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Evaluation of under- and overreporting of energy intake in the 24-hour diet recalls in the European Prospective Investigation into Cancer and Nutrition (EPIC)

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Abstract

Objective: To evaluate under- and overreporting and their determinants in the EPIC 24-hour diet recall (24-HDR) measurements collected in the European Prospective Investigation into Cancer and Nutrition (EPIC).

Design: Cross-sectional analysis. 24-HDR measurements were obtained by means of a standardised computerised interview program (EPIC-SOFT). The ratio of reported energy intake (EI) to estimated basal metabolic rate (BMR) was used to ascertain the magnitude, impact and determinants of misreporting. Goldberg's cut-off points were used to identify participants with physiologically extreme low or high energy intake. At the aggregate level the value of 1.55 for physical activity level (PAL) was chosen as reference. At the individual level we used multivariate statistical techniques to identify factors that could explain EI/BMR variability. Analyses were performed by adjusting for weight, height, age at recall, special diet, smoking status, day of recall (weekday vs. weekend day) and physical activity.

Setting: Twenty-seven redefined centres in the 10 countries participating in the EPIC project.

Subjects: In total, 35 955 men and women, aged 35–74 years, participating in the nested EPIC calibration sub-studies.

Results: While overreporting has only a minor impact, the percentage of subjects identified as extreme underreporters was 13.8% and 10.3% in women and men, respectively. Mean EI/BMR values in men and women were 1.44 and 1.36 including all subjects, and 1.50 and 1.44 after exclusion of misreporters. After exclusion of misreporters, adjusted EI/BMR means were consistently less than 10% different from the expected value of 1.55 for PAL (except for women in Greece and in the UK), with overall differences equal to 4.0% and 7.4% for men and women, respectively. We modelled the probability of being an underreporter in association with several individual characteristics. After adjustment for age, height, special diet, smoking status, day of recall and physical activity at work, logistic regression analyses resulted in an odds ratio (OR) of being an underreporter for the highest vs. the lowest quartile of body mass index (BMI) of 3.52 (95% confidence interval (CI) 2.91–4.26) in men and 4.80 (95% CI 4.11–5.61) in women, indicating that overweight subjects are significantly more likely to underestimate energy intake than subjects in the bottom BMI category. Older people

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were less likely to underestimate energy intake: ORs were 0.58 (95% CI 0.45–0.77) and 0.74 (95% CI 0.63–0.88) for age (≥65 years vs. <50 years). Special diet and day of the week showed strong effects.

Conclusion: EI tends to be underestimated in the vast majority of the EPIC centres, although to varying degrees; at the aggregate level most centres were below the expected reference value of 1.55. Underreporting seems to be more prevalent among women than men in the EPIC calibration sample. The hypothesis that BMI (or weight) and age are causally related to underreporting seems to be confirmed in the present work. This introduces further complexity in the within-group (centre or country) and between-group calibration of dietary questionnaire measurements to deattenuate the diet–disease relationship.

Keywords
EPIC
Calibration
24-Hour dietary recall
Underreporting
Measurement errors
Body mass index

In epidemiological studies aimed at investigating the relationship between diet and diseases of interest, the measures of association may be attenuated due to measurement error when estimating individual exposure. One way to overcome this loss of power is, among others, to increase the heterogeneity of the dietary exposure, thus reducing the impact of measurement error. In epidemiological studies this can be achieved by considering populations with very different dietary habits. This was the rationale for setting up the European Prospective Investigation into Cancer and Nutrition (EPIC)[1], a multi-centre cohort study on diet and cancer conducted in 23 administrative centres in 10 European countries. This study design allows the diet–cancer relationship to be investigated at the individual level, within each of the separate cohorts, and at the ecological level, through the comparison of cancer incidence and dietary habits among cohorts.

In EPIC, individual habitual dietary intake was assessed by means of different validated questionnaires developed and administered independently in each country[2]. Different methods were chosen because the cohorts started and developed separately. Moreover, it was difficult to use the same dietary assessment instrument to capture the large heterogeneity in dietary patterns existing across centres. Semi-quantitative food-frequency questionnaires, modified dietary history questionnaires or combined methods[2] were used to assess usual dietary intakes. Dietary assessment methods are, however, very likely to be affected by random and systematic within-person measurement errors which, in addition, may vary in magnitude and direction depending on the dietary method used[3]. Statistical methods have therefore been proposed to take into account the impact of measurement errors and obtain correct estimates of dietary exposure and cancer incidence associations.

Rosner *et al.*[4] proposed a calibration method to correct for random and systematic error in baseline dietary assessment measurements using a more accurate method as reference (so-called 'reference measurement'). The statistical method requires that, on a sub-sample of the study participants, a second dietary reference measurement is taken in order to estimate the attenuation coefficient, the parameter that will adjust the observed (naïve) diet–cancer relationship. Within the EPIC study framework it was decided to use 24-hour dietary recalls (24–HDRs) to provide reference measurements. A single 24-HDR was collected from a sample of 36 900 participants from the entire EPIC cohort in order to express individual dietary intakes according to the same reference scale and to adjust observed diet–disease associations for attenuation.

The calibration approach requires first that the 24-HDR measurements provide unbiased estimates at the population level. This statistical requirement is, however, difficult to satisfy in practice. Indeed, it has been extensively recognised that all self-reported dietary intakes contain measurement errors[5,6]. However, if the direction and magnitude of systematic dietary measurement errors are approximately constant across study populations, the reference method can be used for within- and between-cohort calibration. The questionnaires are therefore calibrated against a dietary method with only a relative validity, but which is comparable across study populations[7]. In order to satisfy this objective, the 24-HDR interview procedure was highly standardised across EPIC centres, using an *ad hoc* computerised program (EPIC-SOFT)[8].

In the present paper we set out first to evaluate under- and overreporting in 24-HDRs and to provide a comparison of their magnitude across the EPIC centres, in order to gain a better insight into the effect of standardisation of the 24-hour diet recall measurement across study populations. In the absence of perfect reference measurements such as urinary nitrogen or doubly labelled water measurements[9], which are too expensive to use in large epidemiological studies, we used the computed ratio of total energy intake to predicted basal metabolic rate (EI/BMR), as proposed by Goldberg *et al.*[10] and Black[11], as an empirical approach to evaluate the (relative) validity of reported total energy intakes. Furthermore, we investigated the relationship between extreme under- and overreporting observed in the 24-HDRs and their potentially associated factors, using the specific EI/BMR cut-off proposed by Goldberg *et al.*[10].

Another important statistical requirement for calibrating dietary measurements is that the correlation between 24-HDR and dietary questionnaire (DQ) errors be independent. However, this issue is beyond the scope of the present work and will not be addressed in this paper.

Material and methods

The EPIC study population includes over 500 000 participants from 10 countries who completed a baseline dietary and other lifestyle questionnaires[2]. The study participants were either population-based (Bilthoven in The Netherlands, Greece, Spain, Germany, Sweden, Denmark, Norway, Italy, Cambridge and a small part of the Oxford cohort from the UK), participants in breast cancer screening (Utrecht in The Netherlands, Florence in Italy), or teachers and school workers in France. In Oxford, most of the cohort was recruited among subjects with an interest in health and/or vegetarian eating habits. Blood donors were also recruited in different proportions in certain Italian and Spanish centres. In France, Norway, Utrecht (The Netherlands) and Naples (Italy) only women were recruited.

A sub-sample of 36 900 participants gave a single 24-hour dietary recall interview to use as the reference calibration method. The calibration sample was randomly chosen from each cohort, weighted according to the cumulative number of cancer cases expected over 10 years of follow-up by gender and 5-year age strata. Around 4000 24-HDRs were recommended per country, according to calculations detailed elsewhere[12], in order to provide a large sample from each participating cohort. The initial 23 EPIC co-ordinating centres were redefined in France, the UK and Norway. In the UK, the 'health-conscious' group and the subjects recruited from the general population both in Cambridge and Oxford (general population group) were considered separately. In France and Norway, where the study participants were scattered all over the country, the groups were sub-divided into, respectively, four and two geographical regions. Finally 27 centres were considered in the present analysis. Details of the EPIC calibration study design, sampling procedures and population characteristics are described elsewhere in this supplement[13]. The sampling procedures were designed in order to obtain a homogeneous distribution by season and day of interview to control for possible day-to-day and seasonal variations in dietary intakes. A single 24-HDR was collected from a stratified random sample using an *ad hoc* software (EPIC-SOFT), specifically designed to standardise dietary measurements and control the overall interview procedures across heterogeneous study populations[8]. In the absence of a standardised European nutrient database, which is still being developed[14], country-specific food composition tables were used to calculate nutrient intakes. A recent review of the national food composition tables available in countries participating in EPIC[15] suggested that energy measurements are reasonably comparable between countries.

In order to evaluate the (relative) 'validity' and to assess comparability of dietary measurements among EPIC cohorts in the 24-HDR data, we focused on self-reported energy intake values. A fundamental physiological principle of energy metabolism is that energy intake equals energy expenditure if body weight is stable. Recent sophisticated (and expensive) techniques to estimate energy expenditure, such as doubly labelled water, would have made it possible to validate reported energy intake. However, this method is too costly to be applied routinely in epidemiological studies, and alternative ways to evaluate reported energy intake are necessary. The ratio of energy intake (EI) over estimated basal metabolic rate (BMR), taking age, sex, weight and height into account, can be used as an internal validation of reported energy intake[16]. Energy expenditure (EE) over BMR is also known as physical activity level (PAL). The (relative) validity of reported energy intake was assessed by assuming the fundamental equation EI = EE. The reported EI may be expressed as EI/BMR and compared with a reference PAL in a given population. The confidence limits of agreement between EI/BMR and PAL can be determined by considering physiological variations in both BMR and PAL, daily variations in energy intake and the number of repeated measurements per individual. Goldberg *et al.*[10] and more recently Black[11] constructed tables for lower and upper limits of EI/BMR values based on Food and Agriculture Organization/World Health Organization energy requirement estimates and energy expenditures from studies using doubly labelled water measurements[6]. The limits were calculated assuming that the value of PAL equals 1.55. These limits represent the values below or above which it is statistically unlikely that the reported intake represents habitual intake or a low or high intake obtained by chance. Using the EI/BMR cut-off points proposed by Goldberg and Black[10,11] on the basis of intra-individual variations, it is possible to determine whether the mean reported energy intake is a plausible measure at the aggregate (i.e. population) level, and to identify, at the individual level, study participants out of range of physiologically plausible energy intake values. The choice of 1.55 for PAL is motivated by the fact that the EPIC calibration sample was mainly composed of middle-aged study participants[13] with overall moderate physical activity[17]. To calculate the limits of acceptance for EI/BMR, we considered 23% of within-subject variation for energy, 15% of between-subject variation for PAL and 8.5% of within-subject variation for estimated BMR, according to the recent work by Black[11]. Limits were computed according to a 95% confidence interval (CI).

For an evaluation of EI/BMR at the aggregate level, according to the formula in Goldberg *et al.*'s paper[10], it was possible to identify the lower confidence limit, given the number of days of diet assessment and the sample size in the different EPIC centres. Centre- and gender- specific lower limits were therefore considered. Since analyses at the individual level suggested that overreporting was marginal in the EPIC 24-HDR, evaluation of misreporting at the aggregate level focused only on underreporting. As pointed out by Black[11], at the aggregate level, with one dietary measurement per individual and when the sample size (n) is greater than 100, as is the case in the EPIC centres, the number of subjects does not alter Goldberg's cut-off substantially (i.e. it is of little importance to determine the ability to detect bias in the mean intake).

At the individual level ($n = 1$), the intra-individual variability values used in the formula proposed by Goldberg resulted in lower and upper limits equal to 0.88 and 2.72, respectively. Participants with calculated values of EI/BMR lower than 0.88 were therefore considered 'extreme underreporters', and participants with values above 2.72 were considered 'extreme overreporters'. The empirical approach used at the individual level does not identify *all* under- or over-reporters but only those who, under different assumptions, should be considered as physiologically implausible.

Black[18] discusses extensively the sensitivity and the specificity of such limits to identify underreporters in a study population. We refer the reader to a later section of that paper for a more complete discussion about this.

Statistical analysis

Chi-square test statistics were used to test the homogeneity of distributions of mis-, under- and overreporting within countries and across centres. Centre- and country-specific crude and adjusted mean values were calculated for EI/BMR and energy intake before and after exclusion of subjects whose EI/BMR values were below 0.88 and above 2.72. A weighted analysis of covariance model was used to adjust for body mass index (BMI), height and age at recall (continuous variables), with weights calculated to take into account day of recall (weekday vs. weekend day) and physical activity (PA) at work (categorical variables). This procedure was used to relax the assumption of parallelism for adjusting factors across centres. These variables were chosen because they have been found to explain statistically EI/BMR and energy intake variability in the EPIC data.

Table 1 Sample size and percentage of misreporters (Mis-R), underreporters (Under-R) and overreporters (Over-R) in the European Prospective Investigation into Cancer and Nutrition (EPIC) 24-hour dietary recalls, among men and women

	Men				Women			
Country and centre	*n*	% Mis-R	% Under-R	% Over-R	*n*	% Mis-R	% Under-R	% Over-R
Greece	1312	21	20	1	1374	34	33	1
Spain	1777	8	5	3	1443	15	14	1
Granada	214	8	6	2	300	19	19	0
Murcia	243	11	7	4	304	19	18	1
Navarra	444	4	3	1	271	11	10	1
San Sebastian	490	9	4	5	244	9	7	2
Asturias	386	10	5	5	324	16	14	2
Italy	1444	9	7	2	2512	17	16	1
Ragusa	168	13	10	3	138	22	19	4
Naples	–	–	–	–	403	20	19	1
Florence	271	6	4	2	785	17	16	1
Turin	677	9	8	2	392	19	18	1
Varese	328	8	5	2	794	13	13	0
France	–	–	–	–	4639	8	7	2
South coast	–	–	–	–	612	7	6	1
South	–	–	–	–	1396	10	8	2
North-west	–	–	–	–	622	6	5	1
North-east	–	–	–	–	2009	8	6	2
Germany	2268	13	12	1	2150	16	15	1
Heidelberg	1033	16	14	2	1087	16	15	1
Potsdam	1235	11	10	1	1063	17	16	0
The Netherlands	1024	12	9	3	2960	14	13	1
Bilthoven	1024	12	9	3	1086	16	16	1
Utrecht	–	–	–	–	1874	13	12	1
United Kingdom	518	13	12	1	768	17	15	1
General population	404	12	11	1	571	18	17	1
'Health-conscious'	114	17	15	2	197	12	10	2
Denmark	1923	10	8	1	1995	15	13	2
Copenhagen	1356	10	9	1	1485	16	14	1
Aarhus	567	8	7	1	510	12	10	2
Sweden	2765	13	11	1	3285	15	14	1
Malmö	1421	15	14	1	1711	16	15	1
Umeå	1344	10	8	2	1574	14	13	1
Norway	–	–	–	–	1798	13	12	1
South & East	–	–	–	–	1136	13	12	1
North & West	–	–	–	–	662	13	11	2

Physical activity in the EPIC calibration sample was available through two independent variables: physical activity at work, where the type of work of study participants was categorised into four levels (not employed, sedentary, standing and manual/heavy manual work)[17], and a score reflecting activities during leisure time.

Apart from the UK 'health-conscious' group, special diet reflected long-term health problems related to diet (e.g. hyperlipidaemia, hypertension, diabetes, stomach or intestinal problems), particularly in Umeå and, to a lesser extent, Greece.

To explain EI/BMR variability between EPIC centres and to speculate on potential causality of any of the mentioned factors, multivariate statistical models were used to determine the principal sources of EI/BMR variability. Mean and standard deviations of relevant variables were computed by sex-specific quartiles of BMI and, subsequently, EI/BMR.

In addition, multivariate unconditional logistic regression analyses were performed to investigate the role of variables associated with underreporting, by creating a dichotomous outcome (1 = extreme underreporters, with EI/BMR < 0.88; 0 = participants with plausible values) used as the dependent variable in a regression model. Due to the marginal role of overreporting, the present analysis was restricted to underreporting. Age (five categories: <50, 50–55, 55–60, 60–65 and ≥ 65 years), height (continuous), weight (sex-specific quartiles), physical activity (at work and, separately, during leisure time), smoking status (three categories: non-smokers, ex-smokers and smokers), special diet and day of the week (weekday vs. weekend day, Friday within the latter) were included in the statistical models. Categorical variables were fitted by means of dummy indicators. Since energy intake is strongly associated with EI/BMR (partial linear correlation higher than 0.90), it was not included in the various models considered. Educational level and season of recall were not included in the final model because they were not found to be statistically associated to the outcome, in contrast to previous observations[19]. Models with BMI instead of weight were also fitted.

Since underreporting and the distribution of its potential determinants differ between men and women, gender-specific analyses were performed. Throughout the work, significance level equal to 95% was used. All statistical analyses were performed with SAS, version 8.2[20].

Results

The calibration sample has been described in detail

Table 2a Crude and adjusted ratio of energy intake to basal metabolic rate (EI/BMR) mean estimates for the total sample and after exclusion of misreporters (Mis-R): men

			Total				After exclusion				
			Crude		Adjusted*		Crude		Adjusted*		
Country and centre	*n*	Mis-R	Mean	SD	Mean	95% CI	Mean	SD	Mean	95% CI	Low limt†
Greece	1312	21	1.29	0.51	1.31	1.28–1.34	1.41	0.39	1.42	1.40–1.45	1.53
Spain	1777	8	1.62	0.53	1.64	1.61–1.66	1.61	0.42	1.63	1.61–1.65	1.53
Granada	214	8	1.55	0.50	1.60	1.54–1.67	1.56	0.38	1.58	1.53–1.64	1.49
Murcia	243	11	1.57	0.57	1.58	1.51–1.64	1.57	0.43	1.58	1.53–1.63	1.49
Navarra	444	4	1.57	0.44	1.57	1.53–1.62	1.58	0.39	1.58	1.54–1.62	1.51
San Sebastian	490	9	1.72	0.54	1.73	1.69–1.78	1.69	0.43	1.73	1.70–1.77	1.51
Asturias	386	10	1.63	0.58	1.64	1.60–1.69	1.60	0.44	1.61	1.57–1.65	1.51
Italy	1444	9	1.51	0.50	1.48	1.46–1.51	1.53	0.40	1.51	1.49–1.53	1.53
Ragusa	168	13	1.47	0.52	1.50	1.42–1.57	1.51	0.41	1.53	1.47–1.59	1.48
Florence	271	6	1.51	0.47	1.49	1.43–1.55	1.51	0.40	1.50	1.45–1.54	1.50
Turin	677	9	1.47	0.49	1.44	1.41–1.48	1.51	0.40	1.49	1.46–1.52	1.52
Varese	328	8	1.59	0.51	1.55	1.50–1.60	1.60	0.41	1.57	1.53–1.62	1.50
Germany	2268	13	1.39	0.48	1.44	1.42–1.46	1.46	0.37	1.50	1.48–1.51	1.53
Heidelberg	1033	16	1.38	0.50	1.44	1.41–1.47	1.45	0.37	1.50	1.47–1.52	1.52
Potsdam	1235	11	1.40	0.46	1.44	1.42–1.47	1.47	0.37	1.50	1.48–1.52	1.53
The Netherlands	1024	12	1.47	0.53	1.49	1.46–1.53	1.49	0.39	1.51	1.48–1.53	1.52
Bilthoven	1024	12	1.47	0.53	1.50	1.47–1.53	1.49	0.39	1.51	1.48–1.53	1.52
United Kingdom	518	13	1.37	0.43	1.34	1.30–1.38	1.44	0.34	1.41	1.37–1.45	1.51
General population	404	12	1.39	0.41	1.36	1.31–1.41	1.45	0.33	1.43	1.39–1.47	1.51
'Health-conscious'	114	17	1.33	0.47	1.28	1.19–1.37	1.40	0.37	1.34	1.26–1.42	1.47
Denmark	1923	10	1.47	0.48	1.48	1.46–1.51	1.51	0.40	1.52	1.50–1.54	1.53
Copenhagen	1356	10	1.45	0.48	1.47	1.44–1.50	1.50	0.40	1.51	1.48–1.53	1.53
Aarhus	567	8	1.50	0.46	1.52	1.48–1.56	1.54	0.40	1.55	1.52–1.59	1.51
Sweden	2765	13	1.42	0.49	1.38	1.37–1.40	1.48	0.39	1.45	1.43–1.47	1.53
Malmö	1421	15	1.37	0.48	1.34	1.31–1.36	1.45	0.38	1.42	1.40–1.45	1.53
Umeå	1344	10	1.47	0.50	1.43	1.41–1.46	1.50	0.39	1.47	1.45–1.49	1.53

SD – standard deviation; 95% CI – 95% confidence interval.
*Mean values were adjusted by body mass index, height, age at recall, day of recall (weekday vs. weekend day) and physical activity at work.
†Lower limit for evaluation of EI/BMR at the aggregate level, determined as a function of intra-individual variation and centre (country) sample size.

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elsewhere[13], and we list some important characteristics of the study participants in the Appendix. It can be seen that the frequency of special diets in the 24-HDR interviews was high, more so among women (ranging from 11% to 36%) than men (from 7% to 27%). In Table 1 we report the distribution of participants within the three categories of dietary reporting (extreme under-, normal and extreme overreporters) to characterise study subjects according to their reported energy intake.

Extreme underreporting at the individual level was higher in women than in men. The percentage of male participants below 0.88 was 10% overall, ranging from 3% in Navarra (Spain) to 20% in Greece. The percentage of overreporters ranged from 1% (Navarra, general population in the UK, Greece, Potsdam in Germany, Malmö in Sweden, Aarhus and Copenhagen in Denmark) to 5% (San Sebastian, Spain). The proportion of study participants identified as misreporters ranged from 4% (Navarra) to 21% (Greece). Underreporting was heterogeneous across centres only in Italy, Germany and Sweden. A similar picture was observed for misreporting in general.

Among women, underreporting ranged from 5% in North-west France to 33% in Greece, while most of the countries were between 13 and 16%, with an overall percentage of 14%. The percentage of overreporters in women ranged from 0.1% (Varese in Italy, Granada in Spain, Potsdam in Germany) to 4% (Ragusa in Italy). Country-specific analyses in women revealed that, across centres, the percentage of underreporters was statistically heterogeneous in all EPIC countries, except France, Germany and Norway. Overall, heterogeneous misreporting was also observed, except in Germany and Norway.

To evaluate underreporting at the population level, centre- and sex-specific EI/BMR means were calculated and are reported in Tables 2a and 2b. In men, EI/BMR means were above 1.55 only in Varese in Italy (1.59) and in

Table 2b Crude and adjusted ratio of energy intake to basal metabolic rate (EI/BMR) mean estimates for the total sample and after exclusion of misreporters (Mis-R): women

			Total				After exclusion				
			Crude		Adjusted*		Crude		Adjusted*		
Country and centre	*n*	Mis-R	Mean	SD	Mean	95% CI	Mean	SD	Mean	95% CI	Low limt†
Greece	1374	34	1.09	0.44	1.16	1.13–1.18	1.29	0.34	1.34	1.31–1.36	1.53
Spain	1443	15	1.37	0.49	1.41	1.39–1.43	1.45	0.40	1.49	1.46–1.51	1.53
Granada	300	19	1.24	0.42	1.31	1.26–1.36	1.35	0.35	1.41	1.37–1.46	1.50
Murcia	304	19	1.36	0.52	1.41	1.35–1.46	1.47	0.42	1.51	1.46–1.56	1.50
Navarra	271	11	1.38	0.44	1.40	1.35–1.46	1.44	0.37	1.47	1.43–1.52	1.50
San Sebastian	244	9	1.51	0.50	1.51	1.46–1.57	1.54	0.42	1.55	1.50–1.60	1.50
Asturias	324	16	1.38	0.52	1.42	1.37–1.47	1.44	0.41	1.48	1.44–1.53	1.50
Italy	2512	17	1.33	0.47	1.34	1.32–1.36	1.43	0.37	1.42	1.40–1.44	1.53
Ragusa	138	22	1.34	0.54	1.36	1.29–1.44	1.41	0.37	1.42	1.35–1.50	1.48
Naples	403	20	1.30	0.48	1.38	1.34–1.43	1.43	0.38	1.45	1.41–1.49	1.51
Florence	785	17	1.34	0.48	1.33	1.30–1.36	1.43	0.36	1.42	1.40–1.45	1.52
Turin	392	19	1.31	0.47	1.33	1.28–1.37	1.43	0.38	1.44	1.40–1.48	1.51
Varese	794	13	1.34	0.43	1.33	1.30–1.37	1.42	0.37	1.40	1.37–1.43	1.52
France	4639	8	1.48	0.47	1.42	1.41–1.43	1.50	0.38	1.47	1.46–1.48	1.54
South coast	612	7	1.44	0.47	1.36	1.32–1.39	1.47	0.39	1.42	1.39–1.45	1.52
South	1396	10	1.48	0.49	1.43	1.40–1.45	1.51	0.39	1.47	1.45–1.49	1.53
North-west	622	6	1.47	0.41	1.40	1.37–1.44	1.49	0.37	1.46	1.43–1.49	1.52
North-east	2009	8	1.49	0.48	1.44	1.42–1.46	1.51	0.38	1.48	1.47–1.50	1.53
Germany	2150	16	1.31	0.45	1.35	1.33–1.37	1.41	0.36	1.44	1.42–1.46	1.53
Heidelberg	1087	16	1.34	0.47	1.36	1.33–1.38	1.43	0.37	1.45	1.42–1.47	1.52
Potsdam	1063	17	1.28	0.44	1.35	1.32–1.38	1.38	0.36	1.43	1.41–1.46	1.52
The Netherlands	2960	14	1.38	0.47	1.39	1.38–1.41	1.46	0.37	1.48	1.46–1.49	1.53
Bilthoven	1086	16	1.37	0.49	1.37	1.35–1.40	1.47	0.39	1.47	1.45–1.50	1.52
Utrecht	1874	13	1.38	0.45	1.41	1.38–1.43	1.46	0.37	1.48	1.46–1.50	1.53
United Kingdom	768	17	1.29	0.45	1.28	1.25–1.31	1.37	0.34	1.36	1.33–1.39	1.52
General population	571	18	1.26	0.42	1.27	1.23–1.30	1.36	0.34	1.35	1.32–1.38	1.51
'Health-conscious'	197	12	1.38	0.50	1.33	1.27–1.39	1.40	0.35	1.39	1.33–1.44	1.49
Denmark	1995	15	1.38	0.50	1.39	1.37–1.41	1.45	0.39	1.44	1.42–1.46	1.53
Copenhagen	1485	16	1.35	0.48	1.35	1.33–1.37	1.43	0.38	1.42	1.40–1.44	1.53
Aarhus	510	12	1.49	0.54	1.51	1.47–1.55	1.52	0.40	1.52	1.49–1.56	1.51
Sweden	3285	15	1.33	0.46	1.33	1.32–1.35	1.42	0.37	1.42	1.40–1.43	1.53
Malmö	1711	16	1.30	0.45	1.31	1.29–1.34	1.40	0.36	1.40	1.38–1.42	1.53
Umeå	1574	14	1.36	0.46	1.35	1.33–1.37	1.44	0.37	1.44	1.42–1.45	1.53
Norway	1798	13	1.39	0.47	1.36	1.32–1.40	1.46	0.38	1.44	1.42–1.47	1.53
South & East	1136	13	1.39	0.47	1.35	1.31–1.39	1.47	0.38	1.45	1.43–1.47	1.52
North & West	662	13	1.40	0.47	1.37	1.33–1.41	1.45	0.38	1.44	1.41–1.47	1.52

SD – standard deviation; 95% CI – 95% confidence interval.
* Mean values were adjusted by body mass index, height, age at recall, day of recall (weekday vs. weekend day) and physical activity at work.
† Lower limit for evaluation of EI/BMR at the aggregate level, determined as a function of intra-individual variation and centre (country) sample size.

all Spanish centres. However, after exclusion of under- and overreporters at the individual level and adjustment for BMI, height, age at recall, day of recall and physical activity at work, mean values were within acceptable limits also in the Italian centres of Florence (1.50) and Ragusa (1.53). The exclusion of extreme reporters was particularly effective. The crude mean and the mean computed after exclusion were appreciably different in Greece (1.29 vs. 1.41), the UK general population (1.39 vs. 1.45), the UK 'health-conscious' (1.33 vs. 1.40), Heidelberg in Germany (1.38 vs. 1.45), Potsdam in Germany (1.40 vs. 1.47) and Malmö in Sweden (1.37 vs. 1.45). In some centres the adjustment strengthened the tendency to increase mean values while in other situations the effect was the opposite. Overall, exclusion seemed to be more effective than adjustment.

Among women, crude EI/BMR means were always under the expected value of 1.55. By taking the lower limit computed at the population level, San Sebastian in Spain (1.51) was within the acceptable value. Exclusion of under- and overreporters and adjustment brought mean values within the centre-specific lower limits of the expected values of 1.55 only in Murcia in Spain (1.51) and Aarhus in Denmark (1.52). Similarly to men, exclusion had a stronger impact on mean values than adjustment, which is not surprising since the percentage of extreme reporters was higher among women than men. Crude means computed after exclusion of misreporters were higher than the means computed on all subjects. The difference was particularly evident in Turin in Italy (1.31 vs. 1.43), Naples in Italy (1.30 vs. 1.43), Granada in Spain (1.24 vs. 1.35), the UK general population (1.26 vs. 1.36), Greece (1.09 vs. 1.29), Heidelberg in Germany (1.34 vs. 1.43) and Potsdam in Germany (1.28 vs. 1.38).

Mean energy intake values are reported in Tables 3a and 3b. Among men, reported energy was relatively low in Greece (mean 2122 kcal day^{-1}) and in the 'health-conscious' population in the UK (2252 kcal day^{-1}). Substantially higher values were observed in Italy (2614 kcal day^{-1}), The Netherlands (2726 kcal day^{-1}), Denmark (2645 kcal day^{-1}) and Spain (2814 kcal day^{-1}). Among women, low values were observed in Greece (1515 kcal day^{-1}), whereas in Denmark (1941 kcal day^{-1}), The Netherlands (1944 kcal day^{-1}), Norway (1951 kcal day^{-1}) and France (1961 kcal day^{-1}), mean values were higher.

Generally, energy intake values across centres were homogeneous within countries among men and women. Statistically significant differences between adjusted energy intake means, after exclusion, were observed among men within Spain – San Sebastian (2990 kcal day^{-1}) vs. Granada (2732 kcal day^{-1}) – and

Table 3a Crude and adjusted energy intake (kcal) mean estimates for the total sample and after *exclusion of misreporters: men*

		Total				After exclusion			
		Crude		Adjusted*		Crude		Adjusted*	
Country and centre	*n*	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Greece	1312	2122	831	2280	871	2313	680	2471	697
Spain	1777	2814	921	2846	879	2799	755	2834	703
Granada	214	2638	817	2760	852	2663	631	2732	682
Murcia	243	2677	978	2765	851	2675	744	2774	673
Navarra	444	2706	796	2745	857	2719	714	2751	683
San Sebastian	490	3077	961	2998	852	3032	778	2990	673
Asturias	386	2788	953	2862	853	2752	784	2821	687
Italy	1444	2614	847	2618	857	2652	703	2670	688
Ragusa	168	2561	886	2628	846	2618	677	2677	675
Florence	271	2660	846	2645	843	2657	752	2656	677
Turin	677	2563	828	2553	848	2621	690	2629	681
Varese	328	2705	861	2729	844	2726	698	2764	678
Germany	2268	2485	834	2524	854	2600	665	2619	682
Heidelberg	1033	2477	889	2511	852	2605	679	2606	681
Potsdam	1235	2492	786	2537	844	2596	653	2630	674
The Netherlands	1024	2726	966	2622	866	2771	731	2638	695
Bilthoven	1024	2726	966	2626	864	2771	731	2640	694
United Kingdom	518	2368	719	2331	845	2481	596	2456	682
General population	404	2400	715	2379	841	2507	594	2502	678
'Health-conscious'	114	2252	725	2167	841	2382	595	2286	677
Denmark	1923	2645	833	2631	860	2720	708	2693	690
Copenhagen	1356	2609	833	2601	856	2690	707	2669	687
Aarhus	567	2729	827	2703	849	2791	706	2752	681
Sweden	2765	2412	812	2419	890	2508	658	2530	714
Malmö	1421	2310	787	2359	878	2442	647	2511	705
Umeå	1344	2520	824	2478	856	2573	662	2548	687

SD – standard deviation.
* Mean values were adjusted by body mass index, height, age at recall, day of recall (weekday vs. weekend day) and physical activity at work.

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Table 3b Crude and adjusted energy intake (kcal) mean estimates for the total sample and after exclusion of misreporters: women

		Total				After exclusion			
		Crude		Adjusted*		Crude		Adjusted*	
Country and centre	*n*	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Greece	1374	1515	598	1605	626	1774	474	1847	510
Spain	1443	1899	663	1896	653	2003	552	1990	536
Granada	300	1721	567	1749	622	1873	480	1875	508
Murcia	304	1903	706	1886	623	2056	581	2019	508
Navarra	271	1904	592	1893	619	1985	505	1973	507
San Sebastian	244	2092	694	2052	620	2122	595	2097	507
Asturias	324	1910	696	1915	620	1992	565	1987	507
Italy	2512	1813	622	1864	628	1941	501	1967	505
Ragusa	138	1838	736	1901	639	1928	537	1980	519
Naples	403	1814	655	1930	633	1987	527	2026	505
Florence	785	1829	632	1846	600	1947	484	1965	486
Turin	392	1787	612	1839	630	1942	497	1982	506
Varese	794	1806	578	1857	604	1915	500	1939	481
France	4639	1961	620	1960	626	1994	508	2023	504
South coast	612	1898	614	1873	611	1932	513	1953	492
South	1396	1950	627	1966	607	1993	512	2029	489
North-west	622	1936	538	1939	602	1968	479	2013	486
North-east	2009	1997	638	1986	605	2023	510	2040	486
Germany	2150	1834	619	1866	614	1964	504	1982	494
Heidelberg	1087	1869	638	1873	613	1993	512	1994	491
Potsdam	1063	1799	597	1859	609	1934	494	1970	488
The Netherlands	2960	1944	637	1923	617	2059	515	2034	497
Bilthoven	1086	1946	668	1894	610	2088	530	2026	491
Utrecht	1874	1942	618	1940	622	2042	506	2039	499
United Kingdom	768	1772	587	1770	603	1871	468	1878	485
General population	571	1745	573	1750	598	1865	473	1867	479
'Health-conscious'	197	1851	621	1829	607	1885	457	1906	487
Denmark	1995	1941	679	1929	624	2034	539	2003	500
Copenhagen	1485	1895	654	1877	616	2000	529	1967	489
Aarhus	510	2076	732	2090	629	2126	555	2110	508
Sweden	3285	1847	614	1836	620	1962	501	1950	501
Malmö	1711	1805	605	1817	621	1926	492	1930	498
Umeå	1574	1892	621	1857	601	1999	509	1971	488
Norway	1798	1951	636	1860	612	2043	520	1972	507
South & East	1136	1944	632	1850	623	2045	521	1980	516
North & West	662	1963	642	1874	608	2039	519	1966	507

SD – standard deviation.
* Mean values were adjusted by body mass index, height, age at recall, day of recall (weekday vs. weekend day) and physical activity at work.

within Denmark – Aarhus (2752 kcal day^{-1}) vs. Copenhagen (2669 kcal day^{-1}). Similarly, among women, significant differences were observed within Spain – San Sebastian (2097 kcal day^{-1}) vs. Granada (1875 kcal day^{-1}) – and within Denmark – Aarhus (2110 kcal day^{-1}) vs. Copenhagen (1967 kcal day^{-1}). This corresponds to an absolute difference of 9% and 12% in Spain, and 3% and 7% in Denmark, for men and women, respectively.

After exclusion of extreme reporters, energy intake means increased, as expected, in most of the centres. In Greece, due to the high percentage of participants identified as misreporters, estimates of reported energy intake increased from 2122 kcal day^{-1} (crude value) to 2471 kcal day^{-1} (adjusted after exclusion) in men, and from 1515 kcal day^{-1} (crude value) to 1847 kcal day^{-1} (adjusted after exclusion) in women. Overall, after exclusion, the crude means were 3.3% and 5.8% higher in men and women, respectively. This is not surprising since the percentage of participants identified as underreporters according to Goldberg's cut-off was substantially higher than those identified as overreporters.

Determinants of EI/BMR variability

In Tables 4a and 4b we report means and distribution of some variables of interest for understanding EI/BMR variability by quartiles of sex-specific BMI. There is a strong inverse linear relationship between BMI and EI/BMR in both men and women. The difference in BMI means between the highest and the lowest EI/BMR quartiles is 16% for men and 13% for women. Reported energy intake tends to be underestimated among obese people (most likely at higher values), and overestimated among lean people (for lower values). Tables 5a and 5b show sex-specific quartiles of EI/BMR. Energy intake explains the majority of its variability. It also seems that weight (and BMI) plays a role in explaining part of the

Table 4a Mean and distribution of relevant variables by sex-specific quartiles of body mass index (BMI): men

	BMI quartile			
	1	2	3	4
BMI (kg m^{-2})	22.9	25.6	27.6	31.6
EI/BMR	1.58	1.48	1.41	1.32
EI (kcal)	2607	2556	2504	2452
BMR	1656	1731	1783	1868
Weight (kg)	71.1	78.2	83.9	93.8
Height (cm)	175.4	174.3	173.7	172.4
Age (years)	56.1	56.4	56.8	57.8
PA at work (%)				
Non-worker	25.3	23.1	23.5	28.0
Sedentary	26.6	26.5	25.2	21.7
Standing	24.8	26.1	26.1	22.9
(Heavy) Manual	21.8	24.7	25.3	28.2
PA at leisure (%)				
Low	23.1	23.8	26.4	26.7
Moderate	26.0	25.8	24.1	24.1
Intense	25.6	25.6	24.4	24.3

EI – energy intake; BMR – basal metabolic rate; PA – physical activity.

Table 5a Mean and distribution of relevant variables by sex-specific quartiles of ratio of energy intake to basal metabolic rate (EI/BMR): men

	EI/BMR quartile			
	1	2	3	4
BMI (kg m^{-2})	28.0	27.1	26.6	26.0
EI/BMR	0.88	1.25	1.54	2.11
EI (kcal)	1590	2221	2697	3610
BMR	1884	1779	1746	1710
Weight (kg)	85.4	82.6	80.7	78.6
Height (cm)	174.1	174.5	174.0	173.3
Age (years)	57.0	56.5	56.7	56.7
PA at work (%)				
Non-worker	27.4	23.6	25.0	24.0
Sedentary	25.8	27.2	24.8	22.3
Standing	24.7	25.5	25.0	24.8
(Heavy) Manual	19.3	22.5	25.6	32.6
PA at leisure (%)				
Low	26.4	26.1	24.8	22.6
Moderate	25.3	25.0	24.8	24.9
Intense	23.4	24.1	25.4	27.3

BMI – body mass index; PA – physical activity.

EI/BMR heterogeneity. Physical activity should also be taken into account since it is one of the components that determine individual energy intake. PA at work is significantly related to EI/BMR, the higher the latter the more active the type of work, and this association is stronger in men than in women. As for PA at leisure time, once again higher EI/BMR ratios are associated with higher activity, and the evidence is stronger for men than for women.

After adjustment for age, height, special diet, smoking status and physical activity at work, unconditional logistic regression showed a strong positive association between weight (and BMI) and underreporting (Table 6). The odds ratio (OR) of being an underreporter for the highest vs. the lowest quartile of weight was 3.79 (95% CI 3.10–4.62) in men and 4.75 (95% CI 4.12–5.42) in women, indicating that overweight subjects are significantly more likely to underestimate energy intake than slim subjects. ORs for BMI were surprisingly similar to the estimates observed for weight in both men and women. The effect of age was slightly higher in men (0.58, 95% CI 0.45–0.77) than in women (0.74, 95% CI 0.63–0.88) for the highest age category. Physical activity at work was, as expected, inversely associated with underreporting, with similar effects in the two genders, while no effect was observed for leisure physical activity. Recalling the weekend diet lowered the risk of reporting implausible energy values. Current smokers (vs. non-smokers) showed a significant OR only in women (1.37, 95% CI 1.22–1.54). Relatively

Table 4b Mean and distribution of relevant variables by sex-specific quartiles of body mass index (BMI): women

	BMI quartile			
	1	2	3	4
BMI (kg m^{-2})	20.7	23.5	26.1	31.5
EI/BMR	1.55	1.41	1.32	1.17
EI (kcal)	2003	1901	1849	1744
BMR	1293	1350	1401	1501
Weight (kg)	56.1	62.6	68.6	80.5
Height (cm)	163.22	162.3	161.6	159.7
Age (years)	53.4	54.8	55.9	57.1
PA at work (%)				
Non-worker	20.0	22.3	26.0	31.6
Sedentary	28.3	27.0	24.1	20.6
Standing	27.3	26.0	24.5	22.2
(Heavy) Manual	19.8	24.2	27.8	28.2
PA at leisure (%)				
Low	24.8	24.2	24.9	26.1
Moderate	24.8	24.6	24.6	26.0
Intense	23.0	25.0	26.0	26.0

EI – energy intake; BMR – basal metabolic rate; PA – physical activity.

Table 5b Mean and distribution of relevant variables by sex-specific quartiles of ratio of energy intake to basal metabolic rate (EI/BMR): women

	EI/BMR quartile			
	1	2	3	4
BMI (kg m^{-2})	27.5	25.7	24.8	23.8
EI/BMR	0.82	1.17	1.46	1.99
EI (kcal)	1171	1632	2005	2689
BMR	1426	1390	1376	1352
Weight (kg)	72.1	68.0	66.4	63.8
Height (cm)	160.7	161.6	162.0	162.3
Age (years)	55.8	55.6	55.1	54.8
PA at work (%)				
Non-worker	28.5	25.4	23.4	22.8
Sedentary	24.0	24.4	27.1	24.4
Standing	22.3	24.8	26.0	26.9
(Heavy) Manual	23.9	24.7	24.4	26.9
PA at leisure (%)				
Low	25.8	25.2	25.5	23.4
Moderate	24.4	25.2	25.0	25.5
Intense	25.7	24.3	24.7	25.3

BMI – body mass index; PA – physical activity.

Table 6 Relative risk estimates (RR) for being identified as an underreporter, 95% confidence interval (95% CI), lower cut-off limits (Cut-off) (category labels when categorical variables used), prevalence of categories among subjects with ratio of energy intake to basal metabolic rate lower than 0.88 (% <0.88) (cases), Likelihood Ratio Test statistics (LRT) and *P*-values (*P1*, *P2*) for variables associated with underreporting. Gender-specific logistic regression models were adjusted by variables in the BASE model, height (continuous) and CENTRE

		Men							Women						
	Predictor	RR	95% CI	Cut-off	% <0.88	LRT	*P1**	*P2*†	RR	95% CI	Cut-off	% <0.88	LRT	*P1**	*P2*†
BASE model	WEIGHT	1	–	–	6.0				1	–	–	7.4			
		1.51	1.23–1.86	74.0 (kg)	7.9				1.63	1.40–1.89	59.5 (kg)	10.8			
		2.17	1.78–2.65	80.8 (kg)	10.8				2.40	2.08–2.47	66.0 (kg)	15.2			
		3.79	3.10–4.62	88.6 (kg)	16.6	202.3	<0.01	<0.01	4.75	4.12–5.42	74.1 (kg)	25.5	702.2	<0.01	<0.01
	AGE	1	–	–	10.1				1	–	–	13.4			
		1.02	0.84–1.24	50 (years)	10.6				0.93	0.83–1.04	50 (years)	13.5			
		1.15	0.95–1.39	55 (years)	12.5				0.88	0.78–0.99	55 (years)	14.2			
		0.52	0.42–0.64	60 (years)	7.4				0.73	0.64–0.84	60 (years)	13.9			
		0.58	0.45–0.77	65 (years)	13.2	82.6	<0.01	<0.01	0.74	0.63–0.88	65 (years)	15.5	24.7	<0.01	<0.01
	PA AT WORK‡	1	–	1	12.0				1	–	1	16.2			
		0.88	0.74–1.05	2	10.4				0.91	0.81–1.03	2	13.3			
		0.86	0.71–1.04	3	9.7				0.86	0.76–0.98	3	11.9			
		0.77	0.62–0.94	4	8.9	9.1	0.12	0.02	0.83	0.70–0.98	4	13.6	9.8	0.02	<0.01
	DAY OF WEEK§	1	–	1	11.4				1	–	1	14.9			
		0.72	0.64–0.82	2	8.7	24.8	<0.01	–	0.71	0.65–0.78	2	12.1	53.8	<0.01	–
	SMOKE STATUS	1	–	NEVER	9.3				1	–	NEVER	13.4			
		1.10	0.95–1.27	EX	11.3				1.14	1.02–1.28	EX	14.0			
		1.15	0.98–1.35	CURRENT	10.4	3.42	0.33	–	1.37	1.22–1.54	CURRENT	16.7	28.9	<0.01	–
	SPECIAL DIET	1	–	NO	9.2				1	–	NO	12.0			
		1.88	1.62–2.17	YES	16.9	74.2	<0.01	–	1.92	1.74–2.12	YES	21.2	200.0	<0.01	–
Other	BMI¶	1	–	–	5.8				1	–	–	5.4			
		1.62	1.32–1.98	24.6 ($kg\,m^{-2}$)	8.4				1.58	1.33–1.87	22.3 ($kg\,m^{-2}$)	9.0			
		2.15	1.77–2.62	26.5 ($kg\,m^{-2}$)	10.6				2.51	2.14–2.94	24.7 ($kg\,m^{-2}$)	14.7			
		3.52	2.91–4.26	29.0 ($kg\,m^{-2}$)	16.8	208.1	<0.01	<0.01	4.80	4.11–5.61	26.1 ($kg\,m^{-2}$)	26.2	589.0	<0.01	<0.01
	PA AT LEISURE‖	1	–	LOW	10.8				1	–	LOW	14.3			
		1.02	0.88–1.18	MODERATE	10.7				0.92	0.83–1.02	MODERATE	13.5			
		0.92	0.79–1.06	INTENSE	9.8	3.39	0.34	0.28	1.00	0.90–1.11	INTENSE	14.4	3.42	0.33	0.93

PA – physical activity; BMI – body mass index.
* *P1* – *P*-value for Likelihood Ratio Test statistics.
† *P2* – *P*-value for trend, calculated by the use of a score variable (1, 2, . . ., etc.).
‡ PA AT WORK categories: 1 = not employed, 2 = sedentary activity, 3 = standing activity, 4 = (heavy) manual work.
§ DAY OF WEEK categories: 1 = Monday, Tuesday, Wednesday and Thursday, 2 = Friday, Saturday and Sunday.
¶ Estimated in the base model, instead of weight.
‖ Estimated in the base model, instead of PA at work.

high odds ratios were observed for participants who reported following a special diet on the recalled day.

When centre- and sex-specific quartiles were used, results were similar (data not shown). Fitting models with different predictors, we also checked that the regression parameters for the variables that were consistently included (physical activity, special diet, day of the week and smoking status) did not vary substantially.

Discussion

In the present work we evaluated misreporting in the EPIC 24-HDR data. In the EPIC calibration sample there is evidence of underreporting, while overreporting has only a minor impact. Using Goldberg's cut-off points it was possible to identify centres at the aggregate level and study participants at the individual level as extreme underreporters, after considering between- and within-subject variability of EI/BMR components. At the aggregate level we observed EI/BMR means under the expected value of 1.55 in the vast majority of the EPIC centres. This cut-off level was chosen as the reference value given the calibration study population's age and physical activity. Adjusting for possible confounding changed the magnitude of estimates but did not substantially alter the ranking of centres. Notably, in Bilthoven (The Netherlands), where the study participants are younger than in the rest of the study, adjustment lowered mean energy estimates due to the observed negative correlation between age and reported energy intake. Adjusted means for energy were 7.5% and 5.9% lower than crude estimates in men and women, respectively.

Values of EI/BMR below 0.88 at the individual level are very likely to be the result of variations in reported energy intake beyond day-to-day variability. Analyses conducted at the individual level revealed that the percentage of people identified as extreme underreporters was always under 13% in men (except Greece, 20%) and under 17% in women (except Greece, 33%). Study participants in Greece have among the lowest values for physical activity, which might partially explain the extremely low values for self-reported energy intake. However, a recent study to validate protein intake through urinary nitrogen measurements in the EPIC 24-HDR[21] showed evidence of underestimation of protein intake in Greece, supporting the interpretation that the underreporting of EI observed in the present study is real and not due to lower than expected physical activity.

Underreporting was generally heterogeneously distributed among countries, but homogeneously among centres within the different countries, in both male and female study populations.

In the EPIC 24-HDR data we observed an inverse linear relationship between BMI (or weight) and EI/BMR, thus suggesting that obese (or overweight) people tend to underreport energy intake. This association seems to be equally present in men and women, but is slightly stronger among the latter, a phenomenon previously reported in the literature[5,22–28]. Moreover, logistic regression analyses suggested that participants in the top BMI quartile have a considerably higher probability of being identified as an extreme underreporter than do participants with plausible values.

However, there are limitations to this interpretation when inferring a possible relationship between BMI and underreporting. First of all, this conclusion is based on the assumption that physical activity is constant in the population. Obese people may, however, be physically less active than non-obese, and actually have lower energy intakes, so the uniformly accepted PAL value of 1.55 for the general population may not apply equally to these subjects. Secondly, although the use of Goldberg's limits to identify under- and overreporters is very useful, a PAL of 1.55 assumes a sedentary lifestyle. This figure was chosen by the authors in order to avoid overestimation of underreporting. However, physical activity is very heterogeneous within any given population, and may be associated with a particular group of people. In the present work it has been assumed that 1.55 was a reasonable choice owing to the age span and other characteristics of the EPIC calibration sample.

Two indicators for physical activity were considered throughout the analyses. These variables do not provide individual quantitative estimates, but allow study participants to be ranked according to type of physical activity at work or during leisure. Their use made it possible to take into account the differences in participants' physical activity and to correct for possible confounding effects when calculating adjusted means or risk ratio estimates.

Furthermore, it is assumed that the equation proposed by Schofield *et al.*[16] for BMR works equally well for all subjects in a given population. The linear relationships of height and weight, stratified by age group and gender, to estimate the basal metabolic rate may work less accurately for overweight people. These equations may lack precision because they are supposed to work well on average, statistically speaking, but not necessarily at the individual level. Moreover, a non-linear relationship may exist between BMR and weight, specifically for high values of weight. This would lead to imprecise estimates of BMR for a particular category of subjects (for example obese people), thus weakening the validity of estimated BMR. In a recent work, Black[11] observed a non-linear relationship between estimated and measured BMR in women, suggesting that BMR of obese subjects may be overestimated, thus accentuating the extent of underreporting evaluated with EI/BMR. However, an appreciable effect seems to be present only for women with BMI $> 35\,\mathrm{kg\,m^{-2}}$, which represents only 3.6% of women in the EPIC 24-HDRs.

The evaluation of the relationship between EI/BMR and BMI (or weight) is problematic since both terms are a function of height and weight, and therefore share a common source of variation. Part of the statistical association observed may simply be due to the common source of variability between EI/BMR and its components and not to a true causal relationship between weight (or BMI) and age and underreporting.

In this study, the hypothesis that some factors, specifically BMI (and weight), are significant determinants of underreporting is based on a considerable list of assumptions. The authors are aware of the limitations of this speculation, but intend to provide insights into questions that will very likely be one of the most challenging fields of research in nutritional epidemiology. We therefore strongly believe that there is room for an *ad hoc* study designed to further evaluate and test our conjectures.

In a multi-centre study, the aim of calibration is to express dietary measurements on a common scale and to correct for bias due to measurement errors in the DQ measurements. Measurement error attenuates the relationship between exposure and disease towards the null hypothesis of no association. The objective of calibration is therefore to estimate the attenuation parameter λ to adjust dietary exposure assessments so that relative risk estimates calculated for a quantitative *per unit* difference in exposure level are no longer biased by errors in DQ measurements[4,29,30]. In the EPIC calibration setting, attenuation coefficients are estimated by regressing the 24-HDR reference measurements (R) on DQ measurements under the assumption, among others, that R is linearly related to true habitual intake (T) as $R = \alpha_R + \beta_R T + \varepsilon_R$, where $\beta_R = 1$, $E[e_R|T] = 0$ and $\mathrm{Var}(e_R) = \sigma^2_{eR}$. It is therefore assumed that the reference measurements are unbiased, or – equivalently – that error is strictly random, after the α_R term captures the systematic component.

In a multi-centre setting, calibration and data analysis have a within-group (countries or centres) component and a between-group (ecological) component. Underreporting in the 24-HDR indicates that the EPIC reference measurements are not unbiased at the group level. However, if underreporting is distributed randomly between subjects within groups, 24-HDR can still be used to calibrate DQ measurements onto a reference scale without absolute validity, but which is common across subjects. Moreover, if the degree of underreporting is approximately constant across study population groups, the questionnaire measurements can still be calibrated for between-group calibration[7]. After exclusion of misreporters, adjusted EI/BMR means were consistently less than 10% different from the expected value of 1.55 for PAL (except for women in Greece and in the UK), with overall differences equal to 4.0% and 7.4% for men and women, respectively. These results seem to be confirmed by the validation study on protein intake in the EPIC 24-HDR previously mentioned[21], where very similar results on underestimation of protein intakes were observed. Moreover, a similar picture was observed after considering PAL values equal to 1.65, thus assuming higher PAL for the EPIC calibration sub-sample.

However, the fact that some factors may have a causal effect on underreporting implies that measurement error in the 24-HDR estimates for energy intake also contains a systematic component. It reflects the tendency of study participants with specific characteristics (e.g. BMI, age, etc.) to under- or overreport dietary intake systematically and may be the result of within-person systematic error not randomly distributed between subjects. Kipnis *et al.*[31] refer to it as person- and group-specific bias in reporting dietary intakes. Several strategies are advisable; for example, the use of BMI-specific attenuation factors. On the basis of several studies that reported serious underreporting in groups of people with high BMI[26–28], Prentice[32] proposed a model in which the degree of attenuation depends on the individual. This model suggests that the overall level of attenuation may be far greater than previously thought. Although the effect of BMI on underreporting has been suggested repeatedly and different calibration approaches discussed, no uniformly accepted evidence about the effect of BMI on attenuation has been reached[33].

The prevalence of a special diet at recall is high (16.3% and 20.6% in men and women, respectively), and 26.3% and 31.3% of extreme male and female underreporters had a special diet during the recall. These values undoubtedly require further evaluation.

In a recent paper Black[18] discusses the sensitivity and specificity of the Goldberg cut-off for EI/BMR to identify extreme underreporters. The use of 1.55 for PAL to determine the individual cut-off point to identify underreporters has moderately low sensitivity but extremely high specificity, meaning that all of the participants identified as high underreporters are very likely to have truly underestimated energy intake, while some of the energy measurements considered to be plausible were effectively underestimated. This seems to strengthen the validity of our findings, since potential misclassification of study participants according to underreporting status, which is likely to be the case here, would lead to weaker effects.

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Appendix

Table A1 Age, anthropometry and frequency of special diet at recall in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration sub-populations: men

Country and centre	*n*	Age (years)*		Height (cm)		Weight (kg)		BMI (kg m^{-2})		% Special diet
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Greece	1312	60.5	9.8	168.5	6.7	80.8	11.8	28.4	3.7	25
Spain	1777	55.1	7.4	169.9	6.3	80.2	10.6	27.8	3.3	14
Granada	214	58.1	6.7	169.2	6.4	82.2	10.6	28.7	3.3	22
Murcia	243	55.6	7.4	168.4	6.0	78.1	10.0	27.6	3.3	9
Navarra	444	56.3	6.8	169.1	6.0	80.1	9.9	28.0	3.2	20
San Sebastian	490	51.5	6.8	171.7	6.3	80.3	10.9	27.2	3.2	6
Asturias	386	56.2	7.5	169.9	6.4	80.5	11.0	27.9	3.2	18
Italy	1444	55.2	7.0	171.7	6.8	78.3	10.8	26.5	3.2	8
Ragusa	168	53.5	6.8	168.9	6.1	78.2	11.7	27.4	3.7	3
Florence	271	54.4	7.3	173.0	6.7	79.1	11.2	26.4	3.3	10
Turin	677	55.0	7.0	171.7	6.9	78.2	10.5	26.5	3.0	7
Varese	328	57.1	6.2	171.8	6.7	77.6	10.6	26.3	3.2	12
Germany	2268	54.6	7.3	175.3	6.6	83.2	12.1	27.1	3.6	19
Heidelberg	1033	53.7	7.0	175.9	6.6	83.3	12.4	26.9	3.7	20
Potsdam	1235	55.4	7.4	174.8	6.6	83.1	11.8	27.2	3.6	18
The Netherlands	1024	50.0	7.4	177.7	7.1	83.8	12.5	26.5	3.6	6
Bilthoven	1024	50.0	7.4	177.7	7.1	83.8	12.5	26.5	3.6	6
United Kingdom	518	57.5	8.9	175.9	7.1	79.5	11.2	25.7	3.5	27
General population	404	58.1	9.1	175.4	7.1	81.1	11.1	26.4	3.3	12
'Health-conscious'	114	55.4	7.7	177.6	7.0	73.7	9.3	23.4	2.8	81
Denmark	1923	56.7	4.3	177.1	6.5	83.4	12.2	26.6	3.6	7
Copenhagen	1356	57.0	4.4	177.2	6.7	83.5	12.5	26.6	3.6	8
Aarhus	567	56.0	4.2	176.9	6.2	83.0	11.6	26.5	3.4	4
Sweden	2765	61.1	7.3	176.7	6.5	82.4	11.9	26.4	3.3	23
Malmö	1421	64.2	6.2	176.4	6.6	82.5	12.3	26.5	3.4	16
Umeå	1344	57.8	6.9	177.1	6.4	82.4	11.5	26.3	3.2	30

BMI – body mass index; SD – standard deviation.
* At the time of interview.

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Table A2 Age, anthropometry and frequency of special diet at recall in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration sub-populations: women

		Age (years)*		Height (cm)		Weight (kg)		BMI (kg m^{-2})		
Country and centre	*n*	Mean	SD	Mean	SD	Mean	SD	Mean	SD	% Special diet
Greece	1374	57.2	9.9	156.1	6.3	70.8	11.8	29.1	4.9	25
Spain	1443	52.9	8.3	158.6	5.9	68.1	10.6	27.1	4.3	18
Granada	300	54.6	8.1	157.6	5.3	69.4	10.4	28.0	4.3	18
Murcia	304	51.6	8.6	158.8	6.3	69.3	10.9	27.6	4.7	12
Navarra	271	53.6	7.8	158.5	5.9	67.1	9.5	26.8	3.9	18
San Sebastian	244	51.8	8.2	160.0	6.0	66.6	11.7	26.0	4.6	10
Asturias	324	52.9	8.4	158.6	5.9	67.6	10.2	26.9	4.0	27
Italy	2512	54.7	7.3	158.6	6.1	65.1	10.9	25.9	4.3	15
Ragusa	138	50.6	8.3	156.1	5.5	65.0	11.5	26.7	4.5	8
Naples	403	54.2	6.7	157.2	5.6	67.9	11.4	27.5	4.5	22
Florence	785	55.2	7.0	160.0	6.1	65.3	11.0	25.6	4.2	15
Turin	392	54.2	6.9	159.4	6.2	64.6	10.7	25.4	4.0	10
Varese	794	55.3	7.6	158.0	5.9	63.8	10.4	25.6	4.2	16
France	4639	57.0	6.9	161.4	5.7	61.1	9.8	23.5	3.5	22
South coast	612	57.6	6.8	161.4	5.2	60.3	9.1	23.1	3.2	26
South	1396	56.6	7.0	161.4	5.7	60.4	9.4	23.2	3.3	17
North-west	622	56.9	6.7	160.7	5.5	60.4	10.0	23.4	3.7	29
North-east	2009	57.1	7.0	161.7	5.9	62.2	10.3	23.8	3.7	22
Germany	2150	51.6	8.6	163.3	6.3	68.6	12.6	25.8	4.7	18
Heidelberg	1087	50.3	8.5	164.2	6.2	67.7	12.4	25.1	4.8	21
Potsdam	1063	53.0	8.6	162.4	6.3	69.6	12.7	26.4	4.6	15
The Netherlands	2960	55.1	8.3	164.8	6.1	70.4	12.1	25.9	4.4	20
Bilthoven	1086	48.9	7.5	165.2	6.3	70.3	12.6	25.8	4.5	11
Utrecht	1874	58.7	6.3	164.6	5.9	70.5	11.8	26.0	4.3	26
United Kingdom	768	55.6	8.9	162.3	6.1	66.1	11.3	25.1	4.2	36
General population	571	56.1	9.0	162.0	6.0	67.3	11.3	25.7	4.2	24
'Health-conscious'	197	54.1	8.7	163.3	6.4	62.6	10.6	23.5	3.8	72
Denmark	1995	56.8	4.4	164.6	6.0	69.0	11.8	25.5	4.2	11
Copenhagen	1485	57.1	4.4	164.7	6.0	69.3	11.9	25.6	4.2	13
Aarhus	510	55.9	4.4	164.4	5.7	68.2	11.2	25.2	4.1	8
Sweden	3285	58.6	8.4	163.7	5.8	69.2	11.5	25.8	4.2	28
Malmö	1711	61.4	7.8	163.4	5.8	69.3	11.7	26.0	4.3	21
Umeå	1574	55.6	8.0	164.0	5.7	69.2	11.3	25.7	4.1	36
Norway	1798	49.3	4.3	166.9	5.6	67.2	10.5	24.1	3.6	16
South & East	1136	49.5	4.3	167.2	5.5	66.8	10.3	23.9	3.5	16
North & West	662	49.0	4.3	166.5	5.8	67.7	10.9	24.4	3.7	16

BMI – body mass index; SD – standard deviation.
* At the time of interview.

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Table A3 Physical activity at work in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration sub-populations: men

	Non-worker		Sedentary occupation		Standing occupation		Manual work		(Heavy) Manual work		Missing	
Country and centre	*n*	%	n	%	*n*	%	*n*	%	*n*	%	*n*	%
Greece	545	41.5	277	21.1	200	15.2	219	16.7	23	1.8	48	3.7
Spain	116	6.5	590	33.2	574	32.3	395	22.2	102	5.7	–	–
Granada	13	6.1	88	41.1	70	32.7	28	13.1	15	7.0	–	–
Murcia	17	7.0	86	35.4	83	34.2	31	12.8	26	10.7	–	–
Navarra	26	5.9	135	30.4	146	32.9	115	25.9	22	5.0	–	–
San Sebastian	4	0.8	169	34.5	128	26.1	173	35.3	16	3.3	–	–
Asturias	56	14.5	112	29.0	147	38.1	48	12.4	23	6.0	–	–
Italy	460	31.9	480	33.2	253	17.5	158	10.9	78	5.4	15	1.0
Ragusa	22	13.1	64	38.1	40	23.8	16	9.5	24	14.3	2	1.2
Florence	60	22.1	115	42.4	47	17.3	32	11.8	14	5.2	3	1.1
Turin	247	36.5	209	30.9	115	17.0	70	10.3	27	4.0	9	1.3
Varese	131	39.9	92	28.0	51	15.5	40	12.2	13	4.0	1	0.3
Germany	773	34.1	894	39.4	464	20.5	120	5.3	15	0.7	2	0.1
Heidelberg	278	26.9	465	45.0	227	22.0	54	5.2	9	0.9	–	–
Potsdam	495	40.1	429	34.7	237	19.2	66	5.3	6	0.5	2	0.2
The Netherlands	237	23.1	359	35.1	166	16.2	90	8.8	81	7.9	91	8.9
Bilthoven	237	23.1	359	35.1	166	16.2	90	8.8	81	7.9	91	8.9
United Kingdom	218	42.1	136	26.3	63	12.2	69	13.3	16	3.1	16	3.1
General population	173	42.8	101	25.0	51	12.6	51	12.6	15	3.7	13	3.2
'Health-conscious'	45	39.5	35	30.7	12	10.5	18	15.8	1	0.9	3	2.6
Denmark	304	15.8	820	42.6	325	16.9	352	18.3	122	6.3	–	–
Copenhagen	217	16.0	590	43.5	223	16.4	241	17.8	85	6.3	–	–
Aarhus	87	15.3	230	40.6	102	18.0	111	19.6	37	6.5	–	–
Sweden	1091	39.5	625	22.6	684	24.7	297	10.7	52	1.9	16	0.6
Malmö	752	52.9	359	25.3	207	14.6	83	5.8	19	1.3	1	0.1
Umeå	339	25.2	266	19.8	477	35.5	214	15.9	33	2.5	15	1.1

Table A4 Physical activity at work in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration sub-populations: women

	Non-worker		Sedentary occupation		Standing occupation		Manual work		(Heavy) Manual work		Missing	
Country and centre	*n*	%	n	%	*n*	%	*n*	%	*n*	%	*n*	%
Greece	864	62.9	213	15.5	214	15.6	76	5.5	–	–	7	0.5
Spain	49	3.4	174	12.1	1191	82.5	25	1.7	4	0.3	–	–
Granada	8	2.7	25	8.3	264	88.0	3	1.0	–	–	–	–
Murcia	4	1.3	44	14.5	247	81.3	6	2.0	3	1.0	–	–
Navarra	13	4.8	27	10.0	226	83.4	5	1.8	–	–	–	–
San Sebastian	2	0.8	44	18.0	192	78.7	6	2.5	–	–	–	–
Asturias	22	6.8	34	10.5	262	80.9	5	1.5	1	0.3	–	–
Italy	1419	56.5	594	23.6	291	11.6	145	5.8	49	2.0	14	0.6
Ragusa	67	48.6	41	29.7	24	17.4	3	2.2	3	2.2	–	–
Naples	231	57.3	112	27.8	27	6.7	22	5.5	11	2.7	–	–
Florence	417	53.1	209	26.6	109	13.9	35	4.5	10	1.3	5	0.6
Turin	233	59.4	75	19.1	46	11.7	26	6.6	12	3.1	–	–
Varese	471	59.3	157	19.8	85	10.7	59	7.4	13	1.6	9	1.1
France	1753	37.8	706	15.2	1879	40.5	76	1.6	–	–	225	4.9
South coast	265	43.3	77	12.6	244	39.9	6	1.0	–	–	20	3.3
South	534	38.3	198	14.2	573	41.0	22	1.6	–	–	69	4.9
North-west	240	38.6	85	13.7	251	40.4	12	1.9	–	–	34	5.5
North-east	714	35.5	346	17.2	811	40.4	36	1.8	–	–	102	5.1
Germany	843	39.2	748	34.8	498	23.2	46	2.1	3	0.1	12	0.6
Heidelberg	388	35.7	373	34.3	280	25.8	33	3.0	2	0.2	11	1.0
Potsdam	455	42.8	375	35.3	218	20.5	13	1.2	1	0.1	1	0.1
The Netherlands	1495	50.5	507	17.1	458	15.5	270	9.1	143	4.8	87	2.9
Bilthoven	506	46.6	204	18.8	173	15.9	83	7.6	34	3.1	86	7.9
Utrecht	989	52.8	303	16.2	285	15.2	187	10.0	109	5.8	1	0.1
United Kingdom	340	44.3	223	29.0	144	18.8	46	6.0	–	–	15	2.0
General population	257	45.0	157	27.5	104	18.2	40	7.0	–	–	13	2.3
'Health-conscious'	83	42.1	66	33.5	40	20.3	6	3.0	–	–	2	1.0
Denmark	589	29.5	680	34.1	339	17.0	363	18.2	23	1.2	1	0.1
Copenhagen	442	29.8	530	35.7	231	15.6	259	17.4	22	1.5	1	0.1
Aarhus	147	28.8	150	29.4	108	21.2	104	20.4	1	0.2	–	–
Sweden	1048	31.9	791	24.1	948	28.9	398	12.1	80	2.4	20	0.6
Malmö	755	44.1	462	27.0	406	23.7	80	4.7	2	0.1	6	0.4
Umeå	293	18.6	329	20.9	542	34.4	318	20.2	78	5.0	14	0.9
Norway	–	–	–	–	–	–	–	–	–	–	1798	100.0
South & East	–	–	–	–	–	–	–	–	–	–	1136	100.0
North & West	–	–	–	–	–	–	–	–	–	–	662	100.0

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