunflower oil. The hourly breakdown of fat and carbohydrate oxidation did not reveal any significant differences (Figs. 3 and 4).

4. Discussion

This is the first study using a single-meal approach and indirect calorimetry to demonstrate that consumption of olive oil rich in oleic acid increases energy expenditure compared with oils containing other long chain unsaturated fatty acids. This result supports the findings of previous research in both animals [9-11] and humans [14,15]. The type of fat influences the fat oxidation rate. In particular, studies using indirect calorimetry [3,5,23,24] and isotope-

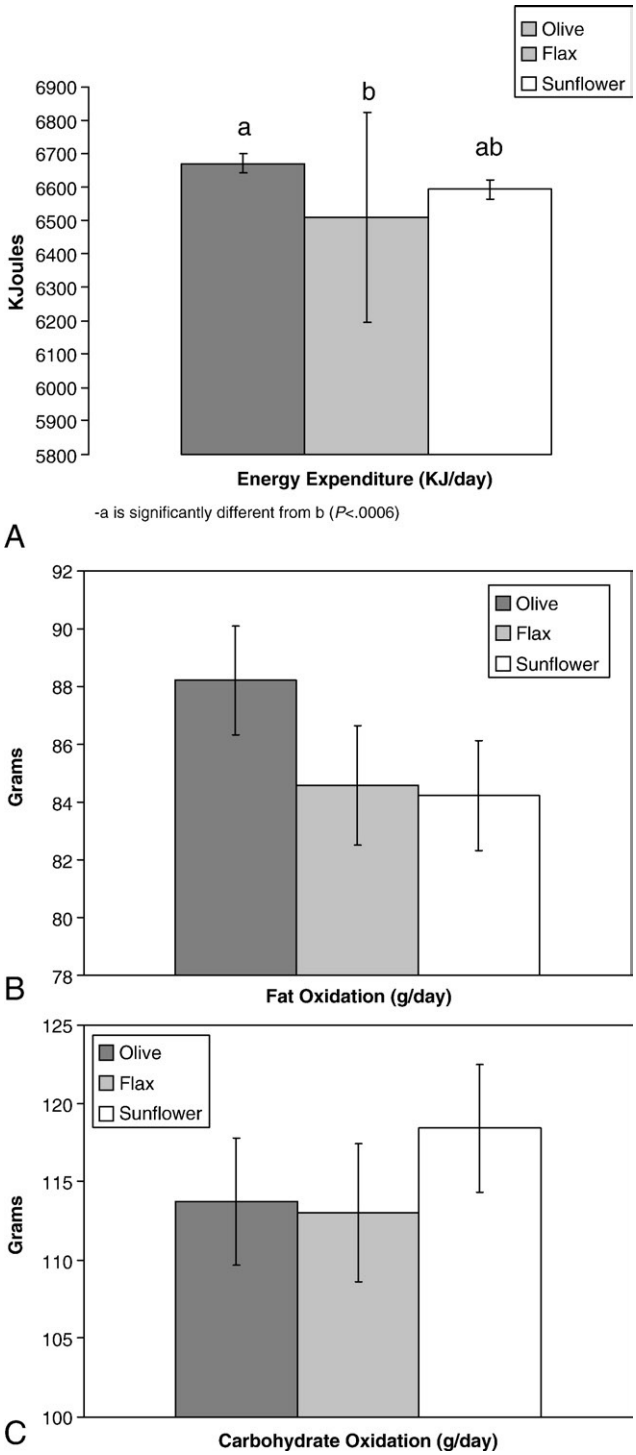

Fig. 1. Overall mean (±SEM) daily (A) energy expenditure, (B) fat oxidation, and (C) carbohydrate oxidation as a function of dietary oil consumed. *a* is significantly different from *b* ($P < .0006$). N = 15.

labeled fatty acids [4,7] techniques have shown that long chain unsaturated fatty acids are more readily oxidized when compared with long chain saturated fatty acids. In the present study, the effects of oleic and linoleic acids were not compared with long chain saturated fatty acids as was the case in much of the previous work. Instead, the comparison

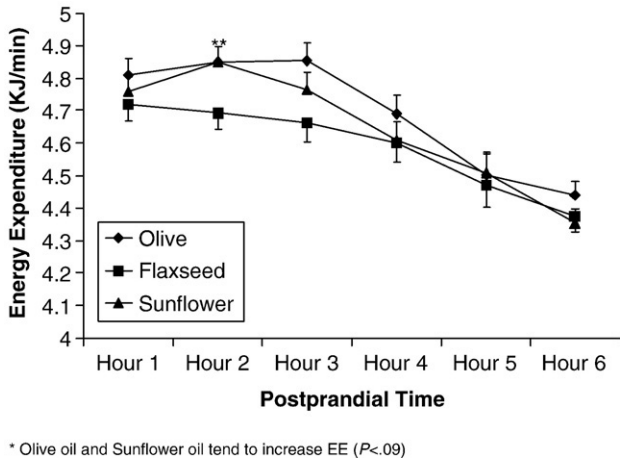

Fig. 2. Effect of olive, flaxseed, and sunflower oil test meal on mean (±SEM) postprandial energy expenditure in normal-weight men; N = 15. * Olive oil and sunflower oil tend to increase energy expenditure ($P < .09$).

was made with linolenic acid, an unsaturated fatty acid with 18 carbons. In a previous study that used isotope-labeled fatty acids, Jones et al [14] showed that the oxidation rate of oleic acid exceeded that of linoleic acid in healthy adult male subjects. On the contrary, the research team of DeLany et al [7], also using isotope-labeled fatty acids, reports that of the 18-carbon fatty acids, linolenic acid is the most highly oxidized, followed by oleic acid and then linoleic acid. In contrast to findings from DeLany et al [7], our research team did not observe similar increased rates of oxidation in subjects fed diets containing linolenic acid in comparison to oleic and linoleic acid. Our results show a preference for oleic acid to enhance energy expenditure. The differences between the current study and the study by DeLany et al [7] may be related to the methodology used. The present study measured energy expenditure using indirect calorimetry, whereas DeLany et al [7] measured the oxidation rate of individual fatty acids using tracer techniques. The technique used by DeLany et al [7] reflects the oxidation of a single

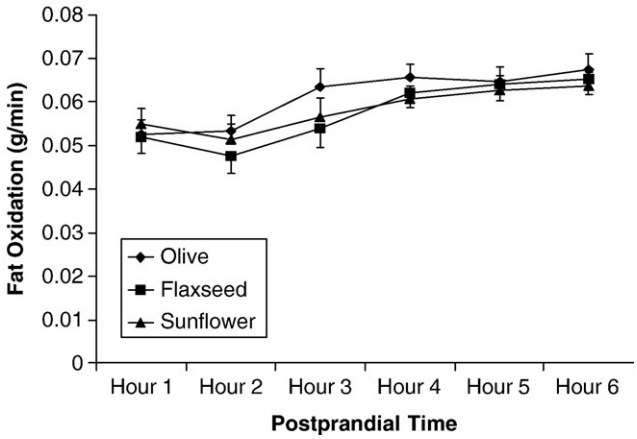

Fig. 3. Effect of olive, flaxseed, and sunflower oil test meal on mean (±SEM) postprandial fat oxidation in normal-weight men; N = 15.

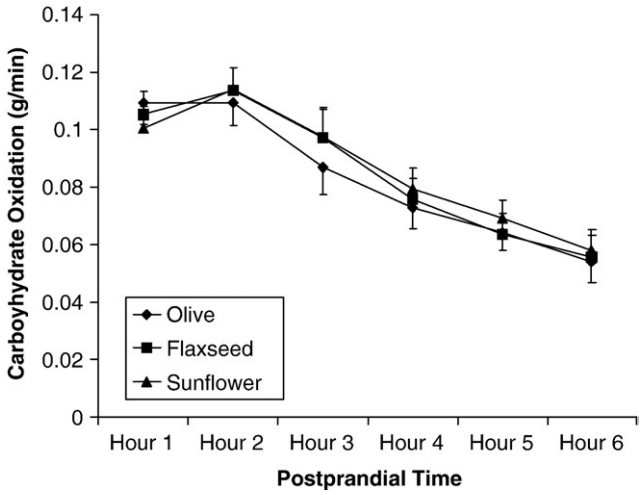

Fig. 4. Effect of olive, flaxseed, and sunflower oil test meal on mean (±SEM) postprandial carbohydrate oxidation in normal-weight men; N = 15.

fatty acid, whereas the technique used here reflects the change in energy expenditure when altering the pattern of dietary fatty acids. Because fatty acids are known to act as transcription factors [25], the measurement of total fat oxidation rate and energy expenditure rather than a single fatty acid oxidation rate may provide more insight into the metabolic role of specific fatty acids.

The present study is similar to earlier work by Forsgren [15] who measured expired $^{14}CO_2$ after oral administration of 1-^{14}C–labeled fatty acids including oleic, linoleic, and linolenic acids. After 24 hours of measurement, oleic acid showed the highest recovery (39%), followed by linoleic acid (28%) and linolenic acid (23%). Although similar trends appear between the 2 studies, results should be interpreted with caution because the current study differed in measurement techniques and fatty acid origin and because the period for data collection was only 6 hours, as opposed to 24 hours. In fact, if we examine the recovery trends of Forsgren [15] at the 6-hour time point, an entirely different trend emerges whereby linoleic acid shows the highest recovery followed by linolenic and oleic acids. The authors attributed this change over time as an effect of peak metabolism of particular fatty acids being reached at different time points postprandially. This idea brings to light the importance of the postprandial measurement period and highlights the value of establishing the appropriate data collection period that best represents what is happening in human metabolism. Overall, the period of postprandial data collection may in fact affect the results that are seen in the current research study.

Another limitation of this type of research is the possible effect of subjects' antecedent diet on substrate oxidation, resting energy expenditure, and TEF. The importance of pretrial diet was also outlined by Jones [13] who found that rats fed a pretrial diet containing equal quantities of linoleic, oleic, and linolenic acids for 10 weeks exhibited no difference in the capacity to oxidize 18-carbon unsaturated fatty acids. The author commented that this result suggested that differences previously observed in fatty acid oxidation were related to the particular blend of fatty acids provided and not to the capacity of the organism to oxidize specific fatty acids at different rates [13]. Furthermore, it is possible that the quantity and quality of a subject's habitual fat intake can influence substrate oxidation and the partitioning of fat for either energy or storage. For instance, Cooling and Blundell [26] reported that habitual high fat consumers had higher fat oxidation rates than low fat consumers. The present study used a crossover design, which minimizes potential confounding because every subject serves as his own control. Future studies should consider analyzing the habitual diets of subjects to determine if individual fatty acids are handled differently depending on historical dietary habits. In addition, future studies should be carried out with extended feeding durations.

Nevertheless, there are technical as well as plausible biological explanations to support our results. Leyton et al [12] offers a possible clarification as to why linolenic acid shows a higher expired $^{14}CO_2$ level, stating that oxidized linolenic acid liberates [1-^{14}C] acetyl coenzyme A that is incorporated in saturated fatty acids such as myristic and palmitic acid. Therefore, the label observed in the CO_2 may not be derived from the original fatty acid, but could come from fatty acids that have been elongated or synthesized de novo. This possibility illustrates some of the difficulties inherent in the interpretation of substrate oxidation data. A plausible biological mechanism to explain the preferential oxidation of oleic acid is that it is preferentially incorporated into TG, which are a ready source of energy [12]. In addition, another plausible molecular mechanism is offered by animal studies by Rodriguez et al [11] who reported that rats fed a diet rich in olive oil compared with one rich in sunflower oil experienced an up-regulation of uncoupling protein, a protein that allows heat production by uncoupling respiration from adenosine triphosphate synthesis, which is an important component of energy expenditure. However, further investigation in human tissue should be considered.

The oils chosen in this particular study were all of plant origin to avoid secondary compositional differences that could potentially result when comparing plant- vs animal-derived products. It is proposed that the differences in the composition of fatty acids in the test oils exert different effects on energy expenditure. However, because each oil was derived from a separate plant source, one cannot rule out the influence of other factors present in those oils.

In conclusion, the results of this study suggest for the first time using indirect calorimetry that human handling of olive, sunflower, and flaxseed oil varies. In particular, the data indicate that olive oil offers a slight advantage toward increased energy expenditure over time in healthy normal-weight men.

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