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Energy density and 6-year anthropometric changes in a middle-aged adult cohort

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Dietary energy density (ED) may be a good predictor of weight gain because of its association with the regulation of appetite control signals. Among the participants of the 'SUpplementation en VItamines et Mineraux AntioXydants' prospective study, 2707 subjects were included in the present study. Changes in weight, waist circumference (WC), hip circumference (HC) and waist:hip ratio were calculated using measured data collected in 1995/1996 and 2001/2002. The mean changes in various anthropometric indicators according to baseline body-weight status (BMI $<$ or $\geq 25\,kg/m^2$) and sex-specific tertiles of baseline ED level or 6-year changes in ED were compared by covariance analysis. In overweight subjects, weight gain was positively associated with high dietary ED at baseline (P for trend = 0·03) and with increasing ED during the follow-up (P for trend = 0·0008). Both the WC and HC changes were also positively related to baseline ED and change in ED in overweight subjects. However, the relationships observed for the WC and HC changes were no longer significant after adjustment for weight change. These results support the hypothesis of a deleterious effect of high-energy-dense diets on weight change for overweight subjects. This relationship could be mediated by physical activity level. Further research needs to be performed in other populations to determine whether ED could be effective strategies to prevent weight gain.

Body fat distribution: Cohort studies: Diet quality: Energy density: Weight change

Obesity has become the most frequent nutritional problem in industrialised countries and its prevalence is still increasing[1,2]. Obesity constitutes a major public-health concern because of its implication in the development of several chronic diseases, such as type 2 diabetes, as well as of CVD and certain cancers[1].

Weight gain is due to a positive energy balance, either caused by a decrease in energy expenditure or an increase in energy intake (EI). It is now well recognised that both decreasing physical activity (PA) levels and changes in diet are involved in the obesity epidemic[3]. Among dietary factors, dietary energy density (ED) is of growing interest[1,4], particularly regarding socio-economic disparities in diet quality and obesity[5–7]. ED may be a key element in body-weight regulation because it may alter appetite control signals, namely hunger and satiety[8,9]. Some studies have reported positive associations between ED and EI[4,10,11]. In addition, there is a strong correlation between the ED of foods and their fat content[4,12], which may also encourage weight gain.

However, the results from cross-sectional epidemiological studies that have examined the relationships between dietary ED and body-weight status are not consistent[10,13–20]. Some of them found a positive relationship between ED and weight[10,14,15,19], whereas some others found no significant association[13,20] or only in men[16]. Among the few longitudinal analysis available in free-living subjects, two were performed in women only[21,22] and one in both sexes[23]. All studies found a positive association between ED and weight gain. However, in a Danish middle-aged population, ED was positively associated with 5-year weight gain only in women who were initially obese, whereas an inverse relationship was observed in normal-weight women[23]. No significant association was observed in men. To our knowledge, no observational study has investigated the effect of ED on body fat distribution changes specifically. Abdominal obesity may be a better predictor of CVD[24] or some cancers[25] than the BMI. Therefore, the relationships between the ED and body fat distribution changes need to be studied.

The purpose of the present study was to investigate the relationships between dietary ED and 6-year changes in weight and body fat distribution, as assessed by waist circumference (WC), hip circumference (HC) and waist-to-hip ratio (WHR) in free-living middle-aged French men and women.

Abbreviations: ED, energy density; EI, energy intake; HC, hip circumference; PA, physical activity; WC, waist circumference; WHR, waist:hip ratio.

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Materials and methods

Subjects

Subjects were participants of the 'SUpplementation en VItamines et Mineraux AntioXydants' study, which was initially designed as an 8-year randomised double-blind, placebo-controlled, primary prevention trial, to test the efficacy of a daily antioxidant supplementation at nutritional doses in reducing the incidence of IHD and cancers. Details on the rationale, design, methods of the study and baseline characteristics of the subjects have been described elsewhere[26,27]. Among the 13 017 subjects included in 1994/1995, approximately two-thirds were women aged 35–60 years and one-third were men aged 45–60 years. The 'SUpplementation en VItamines et Mineraux AntioXydants' study was approved by the local Ethical Committee[26,27].

During the follow-up, the participants were invited to a clinical examination that included anthropometric measurements, every 2 years (from 1995 onwards). The subjects were also encouraged to provide dietary data in the form of 24-h dietary records every 2 months. All days of the week and all seasons were represented. For the present study, we included only those subjects who had available anthropometric measurements from the first (1995–6) and last (2001–2) clinical examinations, and who had no missing value for covariates (n 4826). We also selected subjects with at least three 24-h dietary records at baseline (during the year preceding the first clinical examination; n 3434). The subjects with at least one-third of hypoenergetic 24-h dietary records (total EI <3352 kJ/d (800 kcal/d) in men or 2095 kJ/d (500 kcal/d) in women) were excluded. We also excluded subjects with a past history of cancer, CVD, digestive pathologies or thyroid treatment, those who had such events during the follow-up and pregnant women during the follow-up, in order to exclude potential bias which could affect both weight change and dietary intakes (n 3025). Finally, we selected subjects with available data for WC, HC and WHR. In total, 2707 subjects were included in the present study. Longitudinal analysis was performed on a subsample of 1148 subjects who have in addition completed at least three 24-h dietary records at the end of the follow-up (during the year preceding the last clinical examination).

Anthropometric measures

Weight was measured with an electronic scale (Seca, Hamburg, Germany), with the subjects in indoor clothing and no shoes. Height was measured under the same conditions with a wall-mounted stadiometer. BMI was calculated as weight divided by height squared (kg/m^2) and overweight was defined by a BMI ≥ 25 kg/m^2. WC was measured as the circumference midway between the lower ribs and iliac crests, and HC was measured as the largest circumference between waist and thighs, both in standing position using an inelastic tape. WHR was calculated as WC divided by HC. Anthropometric changes (weight, WC, HC and WHR) were calculated in absolute terms as the difference between the last and first measures.

Dietary assessment

Dietary data were collected using the Minitel Telematic Network, a small terminal widely used in France as an adjunct to the telephone at the beginning of the 'SUpplementation en VItamines et Mineraux AntioXydants' study. The subjects were assisted by the conversational features of the software and given an instruction manual for coding foods including photographs for estimating portion or glass sizes, which had been previously validated in a pilot study on 780 subjects[28].

There is no consensus on the definition of ED[4]. Therefore, the use of several calculation methods is recommended[29]. In the present study, ED was calculated for each subject by dividing daily EI (in kJ) by the total weight of food consumed (in grams) with three different methods based on: food only (excluding energetic and non-energetic drinks, water and milk); food and energetic drinks (excluding non-energetic drinks and water); all food and drinks (including water). We constructed sex-specific tertiles of ED to classify the participants as having low, medium or high ED, similarly to Ledikwe *et al.* [10]. As it was recommended to perform at least analyses of ED based on food only[29], only the results based on food are presented in tables in the present report.

Assessment of covariates

Education level was obtained from a self-administered questionnaire at baseline and was coded into three categories according to the highest degree obtained (primary school, high school, university or equivalent). Smoking status (smoker, non-smoker) was assessed at three different time points: from the baseline questionnaire (1994); from a specific questionnaire administered at the middle (1998); at the end of the follow-up (2001). The PA level was assessed twice during the study, using the data from the baseline questionnaire (no regular PA, regular PA <1 h of walking per day and regular PA equivalent to at least 1 h of walking per day) and from a French self-administrated version of the 'Modifiable Activity Questionnaire'[30] administered at the end of follow-up (2001). The questionnaire has been described in detail elsewhere[30,31]. Briefly, information was collected about the type, frequency and duration of each activity performed during the previous 12 months. Using published compendiums[32,33], metabolic equivalent tasks were assigned to each activity reported. The metabolic equivalent tasks are the ratio of the metabolic rate of an activity divided by metabolic rate of an individual at rest (sitting quietly). For each subject, the duration of each PA (in hours per week) was multiplied by its metabolic cost and summed in order to obtain a global score in metabolic equivalent tasks-hour/week. The subjects were then classified into three categories as at baseline (no regular PA, regular PA <1 h of walking per day and regular PA equivalent to at least 1 h of walking per day).

To take into account the potential confounding effect of tobacco cessation and PA modifications during the follow-up, we constructed two longitudinal variables. Using the smoking status declared at inclusion, at the middle and at the end of the follow-up, we created a variable with the following five categories: (1) never smokers; (2) smokers throughout the follow-up period; (3) tobacco cessation; (4) tobacco restart; (5) tobacco cessation and restart during the follow-up. Using the PA data at inclusion and at the end of the follow-up (irregular, regular but inferior to 1 h of walking per day and regular and equivalent to at least 1 h

of walking per day), we created the following six categories: (1) no regular PA; (2) stable, regular low PA; (3) stable, regular high PA; (4) regular PA at inclusion and lower PA at the end of the follow-up; (5) no regular PA at inclusion and higher PA at the end of the follow-up; (6) regular PA at inclusion and higher PA at the end of the follow-up.

Statistical analyses

Descriptive results are reported as percentage or means and standard deviations. The Spearman coefficients were calculated in order to assess the correlations between the ED and macronutrient contents. The analyses of covariance were used to compare the adjusted mean change in anthropometric indicators (body weight, WC, HC and WHR) according to sex-specific tertiles of ED. Linear trend tests across ED tertiles were computed. All analyses were stratified by body-weight status (BMI $<$ or $\geq 25\,kg/m^2$ in 1995/1996) due to a significant interaction between initial weight status and both baseline ED tertiles and tertiles of ED 6-year changes. Variables included in the model were age, sex, education level, changes in PA and smoking status, baseline value of the outcome (weight, WC, HC or WHR) and either total daily EI for the analyses of baseline ED or baseline ED for longitudinal analyses of ED changes. A further adjustment for weight change was made for the analyses on WC, HC and WHR. The statistical significance was determined at $\alpha < 0{\cdot}05$. All statistical analyses were performed using Statistical Analysis Systems statistical software package version 8.2 (SAS Institute, Cary, NC, USA).

Results

Table 1 summarises the characteristics of the subjects according to sex. At baseline, men were 53·0 (SD 4·7) years and women were 48·4 (SD 6·4) years. There were approximately 41 % of the subjects having a university degree or equivalent in both sexes. Approximately 12 % of the subjects were smokers, and women's smoking habits during the follow-up were more stable than those of men. Women were less active than men. They also decreased their PA level during the follow-up more frequently than men and those who did not

Table 1. Characteristics of the subjects according to sex
(Mean values and standard deviations)

	Men		Women		
	Mean	SD	Mean	SD	*P**
n	1155		1552		
Baseline data					
Age (years)	53·0	4·7	48·4	6·4	<0·0001
Educational level (%)					0·0008
Primary	24·0		18·8		
Secondary	34·7		40·5		
University or equivalent	41·3		40·7		
Unemployed (%)	4·6		4·1		0·50
Current smoker (%)	12·2		11·8		0·74
Weight (kg)	75·6	10·4	60·0	9·9	<0·0001
Waist circumference (cm)	90·0	8·9	75·0	8·9	<0·0001
Hip circumference (cm)	98·0	5·6	97·4	8·0	0·02
Waist:hip ratio	0·92	0·06	0·77	0·06	<0·0001
BMI (kg/m^2)	25·1	2·9	23·0	3·6	<0·0001
Energy (kJ)	10635	2553	7921	2030	<0·0001
Weight of foods (g)	1933	469	1505	407	
Energy density (kJ/g)	5·80	0·88	5·67	1·00	0·0002
Longitudinal data					
Tobacco-status changes (%)					0·002
Never smokers	81·0		84·0		
Smokers throughout the follow-up period	6·7		7·9		
Tobacco restart	3·7		3·0		
Tobacco cessation	5·3		3·8		
Both tobacco cessation and restart	3·3		1·4		<0·0001
PA changes (%)					
No regular PA	11·2		14·2		
Stable, regular low PA	6·2		9·7		
Stable, regular high PA	27·5		15·8		
Regular PA at inclusion and lower PA at the end of the follow-up	35·6		41·4		
No regular PA at inclusion and higher PA at the end of the follow-up	12·2		11·1		
Regular PA at inclusion and higher PA at the end of the follow-up	7·3		7·8		
Weight change (kg)	2·05	3·89	2·22	4·17	0·28
Waist-circumference change (cm)	1·02	5·49	2·17	6·50	<0·0001
Hip-circumference change (cm)	0·33	3·79	−1·14	5·94	<0·0001
Waist:hip ratio change	0·01	0·05	0·03	0·08	<0·0001
Energy density change (kJ/g; *n* 1148)	−0·30	0·80	−0·27	0·96	0·53

PA, physical activity.
**P* values are obtained from *t* tests for continuous variables and χ^2- tests for categorical variables.

change their PA habits had no regular PA or had stable, regular low PA more often than men. The percentages of overweight and obese subjects were, respectively, of 42·9 and 5·4 % in men and 15·0 and 5·8 % in women at baseline and 50·1 and 8·0 % in men and 21·9 and 7·4 % in women at the end of the follow-up (data not shown). Women had a lower BMI at baseline (23·0 (SD 3·6) kg/m^2 *v.* 25·1 (SD 2·9) kg/m^2). ED was higher in men than in women (5·80 (SD 0·88) kJ/g *v.* 5·67 (SD 1·00 kJ/g)). Overweight subjects had a significant lower PA level at baseline compared with normal-weight subjects (28 % *v.* 23 % of the irregular activity, respectively, $P = 0{\cdot}003$), but were more inclined to improved their PA during the follow-up (16 % *v.* 10 % of the inactive subjects at baseline who increased their PA, respectively, $P = 0{\cdot}0007$). In the whole sample, ED was positively associated with EI (*r* 0·27, $P < 0{\cdot}0001$) and with the percentage of fat in EI (*r* 0·32, $P < 0{\cdot}0001$). In addition, ED was negatively associated with the percentage of protein in EI ($r -0{\cdot}28$, $P < 0{\cdot}0001$) and with the percentage of water in the food consumed (excluding all drinks; $r -0{\cdot}93$, $P < 0{\cdot}0001$). The association with the percentage of carbohydrate in EI was NS.

Adjusted means with their standard errors for each anthropometric change according to baseline ED tertiles (based on foods only, beverages were excluded from the ED calculation) are presented in Table 2. No significant results were observed in normal-weight subjects, whereas in subjects with a BMI ≥ 25 kg/m^2, weight gain increased across ED tertiles (*P* for trend = 0·03). The WC and HC changes were also increased in the highest ED tertile (*P* for trend = 0·05 and 0·04, respectively), but these positive relationships disappeared after controlling for weight change. No interaction between baseline ED tertiles and sex or menopausal status was found. Moreover, adjustment for menopausal status did not alter the results (data not shown). Similar results were

Table 2. Crude or adjusted anthropometric changes according to baseline energy density (ED) tertiles, France, 1995–2001*

(Mean values with their standard errors)

	ED tertiles						
	T1		T2		T3		
	Mean	SEM	Mean	SEM	Mean	SEM	*P* for trend
In subjects with BMI <25 kg/m^2 (*n* 1826)							
Baseline ED (kJ/g)							
Median	4·84		5·66		6·61		
Mininum-maximum	2·73 – 5·39		5·23 – 6·10		6·03 – 9·34		
Weight change (kg)							
Model 1†	2·26	0·15	2·05	0·14	2·07	0·14	0·36
Model 2‡	2·44	0·23	2·20	0·23	2·20	0·23	0·27
Waist-circumference change (cm)							
Model 1†	1·75	0·26	1·55	0·24	1·72	0·24	0·93
Model 2‡	2·43	0·39	2·25	0·38	2·26	0·38	0·61
Model 3§	2·18	0·33	2·22	0·32	2·22	0·32	0·91
Hip-circumference change (cm)							
Model 1†	−0·24	0·22	−0·70	0·21	−0·51	0·20	0·37
Model 2‡	−0·79	0·34	−1·29	0·33	−1·05	0·32	0·39
Model 3§	−0·89	0·26	−1·24	0·26	−1·26	0·25	0·11
Waist:hip ratio change							
Model 1†	0·019	0·003	0·020	0·003	0·022	0·003	0·42
Model 2‡	0·039	0·004	0·042	0·004	0·042	0·004	0·47
Model 3§	0·038	0·004	0·041	0·004	0·042	0·004	0·35
In subjects with BMI ≥ 25 kg/m^2 (*n* 881)							
Baseline ED (kJ/g)							
Median	4·84		5·69		6·57		
Mininum-maximum	3·07 – 5·39		5·24 – 6·10		6·03 – 8·92		
Weight change (kg)							
Model 1†	1·98	0·27	1·96	0·30	2·94	0·32	0·02
Model 2‡	1·45	0·43	1·41	0·44	2·41	0·45	0·03
Waist-circumference change (cm)							
Model 1†	1·50	0·35	0·66	0·40	2·44	0·42	0·09
Model 2‡	1·08	0·55	0·39	0·56	2·15	0·57	0·05
Model 3§	1·67	0·44	1·02	0·45	2·00	0·46	0·45
Hip-circumference change (cm)							
Model 1†	−0·56	0·29	−0·54	0·33	0·43	0·36	0·03
Model 2†	−0·33	0·48	−0·27	0·49	0·65	0·50	0·04
Model 3§	0·31	0·38	0·38	0·39	0·72	0·40	0·30
Waist:hip ratio change							
Model 1†	0·018	0·003	0·010	0·004	0·019	0·004	0·86
Model 2‡	0·007	0·005	0·002	0·005	0·011	0·005	0·51
Model 3§	0·009	0·005	0·004	0·005	0·010	0·005	0·84

ED calculation was based on food intake only (beverages were excluded).
† Model 1: adjusted for age and sex.
‡ Model 2: adjusted for age, sex, educational level, physical activity and tobacco-status changes, baseline value of the outcome and baseline energy.
§ Model 3: model 2 + weight change.

observed when the ED calculation was based on both foods and energetic drinks (instead of foods only): the relationship between baseline ED and weight gain was close to significance (from 1·37 (SED 0·43) in the first tertile to 2·11 (SED 0·45) in the third tertile, P for trend = 0·09). However, no association between ED and weight gain was found when ED was calculated using all foods and drinks consumed (P for trend = 0·56). Whatever ED definition used, baseline ED was no longer associated with body fat distribution indicators after adjustment for weight change. When further adjustment on percentages of carbohydrate, fat, protein or water in the food was performed in the multivariate regressions, the relationship between baseline ED tertiles and weight gain became NS only when adding the percentage of fat (P for trend became 0·06) or the percentage of water in the food (P for trend became 0·12).

Adjusted means with their standard errors for each anthropometric change according to tertiles of ED 6-year changes, when the ED calculation was based on foods only, are presented in Table 3. No relationship between weight and ED variations was observed in normal-weight subjects, while weight gain increased with increasing dietary ED over 6 years in subjects with a baseline BMI $\geq 25\,kg/m^2$ (P for trend = 0·0008). The relationship between ΔED and weight gain was also significant when the ED calculation was based on food and energetic drink intakes (from 1·52 (SED 0·72) in the first tertile to 3·22 (SED 0·72) in the third tertile, P for trend = 0·02) or on all foods and drinks (from 1·09 (SED 0·71) in the first tertile to 2·61 (SED 0·74) in the third tertile, P for trend = 0·04). In agreement with the results obtained with baseline ED status, the results from longitudinal analysis showed that the change in dietary ED was not

Table 3. Crude or adjusted anthropometric changes according to 6-year variation in energy density (ED) tertiles, France, 1995–2001*
(Means with their standard errors)

	ED tertiles						
	T1		T2		T3		
	Mean	SEM	Mean	SEM	Mean	SEM	*P* for trend
In subjects with BMI < 25 kg/m² (*n* 832)							
ΔED (kJ/g)							
Median	−1·08		−0·34		0·53		
Minimum-Maximum	−2·73 − 0·59		−0·69 − 0·10		0·05 − 4·62		
Weight change (kg)							
Model 1†	2·27	0·19	2·02	0·19	1·90	0·19	0·18
Model 2‡	2·75	0·33	2·49	0·31	2·33	0·31	0·16
Waist-circumference change (cm)							
Model 1†	1·68	0·35	1·44	0·35	1·35	0·35	0·50
Model 2‡	2·86	0·58	2·26	0·54	2·15	0·55	0·19
Model 3§	2·31	0·49	1·94	0·46	2·01	0·46	0·50
Hip-circumference change (cm)							
Model 1†	−0·19	0·29	−0·50	0·29	−0·52	0·29	0·41
Model 2‡	−0·45	0·49	−0·69	0·46	−0·79	0·46	0·45
Model 3§	−0·93	0·40	−0·93	0·37	−0·88	0·38	0·89
Waist:hip ratio change							
Model 1†	0·018	0·004	0·018	0·004	0·018	0·004	0·95
Model 2‡	0·042	0·006	0·033	0·005	0·034	0·005	0·14
Model 3§	0·039	0·006	0·031	0·005	0·033	0·005	0·23
In subjects with BMI ≥ 25 kg/m² (*n* 316)							
ΔED (kJ/g)							
Median	−1·08		−0·30		0·46		
Minimum-maximum	−3·12 − 0·59		−0·63 − 0·10		0·05 − 2·29		
Weight change (kg)							
Model 1†	1·11	0·47	1·09	0·47	2·66	0·47	0·02
Model 2‡	1·14	0·72	1·76	0·70	3·54	0·73	0·0008
Waist-circumference change (cm)							
Model 1†	0·10	0·67	0·89	0·68	1·57	0·67	0·11
Model 2‡	0·30	0·99	1·51	0·97	2·62	1·01	0·02
Model 3§	0·77	0·81	1·48	0·79	1·16	0·83	0·63
Hip-circumference change (cm)							
Model 1†	−1·23	0·48	−0·52	0·49	−0·12	0·49	0·09
Model 2‡	−1·09	0·76	−0·02	0·74	0·50	0·77	0·03
Model 3§	−0·45	0·60	0·29	0·57	−0·29	0·60	0·80
Waist:hip ratio change							
Model 1†	0·010	0·006	0·012	0·006	0·013	0·006	0·72
Model 2‡	0·003	0·008	0·002	0·008	0·002	0·008	0·22
Model 3§	0·004	0·008	0·002	0·008	0·008	0·008	0·56

ED calculation was based on food intake only (beverages were excluded).
† Model 1: adjusted for age and sex.
‡ Model 2: adjusted for age, sex, educational level, physical activity and tobacco-status changes, baseline value of the outcome and baseline ED.
§ Model 3: model 2 + weight change.

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related to any body fat distribution indicator after controlling for body-weight change.

Discussion

In the present study, we showed that in the middle-aged subjects, the relationship between dietary ED and anthropometric changes differed according to baseline weight status. Both baseline dietary ED level and variation in dietary ED during the follow-up were related to an increased 6-year weight gain only in overweight subjects. The positive associations between ED and the changes in WC or HC were also found in overweight subjects, but these relationships were no longer significant after controlling for weight change.

Most previous epidemiological studies investigating the relationship between dietary ED and body weight had cross-sectional design and have found controversial results[10,13–20]. A recent cross-sectional study using the data from a multiethnic population-based cohort study found that ED was consistently associated with overweight status in both sexes, but the increased risk of being overweight associated with a 1 kJ/g in ED varied from 4 to 34 % according to ethnic groups[14]. Few prospective study have examined the association between ED and weight change in free-living subjects[21–23]. ED was positively associated with weight change in two studies performed in American women, which did not report any interaction according to baseline weight status[21,22]. However, in 1762 Danish subjects aged 30–60 years, Iqbal *et al.*[23] found a positive association between ED and subsequent 5-year weight gain among obese women and a negative association among normal-weight women. No significant relationship was observed in men. There are several methodological reasons for the discrepancies with the present results. First, dietary data were collected using two different methods: a single 7-d food record at baseline was used in the Danish study, whereas the present analyses were based on the average intakes of at least three 24-h dietary records. Moreover, Iqbal *et al.* analyses are not adjusted for total EI at baseline and are performed with ED including water. We have performed the present analyses using three different methods of ED calculation. When ED was calculated using all foods and drinks, the results were quite different (NS) from the results found using the two other ED definitions. A recent report using data from the Third National Health and Nutrition Examination Survey (NHANES III) showed a positive association with BMI when ED was defined as the energy content of foods with and without energy-yielding beverages, but no significant relationship with BMI was observed when non-energetic beverages were also taken into account in the ED calculation[15], which is in agreement with the present results. It is well known that the method of ED determination may influence the results[34]. When ED is calculated based on all foods and drinks, water is the major contributor to the ED calculation and may disproportionately influence the dietary ED values. As shown by Rolls *et al.*[35], consuming foods with a high water content was found to be a more effective strategy to reduce EI than drinking water with foods. Therefore, ED that includes all beverages may not be a relevant exposure.

Little is known concerning the contribution of food composition (macronutrient and water) in the relationship between ED and weight change[36–38]. In the present dataset, ED was positively associated with the percentage of fat in EI and negatively associated with both the percentage of protein in EI and the percentage of water in the food consumed (all drinks excluded). These results suggest that both macronutrient content and water in food could intervene in the relationship between ED and weight gain. The present results suggest that fat and water in food are the two main determinants involved in the relationship observed between ED and weight gain. However, a 1 kg-increased weight gain in subjects of the third ED tertile was still observed after adjusting for both the percentages of fat and water in food, indicating that other food components such as fibre content and other mechanisms, such as increased satiety sensation with increased portion size, could also intervene in the relationship.

The results from several intervention studies support the potential beneficial effect of low-ED diets in weight maintenance. Among the seventy-four subjects who participated in a diet programme promoting low-ED and high-complex carbohydrate foods, those who maintained their weight (weight gain $<5\,\%$) after a mean 2·2 years after the end of the programme had a significantly lower ED than weight gainers[39]. Rolls *et al.* tested the effect on weight loss of a diet incorporating one or two servings per day of foods equivalent in energy but with various ED. After 1 year of the follow-up, overweight subjects consuming two servings of high-energy-dense snack foods had a significantly lower weight loss than subjects consuming two servings of low-energy-dense soup or subjects with no special foods added[40]. Ello-Martin *et al.*[41] reported similar results in obese women in a recently published randomised trial: women who reduced fat intake and increased consumption of water-rich foods (particularly fruits and vegetables) had a significantly higher weight loss compared with women who reduced only fat intake. In a 6-month study testing the effect of three behavioural interventions on weight loss in pre-hypertensive and hypertensive subjects, Ledikwe *et al.*[42] found that participants in the highest tertile of ED reduction lost more weight than those in the lowest tertile. In the present study, variation in ED over 6 years was significantly associated with weight gain during the same period, indicating that the positive effect of low ED on weight maintenance observed in the intervention study could also be observed in free-living subjects.

To our knowledge, the relationships between the ED and body fat distribution changes have been evaluated by only two interventional studies[41,42] and no observational study. No differences of changes in fat body mass, lean body mass or WC were found between an intervention group who received advices aiming at decreasing fat intake, and another intervention group who received advices aiming at both decreasing fat intake and increasing fruit and vegetable intakes[41]. However, in another intervention study testing the effects of three different dietary interventions, the WC reduction was more important in subjects with higher ED reduction[42]. In agreement with this result, we showed that WC gain decreased when ED at baseline, or change of ED during the follow-up, increased. However, these studies did not adjust their models for global weight change. The WC reduction may simply be due to the global weight reduction observed in subjects who decreased ED the most. The present study gives a first highlight, indicating that ED could have an effect on global weight change but not specifically on

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abdominal fat change. Further studies are needed in order to investigate these relationships thoroughly.

Several factors may confound the relationship between ED and weight. Energy-dilute foods tend to be more satiating but less palatable, whereas energy-dense foods are palatable but not satiating[4], resulting in an increase in EI. However, in agreement with several other studies, we showed that the positive association between ED and weight remained significant after additional adjustment for EI[14,15]. Furthermore, the differences in the PA level between populations may explain the inconsistent results between observational studies, as well as the deleterious effect of ED observed in overweight people only. In the present sample, overweight subjects had a lower PA level than normal-weight subjects at baseline. In a trial designed to test the relative effect of inactivity and ED on energy balance, nine healthy men were divided into four intervention groups according to the per cent energy of fat from their diets and their level of PA[43]. When a sedentary behaviour or a high-fat diet was imposed separately, they both caused a positive imbalance. However, when both sedentary behaviour and high-fat diet were imposed together, the effect on energy balance appeared to be more than additive. A second intervention study performed in rats by Burneiko *et al.* [44] found that the deleterious effect of a hyperenergetic diet on weight and serum lipid levels (TAG, cholesterol, VLDL and HDL) was less strong in physically active rats compared with physically inactive rats. These results illustrate that PA could modify the effect of diet on metabolism. A possible mechanism explaining this interaction is that neuroendocrine systems involved in appetite control require a certain turnover of substrates in order to be able to detect errors in balance with sufficient precision[9]. This would lead to the creation of some threshold of PA below which appetite control would be ineffective. The present results support this hypothesis. When multivariate models were performed only in subjects without PA modifications during the follow-up, weight gain was positively associated with ED tertiles only in the most inactive subjects (n 350, P for trend = 0·06). No significant relationship was found in subjects with regular low or high PA throughout the follow-up (n 222 and 563, P for trend = 0·77 and 0·13, respectively). This could explain the lack of relationship between ED and weight gain in normal-weight subjects who are more physically active and therefore likely to be able to manage energy-dense diet more easily than overweight subjects.

Some potential limitations of the present study should be mentioned. First, subjects included in the present study were participants of a nutritional intervention study. In addition, we selected the most compliant subjects who completed at least three dietary records at baseline for baseline ED status analyses and those who completed at least three dietary records both at baseline and at the end of the follow-up for longitudinal analyses. Thus, the present sample may have a healthier lifestyle than the general population. Unfortunately, we have no information about the intentionality of weight change. However, since pre-existing illness may lead to unintentional weight loss and changes in dietary habits, we excluded all subjects with medical conditions (cancers, CVD, etc.) that may result in an involuntary weight change to avoid such potential confounding biases[45–47]. Strengths of the present study include the large number of subjects and its longitudinal design. In addition, the present study was based on measured anthropometric data and ED was estimated with several 24-h dietary records. Baseline ED status was estimated from more than five 24-h dietary records for 48 % of the subjects. For the restricted sample of longitudinal analyses, baseline and end of the follow-up ED status were estimated from more than five 24-h dietary records for 58 and 42 % of the subjects, respectively. Finally, available longitudinal data on PA and tobacco consumption allowed us to assess the relationship of ED with anthropometric changes taking into account tobacco and PA modifications during the follow-up.

In summary, in the present prospective study in middle-aged French men and women, both higher baseline ED status and higher ΔED were associated with higher 6-year weight gain only in overweight subjects. Moreover, the relationship between ED and weight gain could be mediated by PA, as the diet effect on weight change seems stronger in inactive subjects. The present results provide additional evidence of a deleterious effect of both high-energy-dense diets and physical inactivity on body weight in middle-aged subjects. Further research needs to be performed to determine the relative effects of ED reduction and PA improvement to prevent weight gain. Lower-income subjects are of particular concern because they have a higher risk of overweight while consuming more energy-dense foods[5–7].

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