

Behavioral, plasma, and calorimetric changes related to food texture modification in men

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Labouré, Hélène, Virginie Van Wymelbeke, Marc Fantino, and Stylianos Nicolaidis. Behavioral, plasma, and calorimetric changes related to food texture modification in men. *Am J Physiol Regulatory Integrative Comp Physiol* 282: R1501–R1511, 2002; 10.1152/ajpregu.00287.2001.—We hypothesized that food texture modifications might alter anticipatory reflexes, feeding behavior, and the postabsorptive consequences of ingestion. Two sets of complete meals with different textures but the same macronutrient composition were prepared. The first set was either a soup containing chunks of food (mixture) or the same soup blended until smooth (purée). The second set was either a rusk (R), a sandwich loaf (SL), or a liquid rusk meal (LR). We measured hunger and fullness feelings after ingestion of each food in a calibrated lunch, the ingestion rate, the duration between lunch and a spontaneous dinner request, the energy value, and the macronutrient composition of the ad libitum dinner. We also studied plasma modifications and respiratory gas exchanges from lunch to dinner. Feelings of hunger and fullness were not affected by texture modifications. The purée soup was consumed faster than the mixture ($P < 0.05$), and insulin, triacylglycerol, and energy expenditure were greater with the purée ($P < 0.05$). LR was less palatable than the other rusk lunch versions ($P < 0.001$), and R was ingested more slowly ($P < 0.05$). The lowest increase in plasma glucose occurred with SL, and the highest energy expenditure was seen with LR ($P < 0.05$). In humans, food texture modification affects not only eating patterns and palatability of ingestants but also metabolic management.

texture; eating behavior; preabsorptive modifications; post-absorptive modifications; insulin; glucose; free fatty acids; oxidative metabolism; chewing; humans

THE SHORT- AND LONG-TERM EFFECTS of diets in which composition, gustatory, olfactory, or even visual parameters were modified have been addressed by many studies (7, 11, 16–19, 21, 34–38, 44). But very few of them have investigated the consequences of texture modification, and none have covered the full range of responses from the pre- to postabsorptive and from the plasma to the calorimetric responses. However, texture modification has become an everyday practice, and both home and collective kitchens use powerful blend-

ers that replace and amplify the work normally done by our own mastication and salivation.

Does modification of food texture alone affect how foods are processed, their quantitative and qualitative metabolism, and final utilization by humans, both in the short and the long term? The first complete investigation of the effects of textural modification on plasma, oxidative metabolism, and long-term behavioral parameters was recently conducted in our laboratory on rats (20). These experiments clearly showed that texture modification was capable of changing some feeding as well as plasmatic and metabolic parameters that, in the long term, also affect body weight. There had been no similar investigation of behavioral, plasmatic, and oxidative metabolic parameters as a sole function of textural changes in humans. Although far fewer than studies on changes in nutrient composition, there have been studies (9, 13–15, 46, 47) that assess one or the other of the above-mentioned parameters as a function of texture in human beings. The texture of food seems to affect satiety sensation after a calibrated meal or preload (5, 16, 40) or the energy intake after a calibrated preload (31, 46) in humans. Because it takes longer to digest and absorb solid food than liquid food (4), it was to be expected that solid food suppresses appetite for a longer time period than liquid food. There is, however, no consistent evidence that solid foods are more satiating than liquid foods. Haber et al. (13), Bolton et al. (5), Tournier and Louis-Sylvestre (46), and Hulshof and De Graaf (16) obtained results suggesting that solid preloads are more satiating than liquid preloads. Kissileff (18), Rolls et al. (37), and Santangelo et al. (40) obtained contrasting results, whereas Pliner (31) found no effects. In the latter studies, apart from differences in the physical state (liquid vs. solid), the foods also differed with respect to macronutrient content (18, 31, 37), volume (5, 18, 31), or temperature (18, 37). Therefore, in these experiments, it is difficult to attribute differences in satiating effect to the different physical states. Even in the studies (13, 16, 40, 46) in which

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solid and liquid meals were of identical composition, the conclusions about the influence of texture on satiety were not clear. Furthermore, these studies do not provide any information on the mechanism whereby texture might influence food intake regulation. Some more recent studies have assessed plasma changes as a result of texture modification treated more or less in isolation (30). Thus it was shown that postprandial plasma insulin response was significantly higher after a liquid meal than after a solid meal (30) but not all the data concurred (13).

A food texture change may be perceptible from the outward appearance of the food and later when it is felt in the mouth. Perception may be modified during chewing, by the duration of the latter, and also by means of stimulation of the gastrointestinal tract mechanoreceptors. Being particularly aware of the role played by the "anticipatory reflexes" (including but not restricted solely to the so-called "cephalic response") revealed in our laboratory (26), we hypothesized that in humans food texture might modify both pre- and postabsorptive plasma levels of metabolites and hormones, eating behavior, and oxidative metabolism. In the present investigation, great care was taken to avoid modifying caloric density, hydration, and nutrient composition. The parameters investigated included assessment of hunger and fullness (respectively satiety and satiation) as well as pre- and postprandial plasma metabolic factors and oxidative metabolism. We used a meal made up of a complete, balanced combination of ingredients requiring consistent mastication before swallowing and/or salivation for the harder food; only the texture of the meal was modified.

MATERIALS AND METHODS

Subjects

Twelve healthy male volunteers, 19–25 yr old (mean \pm SE, 21.5 ± 0.6 yr) with a body mass index ranging from 19 to 23 kg/m² (mean \pm SE, 22.28 ± 0.56 kg/m²), were recruited from the local student population. To be included in the study, subjects had to be nonsmoking, have no family history of metabolic disorders, have a stable body weight for the last 6 mo, and take three meals a day that were balanced in macronutrient terms (~30% fat, 15% protein, and 55% carbohydrate) as evaluated by a 7-day food record. No subjects were taking medication or had any dietary restriction as indicated by the restraint factor (<10) for the food inventory (43). The subjects were instructed to maintain a constant pattern of activity during the study, not to change their eating habits, to avoid intake of alcohol, and to abstain from parties for the 2 days preceding each experimental day.

All subjects gave their informed consent before participation. The official Ethics Committee of Dijon approved the procedure.

Meals

Lunch. Two sets of experimental lunches were prepared. The first was a soup lunch prepared as a mixture of 29.5 g freeze-dried vegetables (Picard Surgelés), 36 g cooked kidney beans (Vivien Paille), 36 g cooked beef, 108 g liquid cream (Bridel), 21.6 g starch (Roquette), and 360 ml beef stock (Grand Arôme, Knorr). The energy content of this ration was

2,090 kJ of which 19.9% was protein, 49.9% carbohydrates, and 30.2% fat (Table 1). After being cooked, the soup was prepared as two versions with different textures. The first was the original texture, referred to as the mixture, and the second was liquidized using a Vorwex macerator and is referred to as purée. In sensory tests completed on these foods (unpublished results), purée was described as a creamy, smooth soup without necessity of mastication, whereas the mixture was found to be heterogeneous, fibrous, and hard, inducing long and difficult chewing and greater salivation. A back extrusion test (unpublished results) showed that the initial slope, the maximal strength, and the work of compression were significantly higher with the mixture.

The second experimental lunch was the rusk lunch. A rusk is a slice of sandwich bread loaf, i.e., a slice of a type of bread that is dried in an oven. There were three versions of this lunch. A solid rusk meal (R), which contained 85 g of rusk (Heudebert), 231 g of unskimmed milk (Candia, 4% lipid) plus 5 g of chocolate powder (Poulain), and 35.8 g water; a liquid rusk meal (LR), with the same composition but with the rusks dissolved in unskimmed chocolate milk; and a sandwich loaf meal (SL) composed of 118.8 g of the same rusks but without being toasted and with 236 g unskimmed chocolate milk. Water was added to R and LR because SL contained more water than the other two versions. The three versions of this lunch had the same macronutrient composition, energy density, and volume. The energy content of the ration was 2,090 kJ with 13.8% as protein, 58.3% as carbohydrates, and 27.9% as fat (Table 1). R and SL were solid foods whereas LR was a liquid food. In this group, a sensory test showed harder mastication for R than for SL and a longer in-mouth duration with R and SL than LR. SL has been found to be softer and more elastic than R according to instrumental measurements (unpublished results). The presentation order of the five experimental lunches was randomized.

Dinner. The dinner was a free choice. It was a typical French buffet composed of 13 different palatable foods (see APPENDIX A), including meats, vegetables, cheeses, desserts, bread, and water. This buffet was available at the request of the subject, when the subject was hungry, with as much food as wanted until the subject was satiated.

Experimental Measurements

Behavioral measurements. At each session, we measured 1) duration of the lunch; 2) time between lunch and a spontaneous request for dinner (an evaluation of the satiety potency of the experimental lunches) by the subjects who were deprived of all time cues (see *Experimental Procedure*); and 3) amounts of food ingested during the free-choice dinner in terms of energy content and macronutrient composition. We also questioned subjects on 1) hunger and fullness feelings, evaluated every 30 min after the lunch by using a 100-mm visual analog scale and 2) the hedonic value of the

Table 1. Composition of experimental lunches

	Soup Lunches		Rusk Lunches	
	Weight, g	Energy provided, %total energy	Weight, g	Energy provided, %total energy
Protein	25	20	22.5	18
Carbohydrate	62.5	50	70	56
Lipids	16.8	30	14.4	26

The total energy content of each lunch group was 2,090 kJ.

experimental lunch evaluated on a 100-mm visual analog scale immediately after ingestion.

Plasma parameters. Venous blood was drawn by insertion of an indwelling double-lumen catheter (8) into a distal vein of the hand in a retrograde direction. This catheter permitted continuous infusion of heparin solution by one channel and withdrawal of noncoagulated blood through the other channel. The heparin solution was mixed with the blood sample in the distal part of the catheter and never entered the venous circulation of the subjects. Blood samples (3 ml) were collected from subjects at the following times: 8 min before lunch; when lunch was served (*time 0*); at 2, 4, 6, 8, 10, 14, 20, 30, 45, 60, 90, and 120 min after the subjects began to eat lunch; and every 60 min until the subjects requested dinner. One milliliter of heparinized blood was separated from every blood sample, to which aprotinin (1,000 KIU or 0.16 mg) was added for glucagon determination. All blood samples (with and without aprotinin) were immediately centrifuged (4,000 *g* at 4°C for 15 min), and plasma samples were separated into aliquot portions. Glucose, triacylglycerol, fatty acids, and glycerol were assayed immediately. Plasma samples for insulin and glucagon were stored at -70°C for later determination.

Plasma glucose was determined by the glucose-oxidase method (Hycel kit, 1% accuracy), triacylglycerol was ascertained via enzymatic means (Hycel kit, 5% accuracy), and fatty acids and glycerol were assessed using a colorimetric enzymatic method (Oxid kit, 5% accuracy; triglyceride GPO-Trinder kit, Sigma, 2% accuracy) with a Lysa 200 instrument (Hycel). Plasma immunoreactive insulin and glucagon were assessed with a RIA kit (Sanofi, Pasteur and Pharmacia, 2 and 4% accuracy, respectively).

Nutrient oxidation rate. Energy expenditure assessments were made by indirect calorimetry. Subjects were equipped with a two-valve facial mask. They breathed in the ambient air and breathed out through the mask. This expired air was collected for 15-min periods in a Tissot spirometer. The oxygen and carbon dioxide concentrations of the expired air were analyzed by means of gas analyzer (analyzer series 1400, Servomex, Paris, France) calibrated at the start of each test with a reference gas mixture (5.012% CO₂ and 12.02% O₂). These measurements began 1 h after the subjects arrived at the laboratory and during 30 min before the lunch. The measurements were repeated again 20 min after the onset of the experimental lunch up to the subject's request for dinner and thereafter for 30 min. To compute nutrient oxidation rates and energy expenditure, we measured protein oxidation. This was inferred from the determination of urine urea (Hycel urea kit; 5% accuracy). For this purpose, urine samples were collected after the lunch meal and at least once during the afternoon. Energy expenditure and carbohydrate and lipid oxidation were computed for every 15-min period using the conventional equation (33) (see APPENDIX B).

Body composition. Energy expenditure and carbohydrate and lipid oxidation were expressed per kilogram of lean body mass. Body composition was measured by dual energy X-ray absorptiometry (QDR 4500W, Hologic). This method measured the body weight and body fat mass. Lean body mass was then calculated.

Experimental Procedure

The study was carried out in a residential metabolic-monitoring ward at Dijon University Hospital. The experiment included five sessions, each lasting one day with lunch differing only in texture. At least 1 wk separated each session.

Subjects went through a habituation test during which experimental rooms and materials (e.g., catheter, Tissot spirometer, and nasal mask) were presented to them. They were also invited to taste each experimental food to limit neophobia; subjects that could not eat all the foods were rejected. An experimental day was also explained. Subjects were instructed to have dinner at regular hours and to eat the same amount of food each evening preceding the test day. Similarly, they were told to have breakfast before 0800 on the morning of each session and to not change its content. Neither foods nor fluids were thereafter allowed until the experimental lunch.

Subjects came to the laboratory at 1130 and left at 2200. On arrival, they were asked to empty their bladders. They were then isolated in an individual, sound-attenuated medical suite where they were maintained supine, under artificial light and with time cues minimized. All personnel were carefully trained to avoid references to time or time intervals. Under these conditions, subjects rapidly lost track of the time (6, 14, 25, 48). When asked about time at the end of the session, they were consistently mistaken (an average error of 45 min). This protocol enabled us to eliminate the temporal determinism involved in food intake (48).

To minimize the disturbance and stress entailed with blood sampling, the sterile venous catheter was inserted at 1145, i.e., 1.5 h before the first sample was taken. At 1245, energy expenditure was recorded over a 30-min period (pre-meal measurement). The experimental lunch was served at 1330, after the first evaluation of hunger and fullness. Subjects were instructed to eat their entire lunch in less than 20 min and to chew their food steadily and avoid swallowing larger pieces whole. When the lunch had been consumed, hunger and fullness were again evaluated, and subjects were asked to score the palatability of what they had eaten.

Twenty minutes after the onset of lunch, respiratory exchange measurements were resumed. This lasted until the subjects requested dinner.

During the afternoon, subjects were instructed to remain awake and immobile in a supine position. The respect of these rules was controlled by the personnel. Subjects were allowed to listen to music or to read using a lectern. When they expressed the desire to have dinner, a hunger evaluation was performed, followed by plasma sampling and respiratory exchange measurements for 30 min. The energy content of the dinner was recorded.

Expression of Results and Statistical Analysis

Expression of results. Data relating to the soup lunches and the rusk lunches were treated separately. Because subjects requested dinner at different times, the variation of hunger and fullness ratings as the variation of metabolic variables was expressed as the mean \pm SE of the 12 volunteers at each time from the value preceding the meal until the time at which the first individual requested dinner (this interval was 240 min after the onset of the lunch). All parameters were then collected 15 and 30 min after the request of the meal. We also computed each subject's "satiety ratio" [i.e., duration of the intermeal interval after the lunch (in min) per energy content of the lunch (in kJ)] and the deprivation ratio [i.e., energy content of the dinner (in kJ) per duration of the intermeal interval before this meal (in min)].

Plasma parameters were studied in two phases: the first phase during the 20 min after the onset of the lunch, considered to correspond to the preabsorptive, reflexively elicited responses, and the second phase from 20 to 240 min after the

onset of the meal, considered to correspond to the postabsorptive phase. The overall responses after the lunch were expressed as the area under the curve (AUC) calculated using the trapezoidal rule from the onset of lunch until the first request of dinner (i.e., 240 min). Total energy expenditure and substrate oxidation were also calculated by accruing these variables over 240 min.

Statistical analysis. Statistical analysis was performed with the NCSS statistical package (version 2000; BMDP statistical software, Los Angeles, CA)

For parameters independent of time (hedonic parameters, lunch duration, intermeal interval duration, energy intake and macronutrient composition of ad libitum dinner, AUC of plasma parameters, and cumulative energy expenditure), we used an ANOVA for repeated measures with the "texture of lunch" as a repeated factor, followed by post hoc comparison with the Tukey-Kramer test when appropriate ($P < 0.05$). Subjects were used as a fixed factor and the texture of the lunch was the main factor.

For time-dependent parameters (evolution of hunger, fullness and plasma and oxidative metabolic parameters), we used a two-way ANOVA for repeated measures with texture of lunch and time as repeated measures followed by post hoc comparison with the Tukey-Kramer test when appropriate ($P < 0.05$).

RESULTS

Hedonic Evaluation and Hunger Ratings

There were no significant differences in the hedonic ratings between the two soup lunches (mixture, 42.3 ± 7.7 mm; purée, 47.7 ± 7.3 mm). For the rusk lunches, LR was significantly less palatable than the other versions [$F(2,22) = 14.38$, $P < 0.001$] (R, LR, and SL, 47.6 ± 7.8 , 16 ± 5.4 , and 47.1 ± 6.7 mm, respectively).

Two-way ANOVA yielded no significant difference according to the lunch texture factor for hunger and fullness ratings either for the soup or the rusk lunches, but the time factor did vary significantly [$F(7,77) = 25.1$, $P < 0.001$ for hunger and $F(7,77) = 48.7$, $P < 0.001$ for fullness] (Fig. 1). For the rusk lunches, subjects in the R group were less hungry than those in the SL and LR groups after lunch (Fig. 1).

Food Intake

For the soup lunches, the mixture was consumed significantly more slowly than purée [$F(1,11) = 28.6$, $P < 0.001$] (Table 2). The mean intermeal interval duration was not significantly different but tended to be longer for the mixture. Intake expressed as total energy at dinner was not significantly different, although there were differences in the proportion of macronutrients that the subjects chose ad libitum; more carbohydrates were consumed after the mixture than after the purée lunches [$F(1,11) = 6.71$, $P < 0.05$].

For the rusk lunches, R was consumed significantly more slowly than SL and LR [$F(2,22) = 10.6$, $P < 0.001$] (Table 2). The mean intermeal interval was not significantly different but tended to be smaller with the more liquid food, i.e., LR. As in the soup group, the choice of macronutrients was influenced by the version of the lunch meal; more protein [$F(2,22) = 4.25$, $P < 0.05$] and fat [$F(2,22) = 5.34$, $P < 0.05$] were consumed after SL than after R. The deprivation ratio was significantly higher after LR than after R [$F(2,22) = 6.63$, $P < 0.01$] (Table 2).

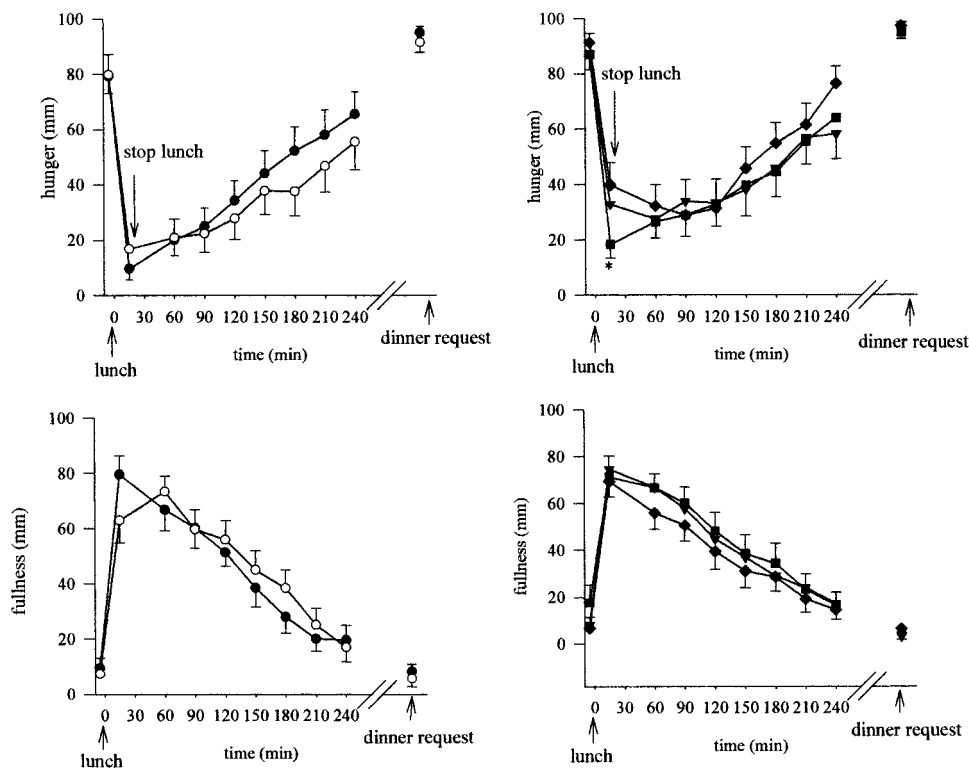


Fig. 1. Temporal pattern of hunger and fullness rating after 5 lunches differing in texture. *Left*: the soup group; *right*, the rusk group. ●, Mixture; ○, purée; ■, rusk; ◆, liquid rusk; ▼, sandwich loaf. Values are means \pm SE; $n = 12$. * $P < 0.05$.

Table 2. Behavioral food intake measurements

	Soup Lunch		Rusk Lunch		
	Mixture	Purée	Rusk	Liquid rusk	Sandwich loaf
Lunch duration, min	15.5 ± 1.3	9.5 ± 0.9*	15.8 ± 1.6†	9.2 ± 1.2‡	10.2 ± 0.9‡
Mean intermeal interval duration, min	342 ± 21	312 ± 17	308 ± 10	290 ± 17	315 ± 17
Deprivation ratio, kJ/min	9.9 ± 1.3	10.7 ± 0.8	9.7 ± 1.5†	14.4 ± 1.5‡	13.2 ± 1.9†‡
Satiety ratio, min/kJ	0.16 ± 0.007	0.15 ± 0.009	0.15 ± 0.005	0.14 ± 0.007	0.15 ± 0.007
Dinner energy intake, kJ	3,308 ± 247	3,252 ± 362	2,945 ± 455	3,933 ± 364	4,012 ± 423
<i>Dinner macronutrient intake</i>					
Carbohydrate, kJ	1,364 ± 84	1,135 ± 143*	1,177 ± 145	1,493 ± 130	1,350 ± 116
Fat, kJ	1,288 ± 147	1,452 ± 212	1,180 ± 252†	1,655 ± 190†‡	1,830 ± 261‡
Protein, kJ	640 ± 64	651 ± 63	578 ± 107†	769 ± 83†‡	817 ± 100‡

Values are means ± SE. *Significantly different from mixture group. Within the rusk lunch group, values with different superscripts are significantly different from each other.

Plasma Parameters

Glucose. In agreement with previous data (3, 23, 45) showing anticipatory reflexes in humans, plasma glucose exhibited early changes that varied among subjects and types of food (Fig. 2). However, these early modifications (generally decreases) were not statistically significant in the 20 min after the onset of lunch. After this reflex modification, the variation follows the typical pattern for postprandial glucose with the highest point earlier after a mixture lunch (at 45 min) than for the other lunches (at 60 min). In the soup lunches, glucose variation was not significantly different between textures, whereas for the rusk lunches the mean postprandial level of glucose [$F(2,22) = 4.7, P < 0.05$] and the AUC were significantly larger after R and LR than after SL [$F(2,22) = 3.99, P < 0.05$] (Table 3).

Insulin. Postabsorptive insulin changes were parallel to glucose changes, reaching their highest level earlier with mixture and SL (at 45 min) than with the other lunch types (at 60 min) (Fig. 2). This large post-absorptive increase is preceded by a preabsorptive rise from 6 to 10 min. The amplitude of this reflex secretion was smaller than the postabsorptive one but deviated significantly from the basal level, particularly after purée (Fig. 2). The AUC of insulin concentration was significantly larger after the purée compared with the mixture version of the soup lunches [$F(1,11) = 6.61, P < 0.05$] (Table 3).

Glucagon. Plasma glucagon also showed the expected early response. There was no significant difference in the soup group, but in the rusk group the plasma glucagon level was higher after SL than after LR [$F(2,22) = 4.53, P < 0.05$] and the AUC was higher after R and SL than after LR [$F(2,22) = 7.79, P < 0.01$] (Table 3).

Fatty acids. For all meals, an early decrease was observed followed by a delayed sharper drop that reached its lowest point ~120 min after the onset of the lunch (Fig. 3). By 240 min after food ingestion began, fatty acid concentrations had returned to the premeal level in the soup group but not in the rusk group. However, after the subjects requested dinner, fatty

acids returned to the premeal level in all meal groups.

Glycerol. Glycerol did not vary significantly in response to eating (Fig. 3). However, an early decrease in glycerol concentration was observed particularly in the soup group. The AUC was not significantly different (Table 3).

Triacylglycerol. Triacylglycerol exhibited a clear-cut early response that varied depending on texture (Fig. 3). For soup lunches, triacylglycerol levels were practically flat with the mixture whereas with the purée an increase did occur at 45 min postingestion. The amplitude of preabsorptive (0–20 min) and postabsorptive periods (20–240 min) was greater for the purée than for the mixture [$F(1,11) = 5.17 (P < 0.05)$ and $F(1,11) = 10.8 (P < 0.01)$ for pre- and postabsorptive period, respectively] (Fig. 3). The AUC was also significantly higher after the purée meal [$F(1,11) = 10.1, P < 0.01$] (Table 3). For the rusk lunches, neither triacylglycerol patterns nor the AUC differed significantly according to the texture.

Oxidative Metabolic Responses

In the resting subjects, food intake was followed by a rapid rise in total metabolic rate (Fig. 4). It is remarkable that although the initial, preabsorptive rise was similar for both soup meals, the subsequent profile was clearly different for the two versions. Energy expenditure continued to increase with the purée whereas it clearly began to decline for the mixture. At 240 min postingestion, the difference was still clear, but had narrowed by the time of request for dinner. Despite this visual difference in the profile of the curve, energy expenditure variations were not significant in the soup group, but cumulative energy expenditure was significantly larger after the purée than after the mixture [$F(1,11) = 4.8, P < 0.05$] (Table 4). Conversely, cumulative energy expenditure was not significantly different for the rusk lunches, whereas the mean energy expenditure was larger for subjects who consumed LR than the other rusk lunches [$F(2,22) = 5.11, P < 0.05$] (Fig. 4).

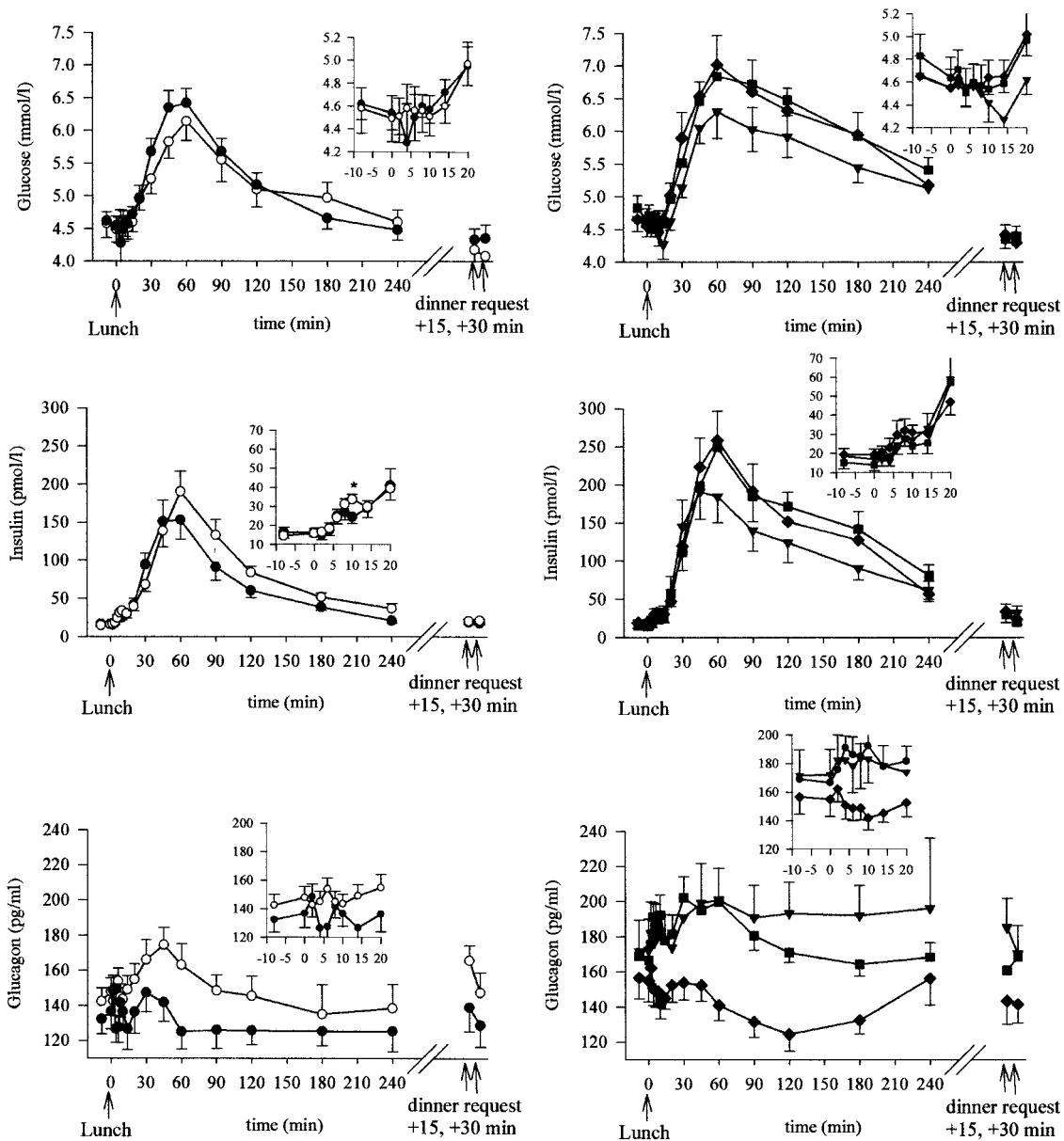


Fig. 2. Temporal pattern of plasma glucose, insulin, and glucagon. *Left*: the soup group; *right*, the rusk group. Symbols are the same as given in Fig. 1 legend. Values are means \pm SE; $n = 12$. * $P < 0.05$.

There were no significant differences in respiratory quotient (RQ) and carbohydrate and lipid oxidation for the various textures. However, RQ tended to fall after purée consumption and increase after mixture con-

sumption. This tendency can be accounted for by lipid oxidation, showing a dramatic increase for the purée version, and by the carbohydrate oxidation pattern, which did indeed decrease.

Table 3. Area under curve at postprandial 240 min

	Soup Lunch		Rusk Lunch		
	Mixture	Purée	Rusk	Liquid rusk	Sandwich loaf
Glucose, mmol	1,282 \pm 36	1,277 \pm 55	1,487 \pm 44 [†]	1,480 \pm 66 [†]	1,374 \pm 56 [‡]
Insulin, pmol	16,093 \pm 2,331*	21,140 \pm 1,736	35,056 \pm 4,319	33,572 \pm 5,761	26,908 \pm 4,368
Glucagon, pg	31,940 \pm 1,764	36,518 \pm 2,178	43,871 \pm 1,688 [†]	34,813 \pm 1,980 [†]	47,532 \pm 4,204 [‡]
Glycerol, g	30.6 \pm 3.2	35.9 \pm 4.6	30.2 \pm 2.3	31.9 \pm 3.7	34.74 \pm 4.9
FFA, mmol	98.1 \pm 5.5	121.5 \pm 27	70.8 \pm 3.7	77.10 \pm 8	77.5 \pm 2.8
TG, mmol	170.6 \pm 16.3*	215.5 \pm 16.3	198.2 \pm 13.3	189.9 \pm 11	195.3 \pm 22.8

Values are means \pm SE. FFA, free fatty acids; TG, triacylglycerol. *Significantly different from purée group. Within the rusk lunch group, values with different superscripts are significantly different from each other.

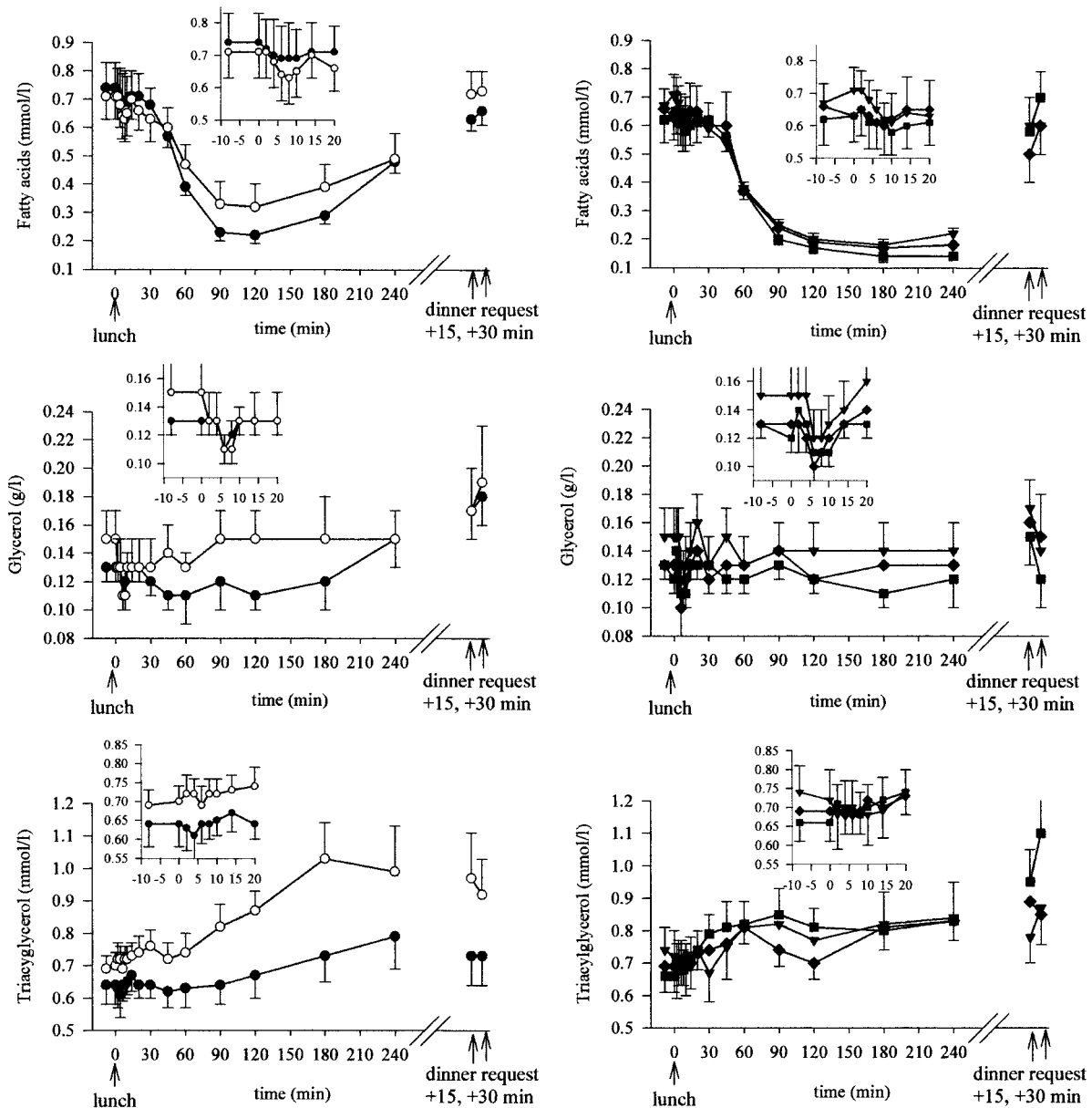


Fig. 3. Temporal pattern of plasma fatty acids, glycerol, and triacylglycerol. *Left*: the soup group; *right*, the rusk group. Symbols are the same as given in Fig. 1 legend. Values are means \pm SE; $n = 12$. * $P < 0.05$.

DISCUSSION

The premeal values for all the plasma parameters, energy expenditure, and lipid or carbohydrate oxidation were not significantly different between tests and hence are consistent with previous studies (22, 26); our findings were the same for the anticipatory reflex modifications in plasma metabolite levels (1, 2, 12, 24, 29, 32, 39, 41, 42). The observation of these rapid modifications previously in our laboratory (26) and elsewhere (3, 23, 45) validates the experimental method used in the current study.

Our main working hypothesis dealt principally with the effect of texture on anticipatory reflexes. Given that the mixture version required greater mastication, we explored the idea that the reflexively elicited re-

sponses would be amplified. Therefore our protocol design included several frequent samplings at the beginning of the eating period (first 20 min) when intestinal absorption is still minimal. This study shows that the metabolic effects of food ingested vary not only as a function of the classic nutrient volume and composition but also as a function of food texture. As we already showed in rats (20), texture change modifies a number of metabolic parameters both in the early preabsorptive phase and in the later postabsorptive phase. The main difference in this reflexive response concerned the triacylglycerol level (higher with purée), and this is consistent with our findings on oxidative metabolism. During the early stage (0–30 min) after ingestion of the purée begins, there is a decrease in the RQ, reflecting

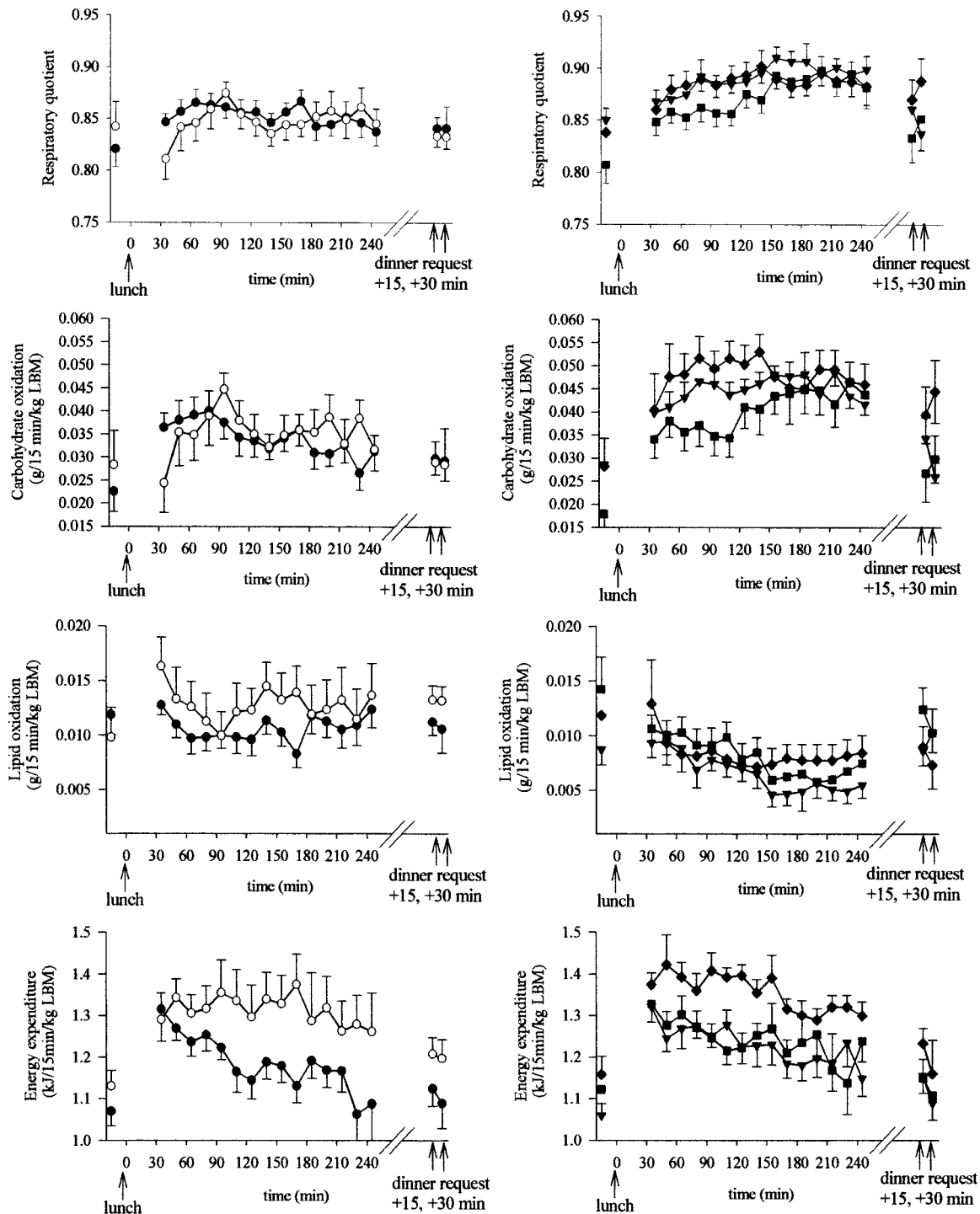


Fig. 4. Temporal pattern of respiratory quotient, carbohydrate oxidation, lipid oxidation, and energy expenditure. *Left*: the soup group; *right*, the rusk group. Symbols are the same as given in Fig. 1 legend. Values are means \pm SE; $n = 12$. LBM, lean body mass.

an increase in the lipid utilization rate compared with carbohydrates. This is shown by the lipid and carbohydrate oxidation curves. In contrast, after ingestion of the soup mixture, the RQ tends to increase.

Further differences depending on the textural versions were observed during the postabsorptive period between 20 and 240 min postingestion. This is the time

interval necessary for intestinal absorption to begin. However, the metabolic responses then are still the result of a mixture of both pre- and postabsorptive mechanisms. During this second period, the AUC for insulin is significantly higher after purée than after the mixture, whereas the glucose level does not differ according to texture. Higher insulin secretion after

Table 4 *Cumulative energy expenditure and carbohydrate and lipid oxidation at postprandial 245 min*

	Soup Lunch		Rusk Lunch		
	Mixture	Purée	Rusk	Liquid rusk	Sandwich loaf
Energy expenditure, kJ/kg LBM	17.8 ± 0.54*	19.8 ± 0.8	18.8 ± 0.78	20.3 ± 0.3	18.7 ± 0.6
Carbohydrate oxidation, g/kg LBM	0.52 ± 0.04	0.53 ± 0.06	0.59 ± 0.06	0.7 ± 0.06	0.66 ± 0.04
Lipid oxidation, g/kg LBM	0.16 ± 0.02	0.19 ± 0.03	0.13 ± 0.02	0.13 ± 0.02	0.10 ± 0.01

Values are means ± SE. LBM, lean body mass. *Significantly different from purée group.

purée could be due to higher glucose absorption, because gastric emptying is faster for the liquid than for the solid (10, 28). The fact that there is no significant difference in glucose levels for these two foods means that the glucose level depends on a variety of factors besides insulin (rate of absorption, glucagon, catecholamines) that cannot be assessed.

There is a clear-cut difference between the two texture versions in the metabolic rate profile. According to ischymetric hypotheses (27), the fact that the metabolic rate decreases in the mixture group while remaining stable in the purée group should have induced hunger earlier among subjects that ate the mixture meal. Under this hypothesis, hunger is promoted by the decline of basal metabolism while satiation and satiety are facilitated by the early and late increment of postprandial basal metabolic rate, respectively (27). However, the time of request for dinner did not differ significantly between the two groups. Perhaps this is because at dinnertime, the difference in energy expenditure was much less than in the postabsorptive period. In the rusk group, energy expenditure for subjects who ate the LR meal remained significantly higher and accordingly their satiety also lasted longer. In other words, there is consistency between some plasma characteristics such as the triacylglycerol and metabolic findings and between these findings and the more persistent satiety in those subjects, even though their "internal clock" tended to impose a more time-dependent onset of dinner.

The common feature of the two versions followed by a persistently high metabolic rate is that both are ingested in liquid form. As far as we know, the literature does not provide information on the link between a more liquid form of ingested food and a higher postprandial metabolic rate and satiety. It is true that the mixture contains a liquid component that could have been readily absorbed. However, mastication should have transformed the mixture in the mouth to a consistency similar to the purée obtained by the blender. Gastric emptying and the kinetics of intestinal absorption differ immensely from one type of diet to another. To better understand the responses observed in this study, it is necessary to add assessment of the kinetics of gastrointestinal emptying and absorption using γ -camera techniques that our Ethical Committee would not authorize.

It would be worthwhile to investigate the influence of texture modification on metabolic parameters when dealing with repeated ingestion of various textural versions and examining the long-term effect of texture

modification. So far, this has been assessed only in rats (20) where it was shown that repeated presentation of a purée and a mixture gradually reduced the initial preference of the mixture over the purée. The preference slowly reversed (20), as if the learned preference took into account some beneficial effect of the purée, which initially was the second choice. Even more impressive in the rat experiment (20) is the fact that, when given a choice between the two versions, the rats not only progressively reverse their preference in favor of the purée but also gain more weight by consuming more of the purée. This long-term consequence was difficult to predict from our short-term data; more long-term metabolic research is required to fully understand this effect.

If a similar experiment was performed on humans who are already familiar with the experimental foods and have eaten them on a regular basis, perhaps the differences between the textural versions would be more marked. Our short-term data are not sufficient to propose better predictions. One can hypothesize that, just as in rats, texture differences affect not only the metabolism of ingestants but also the end point that is body weight itself. The consumption of foods of mixed texture may be better for a controlled program of eating and body weight, whereas purée may be better for body weight gain. Appropriate long-term experiments are needed to more fully understand the effects of food texture differences on body weight.

Conclusion

In conclusion, we can say that texture modification of food significantly influences variations in plasma metabolite levels and oxidative metabolism but only minimally influences eating behavior, at least under our experimental conditions. The low-energy content of the lunches (due to other constraints), the size of the sample, and the variability between subjects might explain the weak amplitude of the differences observed. Further study using larger subject groups, complementary parameters and diets, and repeated, long term measurements are necessary to more fully comprehend the effects on eating behavior.

Outlook

Many humans consume foods that have had texture modified mainly, but not only, by blenders, with the aim of improving the edibility and palatability of the food. The current study has shown that texture modification does affect some aspects of ingestant utiliza-

tion, and more importantly, one of our parallel rat experiments showed that, in the long term, body weight itself is also affected (20). Because of the extent of food texture modification today and its potential health consequences, we feel it is critical to attract more short- and (most importantly) long-term research on this subject, particularly on the influence of texture, focusing on 1) on a variety of foods with modified texture, 2) the various steps of their gastrointestinal transit and cellular metabolism, and 3) the metabolic mechanisms that we could not explore here. Such studies might prove to be very useful in establishing the right diet to better control body weight and various metabolic and diet-dependent pathologies.

APPENDIX A. FREE-CHOICE FOOD ITEMS PROVIDED DURING AD LIBITUM MEALS

Food	Brand	Energy, kJ/100 g	Protein, g/100 g	Fat, g/100 g	Carbohydrate, g/100 g
Bread	NA	994	7.61	1.2	48.84
Tabbouleh	Maggi	531	3.3	3.8	20
Mixed vegetables	Bonduelle	134	1.7	0.23	5.5
Mayonnaise	Amora	3128	1.49	82.5	0
Ham	Saltings of Arrée	514	17.5	5	2
Potato crisps	Carrefour	2332	5.5	36	53
Young turkey	Ronsard	630	22.4	6.79	0
Swiss cheese	SCAFE	1603	28.7	29.7	0
Camembert cheese	Carrefour	1166	21	21.5	0
Natural yogurt "velouté"	Danone	305	4.4	3.4	6.1
Orange	NA	176	1	0.2	8.25
Banana	NA	368	1.15	0.18	20.03
Fruit salad	Carrefour	263	0.4	0.1	15

All products were bought at the Carrefour supermarket. NA, not applicable.

APPENDIX B

Determination of Energy Expenditure and Nutrient Oxidation

Energy expenditure and nutrient oxidation were calculated according to the method of Rigaud and Melchior (33) as follows.

$$EE = 3.913V_{O_2\text{STPD}} + 1.093V_{CO_2\text{STPD}} - 3.341N_2 \quad (B1)$$

$$\text{Carbohydrate oxidation} = 4.545V_{CO_2\text{STPD}} - 3.205V_{O_2\text{STPD}} - 2.865N_2 \quad (B2)$$

$$\text{Lipid oxidation} = 1.672(V_{O_2\text{STPD}} - V_{CO_2\text{STPD}}) - 1.923N_2 \quad (B3)$$

EE represents the energy expenditure (in kcal), and N_2 is the nitrogen quantity (in g) in urine.

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