British Journal of Nutrition (2012), **107**, 910–920
doi:10.1017/S0007114511003564

Dietary reporting errors on 24 h recalls and dietary questionnaires are associated with BMI across six European countries as evaluated with recovery biomarkers for protein and potassium intake

Heinz Freisling[1], Marit M. E. van Bakel[1]†, Carine Biessy[1], Anne M. May[2], Graham Byrnes[3], Teresa Norat[4], Sabina Rinaldi[1], Maria Santucci de Magistris[5], Sara Grioni[6], H. Bas Bueno-de-Mesquita[7], Marga C. Ocké[7], Rudolf Kaaks[8], Birgit Teucher[8], Anne-Claire Vergnaud[4], Dora Romaguera[4], Carlotta Sacerdote[9], Domenico Palli[10], Francesca L. Crowe[11], Rosario Tumino[12], Françoise Clavel-Chapelon[13], Marie-Christine Boutron-Ruault[13], Kay-Tee Khaw[14], Nicholas J. Wareham[15], Antonia Trichopoulou[16,17], Androniki Naska[16,17], Philippos Orfanos[16,17], Heiner Boeing[18], Anne-Kathrin Illner[18], Elio Riboli[4], Petra H. Peeters[2] and Nadia Slimani[1]*

[1]*Dietary Exposure Assessment Group, International Agency for Research on Cancer, 150 Cours Albert Thomas, 69372 Lyon Cedex 08, France*
[2]*Julius Center, University Medical Center, Huispost Str. 6.131, Postbus 85500, 3508 GA, Utrecht, The Netherlands*
[3]*Biostatistics Group, International Agency for Research on Cancer, 150 Cours Albert Thomas, 69372 Lyon Cedex 08, France*
[4]*Department of Epidemiology, Public Health and Primary Care, Imperial College London, St Mary's Campus, Norfolk Place, London W2 1PG, UK*
[5]*Department of Clinical and Experimental Medicine, Federico II University, Via Pansini 5, 80131 Naples, Italy*
[6]*Nutritional Epidemiology Unit, Fondazione IRCCS Istituto Nazionale dei Tumori, Via Giacomo Venezian 1, 20133 Milan, Italy*
[7]*National Institute for Public Health and the Environment (RIVM), PO Box 1, Bilthoven 3720 BA, The Netherlands*
[8]*Division of Cancer Epidemiology, German Cancer Research Center, Im Neuenheimer Feld 280, 69120 Heidelberg, Germany*
[9]*Department of Biomedical Sciences and Human Oncology, University of Torino, Via Santena 7, 10126 Torino, Italy*
[10]*Molecular and Nutritional Epidemiology Unit, Cancer Research and Prevention Institute – ISPO, Via Cosimo il Vecchio 2, 50139 Florence, Italy*
[11]*Cancer Epidemiology Unit, Nuffield Department of Clinical Medicine, University of Oxford, Roosevelt Drive, Oxford OX3 7LF, UK*
[12]*Cancer Registry and Histopathology Unit, 'Civile M.P. Arezzo' Hospital, Via Dante 109, 97100 Ragusa, Italy*
[13]*ERI 20 Nutrition, Hormones and Cancer, INSERM – Institut Gustave Roussy, 114 rue Edouard Vaillant, 94805 Villejuif, France*
[14]*Clinical Gerontology Unit, Department of Public Health and Primary Care, University of Cambridge, Box 251, Addenbrooke's Hospital, Hills Road, Cambridge CB2 2QQ, UK*
[15]*Medical Research Council, Epidemiology Unit, Institute of Metabolic Science, Box 285, Addenbrooke's Hospital, Hills Road, Cambridge CB2 0QQ, UK*
[16]*WHO Collaborating Centre for Food and Nutrition Policies, Department of Hygiene Epidemiology and Medical Statistics, University of Athens Medical School, 75 Mikras Asias, Goudi, GR-11527 Athens, Greece*
[17]*Hellenic Health Foundation, 10-12 Tetrapoleos Street, GR-11527 Athens, Greece*
[18]*Department of Epidemiology, German Institute of Human Nutrition, Arthur-Scheunert-Allee 114-116, 14558 Bergholz-Rehbrücke, Germany*

(Received 10 November 2010 – Revised 23 May 2011 – Accepted 1 June 2011 – First published online 27 July 2011)

Abbreviations: DQ, dietary questionnaires; EI, energy intake; EPIC, European Prospective Investigation into Cancer and Nutrition; 24-HDR, 24 h dietary recalls; LER, low-energy reporter; PABA, *para*-aminobenzoic acid.

* **Corresponding author:** N. Slimani, fax +33 472738361, email slimani@iarc.fr

† Present address: Registre des Handicaps de l'Enfant et Observatoire Périnatal, 23 Avenue Albert 1er de Belgique, 38100 Grenoble, France.

Abstract

Whether there are differences between countries in the validity of self-reported diet in relation to BMI, as evaluated using recovery biomarkers, is not well understood. We aimed to evaluate BMI-related reporting errors on 24 h dietary recalls (24-HDR) and on dietary questionnaires (DQ) using biomarkers for protein and K intake and whether the BMI effect differs between six European countries. Between 1995 and 1999, 1086 men and women participating in the European Prospective Investigation into Cancer and Nutrition completed a single 24-HDR, a DQ and one 24 h urine collection. In regression analysis, controlling for age, sex, education and country, each unit (1 kg/m^2) increase in BMI predicted an approximately 1·7 and 1·3 % increase in protein under-reporting on 24-HDR and DQ, respectively (both $P<0·0001$). Exclusion of individuals who probably misreported energy intake attenuated BMI-related bias on both instruments. The BMI effect on protein under-reporting did not differ for men and women and neither between countries on both instruments as tested by interaction (all $P>0·15$). In women, but not in men, the DQ yielded higher mean intakes of protein that were closer to the biomarker-based measurements across BMI groups when compared with 24-HDR. Results for K were similar to those of protein, although BMI-related under-reporting of K was of a smaller magnitude, suggesting differential misreporting of foods. Under-reporting of protein and K appears to be predicted by BMI, but this effect may be driven by 'low-energy reporters'. The BMI effect on under-reporting seems to be the same across countries.

Key words: Biomarkers: BMI: EPIC-Soft: Protein intake: Potassium intake: Under-reporting

Uncertainty about the validity of dietary self-report instruments due to random and systematic measurement errors is one of the major concerns in nutritional epidemiology because these dietary assessment errors may attenuate risk estimates and obscure diet–disease associations[1–3]. In multi-centre studies, this methodological issue is amplified due to possible between-centre differences in systematic over- or underestimation in dietary intake measurements[4–6].

Self-reported diet tends to be biased towards underestimation of energy intake (EI)[7,8] and specific macronutrients[8–10], although a relative overestimation of foods that are perceived as socially desirable (and related nutrients) may also occur[8,11]. Dietary assessment errors would be less problematic and could be easily corrected for if they were randomly distributed across individuals and food groups but, unfortunately, misreporting appears to occur at higher rates in certain subgroups of the population and with certain foods[12,13]. Having a high BMI has been identified as the most consistent factor that is associated with under-reporting of EI[7,8,14]. However, not all overweight or obese persons under-report their diet[8] and associations between under-reporting and BMI may also depend on the method of dietary assessment used[10,15,16].

Considering the ongoing epidemic of obesity and of diseases associated with obesity worldwide, it is important that BMI-related reporting errors in dietary assessment are addressed. For example, evaluating the patterns of reporting errors among population subgroups as defined by their BMI and whether such errors vary across populations with diverse dietary habits may help to refine measurement error correction methods and aid in the interpretation of nutritional epidemiological findings. Furthermore, detailed analysis of the shortcomings of dietary self-report may eventually help to improve dietary assessment instruments.

Dietary biomarkers do not rely on self-report and thus fulfil the criterion of an independent and objective measure of dietary intake against which the validity of dietary self-report instruments can be tested[1]. Of particular interest are biomarkers that provide an estimate of absolute dietary intake, based on the urinary recovery of nutrients or metabolites from diet. Those so-called 'recovery' biomarkers[17] include N and K from 24 h urinary measurements that allow calculation of daily intake of protein and K, respectively[18,19].

Relatively few methodological studies have used these biomarkers to evaluate the validity of dietary self-report instruments in relation to obesity simultaneously for 24 h dietary recalls (24-HDR) and dietary questionnaires (DQ)[15]. Moreover, previous studies were not able to examine whether possible differences in misreporting between countries depend on BMI.

In an earlier cross-sectional study, protein biomarker data from the same twelve centres as those included in the present analysis were used to validate 24-HDR measurements as a reference method for between-cohort calibration[9]. Despite the presence of measurement error in this reference method, it was concluded that standardised 24-HDR measurements are useful to discriminate population mean estimates and to partially correct the diet–disease associations for attenuation due to measurement errors in baseline DQ measurements[9]. In the present study, we propose to extend these analyses with the aims (1) to evaluate BMI-related reporting errors on 24-HDR and DQ by using recovery biomarkers for protein and K intake and (2) to examine whether the effect of BMI differs between six European countries.

Subjects and methods

Subjects

The study population was a convenience subsample of the European Prospective Investigation into Cancer and Nutrition (EPIC) study[20] and has been described elsewhere[9]. In brief, subjects from the following twelve geographical areas (EPIC centres) were re-contacted between 1995 and 1999 and asked to collect a 24 h urine specimen: Paris (France); Varese, Turin, Florence, Naples and Ragusa (Italy); Greece; Cambridge and Oxford (UK); Heidelberg and Potsdam (Germany); Bilthoven (The Netherlands). Within countries, the data of different centres were combined for the present

analysis except for the two UK centres, where the Oxford cohort includes vegetarians, vegans and other health-conscious individuals.

A total of 1386 volunteers were recruited in the study, but a number of subjects were excluded: 186 having invalid collections of the 24 h urine sample as determined by *para*-aminobenzoic acid (PABA); forty-five who did not complete both self-report instruments (i.e. 24-HDR and DQ); eight having missing values on height, weight and lifestyle baseline data or extreme DQ EI:energy requirement ratios (1 % of the extremes, centre and sex specific, a routine exclusion made on the EPIC baseline questionnaire data); fifty-two subjects reported being on a diet during the 24-HDR. Furthermore, nine subjects with implausible values of height (< 130 cm), BMI (< 16 kg/m^2), waist circumference (< 40 cm or > 160 cm), the combination of a waist circumference (< 60 cm) and BMI (> 25 kg/m^2) and with missing BMI were excluded. Overall, a total of 300 subjects (21·6 %) were excluded, giving a final sample size of 1086 subjects for the present study.

The present study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the local ethics committees in the participating countries and the International Agency for Research on Cancer Institutional Review Board. Written informed consent was obtained from all subjects.

Self-reported diet and anthropometric measurements

Information on 'habitual' dietary intake was assessed at baseline for each individual at recruitment to the EPIC cohorts using semi-quantitative DQ (France, The Netherlands, Germany, Greece and Italy, except Naples) or a semi-quantitative FFQ (UK, Naples) developed and validated in each participating country[20,21].

A single 24-HDR interview was collected from a subsample of each cohort as the dietary reference method for calibration purposes. Trained dietitians conducted all (unannounced) interviews face to face. Food portion sizes were estimated using a common picture book and other available methods such as standard units and household measures[6]. In contrast to the baseline DQ, the 24-HDR interviews were standardised across countries, using the computerised program EPIC-Soft® (International Agency for Research on Cancer, Lyon, Rhone-Alpes, France) with the same structure and interview procedure across countries. More details on the concept of standardisation are given elsewhere[22].

Country-specific nutrient databases were used to estimate protein, K and EI from baseline DQ. Respective intakes from 24-HDR were estimated using the standardised EPIC Nutrient Database. The EPIC Nutrient Database project outlines in detail the methods used to standardise the national nutrient databases across countries[23].

BMI was calculated from measured weight and height and categorised into normal weight (BMI < 25 kg/m^2), overweight (BMI 25 to < 30 kg/m^2) and obese (BMI ≥ 30 kg/m^2). The category < 25 kg/m^2 included eleven underweight subjects with a BMI below 18·5 kg/m^2 (1 % of the sample). For 105 subjects for whom more than 1 year elapsed between completing the questionnaire and anthropometric measurements and for one subject for whom no measured information was available, self-reported data from their questionnaires were used.

24 h urine samples and recovery biomarkers for protein and potassium intake

As the primary purpose of the 24 h urine collections was to validate 24-HDR, the urine samples were collected on the day of the 24-HDR interview or due to organisational reasons within a maximum of 6 d afterwards. The DQ were already collected before the 24-HDR, thus the time interval between collecting the DQ and urine samples was longer and varied from a few days to < 2 months in Bilthoven and the German centres to 2–5 years later in Turin (men), France and Naples[9].

The subjects provided one 24 h urine collection following a standardised protocol[24]. In order to verify completeness, each participant was given three 80 mg tablets of PABA (PABA-check; Laboratories for Applied Biology, London, UK) to be ingested on the day of urine collection[18]. The urine specimens were analysed centrally in Cambridge according to the standard procedures: total N was measured by the Kjeldahl technique (Tecator 1002; Perstorp Analytical Limited, Bristol, UK)[24]; K by using an IL 943 flame photometer (Instrumentation Laboratory, Warrington, UK)[19]; PABA by using colorimetry[25].

The 24 h urine collections containing 85–110 % of the PABA marker were considered complete. Urine specimens containing < 70 % PABA recovery (when fewer than three tablets have been taken and/or urine collection incomplete) and above 110 % (might happen when subjects take drugs that interfere with the colorimetric analysis) were excluded from the analysis. Urine samples with 70–84 % PABA recovery were used after correction for urinary electrolytes up to the expected values at 93 % of PABA recovery[26].

To calculate individual protein intake (g/d) from N excretion, 24 h urinary N was divided by 0·81 and then multiplied by 6·25[18]. Based on published studies that compared K intake with urinary excretion, the values of 24 h urinary K were divided by 0·81 (see the Discussion section) to convert urinary K to dietary K (g/d).

Statistical analysis

Dietary misreporting was defined as the individual log-ratio (log of the ratios of untransformed values) of reported intake to biomarker measurements of protein or K.

At the group level, log-ratios were back-transformed and reported as geometric means across groups. The magnitude of a deviation below or above the ratio of 1 defined the degree of under- or over-reporting. The *P* value for trend across BMI groups was calculated from individual-level regression. A paired *t* test was used to test differences between individual biomarker and dietary measurements within each pair. The means of the ratios were adjusted for age and sex and the 24-HDR data were additionally weighted for day of the week and season of recall using a generalised linear model.

British Journal of Nutrition

Multiple linear regression analyses were used to predict mean log-ratios of reported intake to biomarkers of protein or K by BMI and to control for *a priori* defined covariates including age, sex, education and country (centre). We also performed the regression of each of the urinary measurements (biomarkers) *v.* the respective dietary measurements and BMI to estimate the proportion of the total variability (adjusted R^2) of the biomarkers that can be accounted for by each of the dietary instruments after adjusting for age, sex and country. Urinary and dietary measurements were log-transformed to improve fit of the data (BMI values were untransformed). To show how much of the variability is accounted for by BMI, R^2 values with and without adjustment for BMI were also calculated.

Sensitivity analyses were performed by excluding subjects with reported EI that were unlikely to represent either habitual intake or a randomly low intake according to Goldberg's tables for lower and upper limits of EI over BMR (EI:BMR). Energy under-reporters, i.e. 'low-energy reporters (LER)', have EI:BMR ratios that differ from an assumed moderate physical activity level of 1·55 by more than −2 SD and energy over-reporters differ by more than +2 SD. Variation in BMR and physical activity level, daily variation in EI and the number of days of diet assessment were taken into account[27]. Thus, different cut-offs were used for 24-HDR (one single observation per individual) and DQ (long-term habitual diet). Participants with an EI:BMR ratio lower than 0·88 or higher than 2·72 were excluded from the analysis of the 24-HDR: 110 under-reporters (10·1 %) and thirteen over-reporters (1·2 %). On DQ, corresponding EI:BMR values were 1·14 for the lower limit and 2·10 for the upper limit, leading to exclusions of 271 under-reporters (25·0 %) and 73 over-reporters (6·7 %).

All reported *P* values are two-sided and statistical analyses were performed with SAS version 9.1 (SAS Institute, Cary, NC, USA) or STATA 11.1 (StataCorp, College Station, TX, USA).

Results

The study population consisted mainly of middle-aged people (range of mean age across centres: 51–60 years), except for men and women in The Netherlands and in Ragusa, who were younger (mean age in both centres: 48 years). The sample was 58 % female, reflecting the different sex distributions in the EPIC study (approximately 70 % women). When all countries were combined, 13 % of the subjects were obese, 37 % were overweight and 50 % had a normal weight (Table 1). There was a large variation in the distribution of obesity across countries, ranging from 1 % in France to 43 % in Greece (data not shown). The personal characteristics and the intake of energy and macronutrients of the study population are summarised in Table 1. Table S1 of the supplementary material (available online at http://www.journals.Cambridge.org/bjn) informs about the same variables, but with under- and over-reporters of EI excluded.

Protein under-reporting by BMI group

Tables 2 and 3 show the geometric means of protein intake based on dietary self-report instruments (i.e. 24-HDR and DQ) and biomarker measurements as well as the

Table 1. Personal characteristics and daily intake* of energy and macronutrients of 1086 adults (451 men and 635 women) participating in the European Prospective Investigation into Cancer and Nutrition calibration study by BMI group†
(Mean values with their standard errors)

	All weights		Normal weight		Overweight		Obese	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Age (years)	53·4	0·3	51·4	0·4	54·7	0·4	57·3	0·7
BMI (kg/m^2)	25·5	0·1	22·4	0·1	27·1	0·1	33·0	0·3
Energy (kJ)	8990	100	9020	140	9200	170	8250	270
Protein								
g	84·3	1·0	82·3	1·3	88·8	1·8	79·1	2·7
% kJ	16·1	0·1	15·7	0·2	16·5	0·2	16·4	0·4
Fat								
g	83·0	1·2	83·3	1·7	83·7	2·0	80·1	3·1
% kJ	34·4	0·3	34·2	0·4	33·9	0·5	36·4	0·9
Carbohydrate								
g	238·7	2·9	242·2	4·1	241·3	4·8	217·9	7·6
% kJ	45·0	0·3	45·5	0·4	44·3	0·5	44·6	0·8
Alcohol								
g	15·4	0·8	15·3	1·2	17·8	1·3	9·1	2·4
% kJ	4·6	0·2	4·5	0·3	5·2	0·4	2·7	0·4
Education (% of total)								
None/primary school	22		18		21		39	
Technical and professional school	27		24		33		27	
Secondary school	22		24		20		18	
University degree	25		30		21		13	
Missing	4		4		5		3	

* Calculated from 24 h dietary recalls.
† Normal weight (BMI < 25 kg/m^2), *n* 541; overweight (BMI 25 to <30 kg/m^2), *n* 406; obese (BMI ≥30 kg/m^2), *n* 139.

Table 2. Geometric means of protein intake based on biomarker measurements and dietary self-report instruments, and the respective ratios among adults in the European Prospective Investigation into Cancer and Nutrition calibration study by BMI group*
(Mean values, 95 % confidence intervals, number of subjects and percentages)†

	All sub-populations combined								
	All weights		Normal weight		Overweight		Obese		
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	*P* trend‡
No. of subjects	1086		541		406		139		
PBM§ (g/d)	95·6	93·7, 97·6	86·4	85·3, 89·6	95·7	93·2, 98·3	104·6	100·4, 108·9	
24-HDR (g/d)	81·9	78·8, 85·6	79·4	75·6, 83·1	82·5	78·8, 86·9	83·8	78·1, 90·0	
DQ (g/d)	86·3	84·4, 88·8	82·5	80·0, 85·0	86·3	83·8, 88·8	91·3	86·9, 95·6	
Ratios									
24-HDR:PBM	0·86		0·90		0·86		0·81		0·004
P‖	<0·0001		0·72		<0·005		<0·0001		
DQ:PBM	0·90		0·94		0·90		0·87		0·002
P‖	0·58		<0·0001		0·02		0·01		
Ratios, under- and over-reporters excluded¶									
24-HDR:PBM¶	0·90		0·90		0·91		0·90		0·74
P‖	0·87		0·22		0·73		0·01		
DQ:PBM¶	0·94		0·95		0·95		0·91		0·23
P‖	<0·0001		<0·0001		0·01		0·58		
Under- and over-reporters									
24-HDR¶									
n	123		40		56		27		
%	11·3		7·4		13·8		19·4		
DQ¶									
n	344		147		144		53		
%	31·7		27·2		35·5		38·1		

PBM, protein biomarker; 24-HDR, 24 h dietary recall; DQ, dietary questionnaire.
* Normal weight (BMI <25 kg/m^2); overweight (BMI 25 to <30 kg/m^2); obese (BMI ≥30 kg/m^2).
† All values are adjusted for age and sex; 24-HDR are additionally weighted for day of the week of recall and season.
‡ Calculated from individual-level regression using log-ratios.
§ Protein biomarker = urinary N/0·81 × 6·25.
‖ Paired *t* test of mean of differences between individual biomarker and dietary measurements (24-HDR and DQ) calculated from log-transformed values.
¶ Exclusion of under- and over-reporters of energy intake according to Goldberg *et al.*[27] assuming a physical activity level of 1·55.

respective ratios. The ratios of reported intake to biomarker show a strongly significant (P=0·004) trend to a greater degree of under-reporting of protein intake with increasing BMI using 24-HDR, for men and women of all countries combined. For DQ-derived protein, the estimated trend was slightly less in magnitude but also strongly significant (P=0·002). However, once under- and over-reporters of EI were excluded according to the Goldberg cut-off, there was no evidence of a systematic trend for under-reporting by BMI for either dietary method.

Considering men and women separately, the situation regarding a greater degree of under-reporting with increasing BMI was approximately the same for both sexes, although the trend in men was non-significant (P=0·18), presumably due to stratification leading to reduced power. For women, but not for men, the DQ yielded mean protein estimates closer to the biomarker measurements across BMI groups than did the 24-HDR (Table 3).

The detailed results for protein and K stratified by country are given in Tables S2 and S3 and presented graphically in Fig. S1 (supplementary material for this article can be found at http://www.journals.Cambridge.org/bjn).

Individual-level associations between protein under-reporting and BMI

In the regression analysis, BMI was a significant predictor of the log-ratio of reported intake to biomarker of protein for both dietary methods, after controlling for age, sex, education and country. With each unit (1 kg/m^2) increase in BMI, the log-ratio decreased by −0·017 (95 % CI −0·018, −0·016) and −0·013 (95 % CI −0·015, −0·012) on 24-HDR and DQ, respectively (both P<0·0001). After excluding under- and over-reporters of EI, BMI-related bias was attenuated to −0·007 (95 % CI −0·008, −0·006) and −0·008 (95 % CI −0·009, −0·006) for the 24-HDR and DQ, respectively (both P<0·0001). For example, for the 24-HDR, an approximately 8 % increase in protein under-reporting for a five-unit increase in BMI would be attenuated to approximately 3 %.

The BMI effect on protein under-reporting did not differ for men and women as tested by interaction between BMI and sex (P=0·74 on 24-HDR; P=0·20 on DQ). Similarly, there was no evidence for an interaction between BMI and country on protein under-reporting (P=0·15 on 24-HDR; P=0·29 on DQ). Additional tests to compare the significance of the main effect for country with and without adjustment for BMI showed that the country effect on the validity for the two instruments was independent of the BMI effect for both protein and K (data not shown).

The coefficient of determination was marginally higher on 24-HDR when compared with DQ when performing the regression of protein biomarker *v.* reported intake and BMI (adjusted R^2 0·33 *v.* 0·31). The partial R^2 of BMI was 0·06 and 0·04 on 24-HDR and DQ, respectively; thus, BMI explained 6 and 4 % of the variability in protein biomarker.

Table 3. Geometric means of protein intake based on biomarker measurements and dietary self-report instruments, and the respective ratios among adults in the European Prospective Investigation into Cancer and Nutrition calibration study by sex and BMI group*
(Mean values, 95 % confidence intervals, number of subjects and percentages)†

	All weights		Normal weight		Overweight		Obese		
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	*P* trend‡
Men									
No. of subjects		451		178		217		56	
PBM§ (g/d)	106·4	103·1, 109·9	97·3	93·4, 101·3	105·1	101·3, 109·0	117·9	110·6, 125·7	
24-HDR (g/d)	95·6	89·4, 102·5	93·8	86·3, 101·9	94·4	87·5, 101·9	99·4	88·8, 110·6	
DQ (g/d)	90·6	87·5, 93·8	85·0	81·3, 89·4	89·4	85·6, 93·1	96·9	90·0, 103·8	
Ratios									
24-HDR:PBM		0·89		0·96		0·89		0·82	0·18
P‖		0·04		0·27		0·12		<0·005	
DQ:PBM		0·85		0·88		0·85		0·82	0·009
P‖		<0·0001		0·02		<0·0001		<0·005	
Ratios, under- and over-reporters excluded¶									
24-HDR:PBM¶		0·92		0·92		0·91		0·91	0·75
P‖		0·73		0·32		0·65		0·15	
DQ:PBM¶		0·89		0·89		0·92		0·86	0·99
P‖		0·30		0·41		0·88		0·16	
Under- and over-reporters									
24-HDR¶									
n		42		10		22		10	
%		9·3		5·6		10·1		17·9	
DQ¶									
n		153		55		78		20	
%		33·9		30·1		35·9		35·7	
Women									
No. of subjects		635		363		189		83	
PBM§ (g/d)	84·5	82·3, 86·9	77·2	74·8, 79·7	85·3	82·1, 88·7	91·7	87·0, 96·6	
24-HDR (g/d)	69·4	65·6, 73·8	66·9	63·1, 71·3	70·6	65·6, 75·6	70·6	64·4, 77·5	
DQ (g/d)	78·8	76·3, 81·3	75·6	73·1, 78·8	78·1	75·0, 81·9	82·5	77·5, 87·5	
Ratios									
24-HDR:PBM		0·82		0·86		0·82		0·79	0·05
P‖		<0·005		0·76		0·01		<0·0001	
DQ:PBM		0·93		0·98		0·92		0·90	0·004
P‖		<0·0001		<0·0001		0·33		0·44	
Ratios, under- and over-reporters excluded¶									
24-HDR:PBM¶		0·88		0·87		0·89		0·88	0·60
P‖		0·93		0·42		1·00		0·01	
DQ:PBM¶		0·96		1·00		0·95		0·92	0·03
P‖		<0·0001		<0·0001		<0·005		0·52	
Under- and over-reporters									
24-HDR¶									
n		81		30		34		17	
%		12·8		8·3		18·0		20·5	
DQ¶									
n		191		92		66		33	
%		30·1		25·3		34·9		39·8	

PBM, protein biomarker; 24-HDR, 24 h dietary recall; DQ, dietary questionnaire.
* Normal weight (BMI <25 kg/m^2); overweight (BMI 25 to <30 kg/m^2); obese (BMI ≥30 kg/m^2).
† All values are adjusted for age; 24-HDR are additionally weighted for day of the week of recall and season.
‡ Calculated from individual-level regression using log-ratios.
§ Protein biomarker = urinary N/0·81 × 6·25.
‖ Paired *t* test of mean of differences between individual biomarker and dietary measurements (24-HDR and DQ) calculated from log-transformed values.
¶ Exclusion of under- and over-reporters of energy intake according to Goldberg *et al.*[27], assuming a physical activity level of 1·55.

Potassium under-reporting by BMI group

Table 4 shows a borderline significant (P=0·05) trend of K under-reporting with increasing BMI using 24-HDR, for men and women of all countries combined. After stratification by sex, a non-significant tendency towards BMI-related under-reporting remained for both men and women (Table 5).

On DQ, there was no significant trend across BMI groups either overall or considering men and women separately. Exclusion of under- and over-reporters of EI removed any evidence of a systematic trend also on 24-HDR.

Individual-level associations between potassium under-reporting and BMI

From regression analysis of the log-ratio of reported K intake to K biomarker on BMI, both dietary self-report instruments showed a similar inverse relationship with BMI, controlling

Table 4. Geometric means of potassium intake based on biomarker measurements and dietary self-report instruments, and the respective ratios among adults in the European Prospective Investigation into Cancer and Nutrition calibration study by BMI group*
(Mean values, 95 % confidence intervals, number of subjects and percentages)†

	All sub-populations combined								
	All weights		Normal weight		Overweight		Obese		
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	*P* trend‡
No. of subjects	1055		528		394		133		
KBM§ (g/d)	3·4	3·3, 3·5	3·3	3·2, 3·4	3·5	3·4, 3·6	3·5	3·3, 3·7	
24-HDR (g/d)	3·4	3·3, 3·6	3·4	3·3, 3·6	3·5	3·3, 3·7	3·4	3·1, 3·6	
DQ (g/d)	3·6	3·5, 3·6	3·4	3·3, 3·5	3·6	3·5, 3·7	3·7	3·5, 3·8	
Ratios									
24-HDR:KBM	0·99		1·02		1·01		0·94		0·05
P‖	0·10		0·99		0·30		0·02		
DQ:KBM	1·00		1·00		0·99		1·01		0·94
P‖	0·93		0·22		0·34		0·61		
Ratios, under- and over-reporters excluded¶									
24-HDR:KBM¶	1·03		1·01		1·06		1·01		0·39
P‖	0·17		0·63		0·10		0·98		
DQ:KBM¶	1·02		1·00		1·03		1·02		0·29
P‖	<0·005		0·02		0·01		0·81		
Under- and over-reporters									
24-HDR¶									
n	120		39		55		26		
%	11·4		7·4		14·0		19·6		
DQ¶									
n	335		146		138		51		
%	31·8		27·7		35·0		38·4		

KBM, potassium biomarker; 24-HDR, 24 h dietary recall; DQ, dietary questionnaire.
* Normal weight (BMI <25 kg/m^2); overweight (BMI 25 to <30 kg/m^2); obese (BMI ≥30 kg/m^2).
† All values are adjusted for age and sex; 24-HDR are additionally weighted for day of the week of recall and season.
‡ Calculated from individual-level regression using log-ratios.
§ Potassium biomarker = urinary K/0·81.
‖ Paired *t* test of mean of differences between individual biomarker and dietary measurements (24-HDR and DQ) calculated from log-transformed values.
¶ Exclusion of under- and over-reporters of energy intake according to Goldberg *et al.*[27] assuming a physical activity level of 1·55.

for age, sex, education and country. With each unit increase (1 kg/m^2) in BMI, the log-ratio decreased by −0·007 (95 % CI −0·009, −0·006; $P<0·0001$) using the 24-HDR and by −0·002 (95 % CI −0·004, −0·001; $P<0·01$) for the DQ. Exclusion of under- and over-reporters of EI attenuated the BMI-related bias on 24-HDR to −0·002 (95 % CI −0·004, −0·001; $P<0·01$), and it was no longer statistically significant for the DQ ($\beta = 0·001$; 95 % CI −0·001, 0·003; $P=0·30$).

As for protein, the BMI effect on K under-reporting did not differ for men and women; tested by interaction between BMI and sex ($P=0·22$ on 24-HDR; $P=0·29$ on DQ). Similarly, there was no evidence of heterogeneity in the BMI effect between countries as measured by interaction between BMI and country on K under-reporting ($P=0·75$ on 24-HDR; $P=0·29$ on DQ).

The coefficient of determination was substantially higher for 24-HDR when compared with DQ when performing the regression of K biomarker *v.* reported K intake and BMI (adjusted R^2 0·28 *v.* 0·15). BMI explained only about 1 % of the variability in K biomarker on both dietary methods.

Low-energy reporters and BMI

The probability that a subject was identified as a LER according to the Goldberg cut-off increased by 66 % for each five-unit increase in BMI adjusted for age, sex, education and country (OR from logistic regression: 1·66; 95 % CI 1·31, 2·10; $P<0·0005$).

Discussion

The focus of the present study was mainly on possible between-country differences in BMI-related dietary reporting errors because the same dietary self-report instrument, even if standardised, administered in diverse populations could lead to errors varying both in size and direction. Differential misreporting related to BMI and other person-specific biases have been shown to seriously distort measurement error correction procedures in nutritional epidemiological studies[2,10]. This problem would be amplified in a multi-centre study setting if the effect of BMI differed between centres (countries).

From the ratios of self-reported intake to biomarker measurements, a trend towards increasing under-reporting of both protein and K intake with increasing BMI was apparent on both dietary self-report instruments (i.e. 24-HDR and DQ). These observed differences in the validity of reporting protein and K intake with changing BMI are similar to those described in previous studies, which generally were conducted among less heterogeneous population groups[12,15,24,28,29]. The present study differed from the previous ones in that it recruited participants from twelve European regions (six European countries) with a large

Table 5. Geometric means of potassium intake based on biomarker measurements and dietary self-report instruments, and the respective ratios among adults in the European Prospective Investigation into Cancer and Nutrition calibration study by sex and BMI group*
(Mean values, 95 % confidence intervals, number of subjects and percentages)†

	All weights		Normal weight		Overweight		Obese		
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	*P* trend‡
Men									
No. of subjects	433		172		210		51		
KBM§ (g/d)	3·6	3·4, 3·7	3·5	3·4, 3·7	3·6	3·4, 3·8	3·6	3·3, 4·0	
24-HDR (g/d)	3·8	3·6, 4·1	3·9	3·6, 4·2	3·9	3·6, 4·2	3·7	3·3, 4·2	
DQ (g/d)	3·7	3·5, 3·8	3·6	3·4, 3·7	3·6	3·5, 3·8	3·8	3·5, 4·1	
Ratios									
24-HDR:KBM	1·04		1·08		1·10		0·96		0·17
P‖	0·56		0·34		0·43		0·21		
DQ:KBM	0·97		0·96		0·97		0·99		0·64
P‖	0·01		0·06		0·09		0·38		
Ratios, under- and over-reporters excluded¶									
24-HDR:KBM¶	1·05		1·03		1·12		1·01		0·50
P‖	0·02		0·58		<0·005		0·93		
DQ:KBM¶	0·98		0·94		1·01		0·99		0·15
P‖	0·82		0·29		0·27		0·59		
Under- and over-reporters									
24-HDR¶									
n	40		10		21		9		
%	9·2		5·8		10·0		17·7		
DQ¶									
n	147		54		75		18		
%	33·9		31·4		35·7		35·3		
Women									
No. of subjects	622		356		184		82		
KBM§ (g/d)	3·2	3·1, 3·3	3·0	2·9, 3·2	3·3	3·1, 3·4	3·3	3·0, 3·5	
24-HDR (g/d)	3·1	2·9, 3·3	3·0	2·9, 3·2	3·2	3·0, 3·4	3·1	2·8, 3·4	
DQ (g/d)	3·4	3·3, 3·5	3·3	3·1, 3·4	3·4	3·3, 3·6	3·5	3·3, 3·7	
Ratios									
24-HDR:KBM	0·95		0·98		0·95		0·92		0·12
P‖	<0·005		0·46		<0·005		0·05		
DQ:KBM	1·02		1·04		1·00		1·03		0·55
P‖	0·02		0·01		0·73		0·95		
Ratios, under- and over-reporters excluded¶									
24-HDR:KBM¶	1·01		1·00		1·00		1·01		0·85
P‖	0·65		0·86		0·29		0·92		
DQ:KBM¶	1·05		1·06		1·05		1·05		0·90
P‖	<0·0001		<0·005		0·01		0·42		
Under- and over-reporters									
24-HDR¶									
n	80		29		34		17		
%	12·9		8·2		18·5		20·7		
DQ¶									
n	188		92		63		33		
%	30·2		25·8		34·2		40·2		

KBM, potassium biomarker; 24-HDR, 24 h dietary recall; DQ, dietary questionnaire.
* Normal weight (BMI <25 kg/m^2); overweight (BMI 25 to <30 kg/m^2); obese (BMI ≥30 kg/m^2).
† All values are adjusted for age; 24-HDR are additionally weighted for day of the week of recall and season.
‡ Calculated from individual-level regression using log-ratios.
§ Potassium biomarker = urinary K/0·81.
‖ Paired *t* test of mean of differences between individual biomarker and dietary measurements (24-HDR and DQ) calculated from log-transformed values.
¶ Exclusion of under- and over-reporters of energy intake according to Goldberg *et al.*[27], assuming a physical activity level of 1·55.

geographical variation and with a greater diversity in their dietary patterns[30,31]. The results indicate that the effect of BMI on protein and K under-reporting did not differ between countries, neither using the 24-HDR nor the DQ. This is encouraging and suggests that measurement error correction procedures that adjust for BMI-specific biases should perform equally well across diverse populations in multi-centre studies, at least in the EPIC study. The differences in under-reporting of protein intake between the countries included in the present analysis have been described in Slimani *et al.*[9].

The present study also shows that exclusion of individuals who probably misreported EI according to Goldberg *et al.*[27] removed any evidence of BMI-related bias at the group level and at least attenuated its degree at the individual level for both protein and K on both dietary assessment methods. The main explanation for this finding is that among overweight and obese individuals, there was a higher proportion of 'LER' who also under-reported protein and K. This may in turn either be explained by a higher sensitivity of the Goldberg cut-off in individuals with a higher BMI as they possibly

under-report from lower energy requirements due to lower physical activity such that their EI:BMR ratios are below the cut-off for an assumed physical activity level of 1·55 or by less differential (mis-) reporting of foods. However, the latter seems rather unlikely as dietary under-reporting by obese individuals has already been described as being selective[12]. Although the Goldberg cut-off has limitations when applied at the individual level because of its low sensitivity[32], the present results suggest that its application may be an option to ameliorate the problem of differential misreporting with increasing BMI. It may therefore be conceivable to apply exclusions to overweight and obese individuals only as a straightforward procedure to minimise bias in a dataset. As recommended by Black[32], individuals should also be assigned into appropriate physical activity level categories for calculating the Goldberg cut-off in order to increase its sensitivity, which, however, was out of the scope of the present study. On the other hand, it might be impossible to exclude about one-third of a sample from the analysis, which would be the case according to the present DQ data. For 24-HDR, the problem seems not as extreme, but exclusion of about 10–20 % of a sample would still considerably reduce the power of a study and may specifically exclude (obese) subjects whose diets are of particular interest in relation to diseases.

Using energy-adjusted nutrient intake is an alternative approach for bias correction. Stallone *et al.*[33] compared the performance of both approaches in assessing sociodemographic differences in nutrient intake. They argued that energy adjustment was preferable to excluding LER, mainly because exclusions were highest among lower sociodemographic levels leading to selection bias. Restricting the analysis to plausible energy reporters only may, of course, reduce external validity or generalisability of study findings. However, a primary requirement of a generalisable study is internal validity[34], which seems to be increased by the exclusion of LER. Whether more complex measurement error models, which adjust for BMI-specific bias[14], would be a way out of that dilemma needs further evaluation.

Under-reporting of protein intake is also indicative of a degree of under-reporting of EI, while the use of LER does not necessarily identify under-reporting of protein intake to the same extent due to differential reporting of foods[8]. This implies that energy-adjusted protein intake may still differ between LER and non-LER. In contrast to previous studies[24,35], we found similar energy-adjusted protein intake (% kJ) across BMI groups, confirming that energy adjustment may indeed remove some of the measurement error[2]. This is in line with findings of Lissner *et al.*[15], who showed that correlations between reported protein intake and protein biomarker in obese groups were improved relative to non-obese after energy adjustment. However, this does not exclude non-measured relative changes among the other macronutrients – i.e. fat, carbohydrate and alcohol – due to possible differential reporting of foods.

Compared with protein intake, BMI-related under-reporting of K intake was of a smaller magnitude at the individual level on both instruments, suggesting some food-specific misreporting. The weaker or absent group-level evidence of BMI-related K under-reporting is presumably attributable to loss of power due to categorisation. We explored K misreporting also by evaluating under-reporting of the ratio of K:protein as a proxy for energy-adjusted K intake, which confirmed that relative to protein, K under-reporting was less in magnitude, but still significantly predicted by BMI at the individual level on both methods and in both sexes (data not shown). Differential reporting of nutrients is possibly related to differential reporting of its food sources. In the EPIC study populations, the major food sources of protein and K differ to some extent, thus differential under-reporting of these nutrients is conceivable. Food sources for K from diet are fruits and vegetables (approximately 26 %), non-alcoholic beverages (approximately 14 %), cereals and products (approximately 13 %), meats and products (approximately 13 %) and dairy products (approximately 12 %)[36]. In contrast, protein sources are between 55 and 73 % of animal origin (not counting the UK health-conscious group) and between 24 and 39 % of plant origin, mostly from cereals (approximately 20 %) and less from fruits and vegetables (approximately 6 %)[37]. Although it was not possible to determine whether specific foods were systematically under- or over-reported, we know from the literature that DQ tend to overestimate specific foods, particularly vegetables[11,38] and that LER tend to report more socially desirable foods, including fruits and vegetables[8]. We may speculate that these 'good' foods, which tend to have a higher K content, are more often over-reported. However, as with almost all other nutrients, K intake is also related to EI (Pearson's r between intake of K and energy on 24-HDR and DQ were both 0·64, both $P<0·001$). Thus, the proportion of LER who simultaneously under-report K intake is still higher when compared with LER who differentially report K intake and those individuals are more likely to be overweight or obese. The latter is supported by the results of Zhang *et al.*[28], who showed that under-reporting of K intake was more prevalent in subjects with a higher BMI while subjects with a lower BMI more frequently over-reported.

The differential reporting of protein and K intake might also be attributable to differences in the validity of the two respective biomarkers. There is more uncertainty about the proportion of K intake excreted into urine when compared with N. We found a considerable between-study variation of urinary K excretion (0·76–0·89)[19,39,40–44], and we used the crude mean (0·81) of those studies to correct for extra-renal losses of K. If this factor was, for example, too large, then K excretion would be underestimated, leading to a false conclusion that K intake was not or to a lesser extent under-reported. However, the use of different correction factors (data not shown) did not change the strength of the association between BMI and K under-reporting. This has similarly been shown by Zhang *et al.*[28].

Similar to the results of the Observing Protein and Energy Nutrition study[3,10], we found that a single 24-HDR predicted protein intakes at the individual level almost as well as DQ across BMI categories including obese subgroups and outperformed DQ in predicting K intakes (results of stratification by BMI group are not shown, but they are similar to the

combined analysis). Differences in the performance of the two dietary methods in the present study may be explained by the high degree of standardisation of the 24-HDR across countries within the EPIC calibration study when compared with country-specific DQ. For other nutrients, with higher daily within-person variation in intakes, DQ might perform better relative to 24-HDR.

The two dietary self-report instruments differed slightly between men and women in estimating mean intakes, although the effect of BMI on misreporting was the same for both sexes. In women, the DQ seems to yield higher mean intakes of protein and K that were closer to the biomarker-based measurements across BMI categories when compared with 24-HDR.

Among the limitations of the study are that the convenience sample was not recruited from all centres of the EPIC study. Thus, caution should be taken in the extrapolation of the data to the whole EPIC cohort or general population. Furthermore, due to the small number of participants at the country (centre) level, results may be less consistent in the stratified analysis. Another limitation concerns the collection of the 24 h urine specimens. At least 189 (13·6 %) subjects did not succeed in obtaining a 24 h urine collection. In addition, a large proportion of these subjects were obese. Although the time interval between collection of urinary and dietary measurements varied considerably across centres, particularly on DQ, respective effects were estimated to be probably very modest[9].

In conclusion, under-reporting of protein and K intake appears to be predicted by BMI, but this effect may be driven mostly by individuals who probably misreported EI. The BMI effect on protein and K under-reporting seems to be the same across countries despite their diverse dietary patterns and other cultural differences. These results may aid in the interpretation of nutritional epidemiological findings and suggest that future analyses of EPIC data should be accompanied by a sensitivity analysis to explore the robustness of results obtained with and without exclusion of energy misreporters on DQ and, in case regression calibration is used, on 24-HDR.

Acknowledgements

PANACEA (Physical Activity, Nutrition, Alcohol, Cessation of smoking, Eating out of home And obesity) uses data collected as part of the EPIC, co-financed by the European Commission (PANACEA no. 2005328). The present study was financially supported by the European Commission: Public Health and Consumer Protection Directorate 1993–1994; Research Directorate General 2005–; Ligue contre le Cancer, Societé 3M, Mutuelle Générale de l'Education Nationale, Institut National de la Santé et de la Recherche Médicale (INSERM) (France); German Cancer Aid, German Cancer Research Center, Federal Ministry of Education and Research (Germany); Danish Cancer Society (Denmark); Health Research Fund (FIS) of the Spanish Ministry of Health, the participating regional governments and institutions and the ISCIII (Instituto de Salud Carlos III) of the Spanish Ministry of Health (RETICC DR06/0020) (Spain); Cancer Research UK, Medical Research Council, Stroke Association, British Heart Foundation, Department of Health, Food Standards Agency, the Wellcome Trust (UK); Greek Ministry of Health and Social Solidarity, Hellenic Health Foundation and Stavros Niarchos Foundation (Greece); Italian Association for Research on Cancer, National Research Council (Italy); Dutch Ministry of Public Health, Welfare and Sports (VWS), Netherlands Cancer Registry (NKR), LK Research Funds, Dutch Prevention Funds, Dutch ZON (Zorg Onderzoek Nederland), World Cancer Research Fund (WCRF) (The Netherlands); Swedish Cancer Society, Swedish Scientific Council, Regional Government of Skane (Sweden); Nordforsk (Norway). H. F. contributed to the analysis and interpretation of the data and wrote the manuscript, taking into account comments from all co-authors. M. M. E. v. B., C. B., G. B., A. M. M., P. H. P., T. N., S. R. and N. S. contributed to the conception, analysis and interpretation of the data and drafting of the manuscript. E. R. is the overall coordinator of the EPIC study and all other co-authors were local EPIC collaborators involved in the collection of dietary and other data. All of them gave input on drafting of the manuscript and interpretation of the results. All authors read and approved the final version. The authors declare no conflict of interest.

References

1. Kaaks R & Riboli E (1997) Validation and calibration of dietary intake measurements in the EPIC project: methodological considerations. European Prospective Investigation into Cancer and Nutrition. *Int J Epidemiol* **26**, Suppl. 1, S15–S25.
2. Kipnis V, Subar AF, Midthune D, *et al.* (2003) Structure of dietary measurement error: results of the OPEN biomarker study. *Am J Epidemiol* **158**, 14–21.
3. Schatzkin A, Kipnis V, Carroll RJ, *et al.* (2003) A comparison of a food frequency questionnaire with a 24-hour recall for use in an epidemiological cohort study: results from the biomarker-based Observing Protein and Energy Nutrition (OPEN) study. *Int J Epidemiol* **32**, 1054–1062.
4. Kaaks R, Plummer M, Riboli E, *et al.* (1994) Adjustment for bias due to errors in exposure assessments in multicenter cohort studies on diet and cancer: a calibration approach. *Am J Clin Nutr* **59**, Suppl. 1, S245–S250.
5. Plummer M, Clayton D & Kaaks R (1994) Calibration in multi-center cohort studies. *Int J Epidemiol* **23**, 419–426.
6. Slimani N, Kaaks R, Ferrari P, *et al.* (2002) EPIC calibration study: rationale, design and population characteristics. *Public Health Nutr* **5**, 1125–1145.
7. Hill RJ & Davies PS (2001) The validity of self-reported energy intake as determined using the doubly labelled water technique. *Br J Nutr* **85**, 415–430.
8. Livingstone MBE & Black AE (2003) Markers of the validity of reported energy intake. *J Nutr,* **133**, Suppl. 3, S895–S920.
9. Slimani N, Bingham SA, Runswick SA, *et al.* (2003) Group level validation of protein intakes estimated by 24-hour diet recall and dietary questionnaires against 24-hour urinary nitrogen in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration study. *Cancer Epidemiol Biomarkers Prev* **12**, 784–795.
10. Subar AF, Kipnis V, Troiano RP, *et al.* (2003) Using intake biomarkers to evaluate the extent of dietary misreporting in a large sample of adults: the OPEN study. *Am J Epidemiol* **158**, 1–13.

11. Michels KB, Welch AA, Luben R, *et al.* (2005) Measurement of fruit and vegetable consumption with diet questionnaires and implications for analyses and interpretation. *Am J Epidemiol* **161**, 987–994.
12. Heitmann B & Lissner L (1995) Dietary under-reporting by obese individuals: is it specific or nonspecific? *BMJ* **311**, 986–989.
13. Poppitt SD, Swann D, Black AE, *et al.* (1998) Assessment of selective under-reporting of food intake by both obese and non-obese women in a metabolic facility. *Int J Obes Relat Metab Disord* **22**, 303–311.
14. Ferrari P, Slimani N, Ciampi A, *et al.* (2002) Evaluation of under- and overreporting of energy intake in the 24-hour diet recalls in the European Prospective Investigation into Cancer and Nutrition (EPIC). *Public Health Nutr* **5**, 1329–1345.
15. Lissner L, Troiano RP, Midthune D, *et al.* (2007) OPEN about obesity: recovery biomarkers, dietary reporting errors and BMI. *Int J Obes* **31**, 956–961.
16. Scagliusi FB, Ferriolli E, Pfrimer K, *et al.* (2008) Underreporting of energy intake in Brazilian women varies according to dietary assessment: a cross-sectional study using doubly labeled water. *J Am Diet Assoc* **108**, 2031–2040.
17. Kaaks R, Ferrari P, Ciampi A, *et al.* (2002) Uses and limitations of statistical accounting for random error correlations, in the validation of dietary questionnaire assessments. *Public Health Nutr* **5**, 969–976.
18. Bingham SA & Cummings JH (1985) Urine nitrogen as an independent validatory measure of dietary intake: a study of nitrogen balance in individuals consuming their normal diet. *Am J Clin Nutr* **42**, 1276–1289.
19. Tasevska N, Runswick SA & Bingham SA (2006) Urinary potassium is as reliable as urinary nitrogen for use as a recovery biomarker in dietary studies of free living individuals. *J Nutr* **136**, 1334–1340.
20. Riboli E, Hunt KJ, Slimani N, *et al.* (2002) European Prospective Investigation into Cancer and Nutrition (EPIC): study populations and data collection. *Public Health Nutr* **5**, 1113–1124.
21. Margetts BM & Pietinen P (1997) European Prospective Investigation into Cancer and Nutrition: validity studies on dietary assessment methods. *Int J Epidemiol* **26**, Suppl. 1, S1–S189.
22. Slimani N, Ferrari P, Ocké M, *et al.* (2000) Standardisation of the 24-hour diet recall calibration method used in the European Prospective Investigation into Cancer and Nutrition (EPIC): general concepts and preliminary results. *Eur J Clin Nutr* **54**, 900–917.
23. Slimani N, Deharveng G, Unwin I, *et al.* (2007) The EPIC nutrient database project (ENDB): a first attempt to standardize nutrient databases across the 10 European countries participating in the EPIC study. *Eur J Clin Nutr* **61**, 1037–1056.
24. Bingham SA, Cassidy A, Cole T, *et al.* (1995) Validation of weighed records and other methods of dietary assessment using the 24 h urine nitrogen technique and other biological markers. *Br J Nutr* **73**, 531–550.
25. Bingham SA, Williams R, Cole TJ, *et al.* (1988) Reference values for analytes of 24-h urine collections known to be complete. *Ann Clin Biochem* **25**, 610–619.
26. Johansson G, Bingham SA & Vahter M (1999) A method to compensate for incomplete 24 h urine collections in nutritional epidemiological studies. *Public Health Nutr* **2**, 587–591.
27. Goldberg GR, Black AE, Jebb SA, *et al.* (1991) Critical evaluation of energy intake data using fundamental principles of energy physiology: 1. Derivation of cut-off limits to identify under-recording. *Eur J Clin Nutr* **45**, 569–581.
28. Zhang J, Temme EH, Sasaki S, *et al.* (2000) Under- and over-reporting of energy intake using urinary cations as biomarkers: relation to body mass index. *Am J Epidemiol* **152**, 453–462.
29. Neuhouser ML, Tinker L, Shaw PA, *et al.* (2008) Use of recovery biomarkers to calibrate nutrient consumption self-reports in the Women's Health Initiative. *Am J Epidemiol* **167**, 1247–1259.
30. Slimani N, Fahey M, Welch AA, *et al.* (2002) Diversity of dietary patterns observed in the European Prospective Investigation into Cancer and Nutrition (EPIC) project. *Public Health Nutr* **5**, 1311–1328.
31. Freisling H, Fahey MT, Moskal A, *et al.* (2010) Region-specific nutrient intake patterns exhibit a geographical gradient within and between European countries. *J Nutr* **140**, 1280–1286.
32. Black AE (2000) The sensitivity and specificity of the Goldberg cut-off for EI:BMR for identifying diet reports of poor validity. *Eur J Clin Nutr* **54**, 395–404.
33. Stallone DD, Brunner EJ, Bingham SA, *et al.* (1997) Dietary assessment in Whitehall II: the influence of reporting bias on apparent socioeconomic variation in nutrient intakes. *Eur J Clin Nutr* **51**, 815–825.
34. Franceschi S & Plummer M (2005) Intervention trials. In *Handbook of Epidemiology*, 1st ed., pp. 345–370 [W Ahrens and I Pigeot, editors]. Heidelberg: Springer.
35. Voss S, Kroke A, Klipstein-Grobusch K, *et al.* (1998) Is macronutrient composition of dietary intake data affected by underreporting? Results from the EPIC-Potsdam Study. European Prospective Investigation into Cancer and Nutrition. *Eur J Clin Nutr* **52**, 119–126.
36. Welch AA, Fransen H, Jenab M, *et al.* (2009) Variation in intakes of calcium, phosphorus, magnesium, iron and potassium in 10 countries in the European Prospective Investigation into Cancer and Nutrition study. *Eur J Clin Nutr* **63**, Suppl. 4, S101–S121.
37. Halkjaer J, Olsen A, Bjerregaard LJ, *et al.* (2009) Intake of total, animal and plant proteins, and their food sources in 10 countries in the European Prospective Investigation into Cancer and Nutrition. *Eur J Clin Nutr* **63**, Suppl. 4, S16–S36.
38. Goldbohm RA, van den Brandt PA, Brants HA, *et al.* (1994) Validation of a dietary questionnaire used in a large-scale prospective cohort study on diet and cancer. *Eur J Clin Nutr* **48**, 253–265.
39. Mickelsen O, Makdani D, Gill JL, *et al.* (1977) Sodium and potassium intakes and excretions of normal men consuming NaCl or a 1:1 mixture of sodium and potassium chlorides. *Am J Clin Nutr* **30**, 2033–2040.
40. McDonald JT & Margen S (1979) Wine versus ethanol in human nutrition. II. Fluid, sodium, and potassium balance. *Am J Clin Nutr* **32**, 817–822.
41. Voors AW, Dalferes ER Jr, Frank GC, *et al.* (1983) Relation between ingested potassium and sodium balance in young Blacks and whites. *Am J Clin Nutr* **37**, 583–594.
42. Holbrook JT, Patterson KY, Bodner JE, *et al.* (1984) Sodium and potassium intake and balance in adults consuming self-selected diets. *Am J Clin Nutr* **40**, 786–793.
43. Clark AJ & Mossholder S (1986) Sodium and potassium intake measurements: dietary methodology problems. *Am J Clin Nutr* **43**, 470–476.
44. Dériaz O, Thériault G, Lavallée N, *et al.* (1991) Human resting energy expenditure in relation to dietary potassium. *Am J Clin Nutr* **54**, 628–634.

British Journal of Nutrition