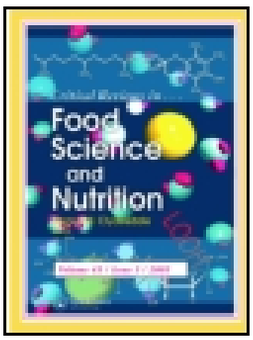

Critical Reviews in Food Science and Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

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**To cite this article:** Qi Cui, Yang Xia, Qijun Wu, Qing Chang, Kaijun Niu & Yuhong Zhao (2021): Validity of the food frequency questionnaire for adults in nutritional epidemiological studies: A systematic review and meta-analysis, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2021.1966737

**To link to this article:** https://doi.org/10.1080/10408398.2021.1966737

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2021.1966737

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REVIEW



# Validity of the food frequency questionnaire for adults in nutritional epidemiological studies: A systematic review and meta-analysis

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**ABSTRACT**

As the most widely used tool for assessing dietary intake, the validity of food frequency questionnaires (FFQs) should be evaluated before application. A comprehensive search of the PubMed and Web of Science databases was conducted for publications from January 2000 to April 1, 2020. Pooled estimates were calculated for correlation coefficients and mean differences for energy and 61 nutrients between FFQs and standard methods. The literature search identified 130 articles that included 21,494 participants. Subgroup analyses according to the number of administrations of the reference method, sample size, administration methods, FFQ items, reference periods, quality of the studies, gender, and regions were also performed. We conducted a meta-analysis by summarizing the available evidence to comprehensively assess the validity of FFQs stratified by the reference method type (24-hour recall (24HRs) and food records (FRs). We also performed subgroup analyses to examine the impact on the final summary estimates. After a meta-analysis of the FFQs' validity correlation coefficients of the included studies, this study showed that the range (median) of the validity coefficients of the 24HRs as reference methods was 0.220–0.770 (0.416), and for the FRs, it was 0.173–0.735 (0.373), which indicated that FFQs were suitable to assess the overall dietary intake in nutritional epidemiological studies. The results of the subgroup analysis showed that the number of administrations of the reference method, administration mode, number of items, reference periods, sample size, and gender mainly affected the validity correlation of FFQs.

**KEYWORDS**

Food frequency questionnaire; validity; correlation coefficient; standardized mean difference; 24-hour recall; food record

## Introduction

The food frequency questionnaire (FFQ) is the most widely used tool to assess dietary intake because it is relatively inexpensive, easy to administer, and describes long-term food habits (Subar 2004). FFQs include a preselected list of foods, for which individuals are asked to describe the typical consumption frequency over time and sometimes to state the average amount consumed (Hu et al. 1999). FFQs are used to predict associations between dietary factors and disease or health outcomes and rank participants accurately according to their dietary and nutrition intake in large-scale surveys (Willett et al. 1988).

Because dietary habits vary depending on participants' social, cultural, and ethnic backgrounds, FFQs need to be current, specific, and culturally appropriate for the target population (Cade et al. 2002). Before FFQs are used, the particular design and quality of FFQs in the target population must be considered (Wakai 2009). Reproducibility is one important aspect of the quality of FFQ. A recent meta-analysis on the reproducibility of FFQs was performed to systematically assess the repeatability of FFQ and explore factors related to the reproducibility of FFQ (Cui et al. 2021). Another important aspect of the quality of FFQ is validity. Validation studies are to assess whether the questionnaire is measuring what it should measure or to assess the degree to which the questionnaire agrees with a "gold standard" or other standard measures of diet (Cade et al. 2002). Although there is no perfect measure of dietary intake, multiple days of 24-hour recalls (24HRs) and food records (FRs) have frequently been used as the reference methods in many validation studies. They are open-ended and do not have the same restrictions as semi-quantitative FFQs that use a limited food list or fixed portion size (Whitton et al. 2017). As FFQ presents similar source of error to 24HRs rather than FRs (Cade et al. 2004), we focused our analysis on the validity of FFQs stratified by the reference method type.

In addition, some questionnaire characteristics have proven to be related to the validity of FFQs, such as FFQ length, portion size use, and "origin" of FFQ (e.g., the Willett type, the Block type, the European Prospective Investigation into Cancer and Nutrition (EPIC) type) (Molag et al. 2007). For example, a previous meta-analysis of the

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Supplemental data for this article is available online at https://doi.org/10.1080/10408398.2021.1966737.
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validity of FFQs targeting adolescents was performed to investigate their overall accuracy and found interviewer administration mode, reference period of the previous year/6 months and high number of food items might reduce FFQ accuracy (Tabacchi et al. 2016). The accuracy of dietary assessment among adolescents differs from adults because the ability of adolescents to assess dietary information is affected by factors such as motivation to complete evaluations, reporting bias associated with unstructured eating patterns, the level of attention paid to body image, and weight status (Livingstone and Robson 2000; Livingstone, Robson, and Wallace 2004). However, no study has reviewed the complex factors that can affect FFQs' accuracy among adults. Moreover, energy and nutrients measured by FFQs exceeded those recorded from recalls or FRs (Dehghan et al. 2013; Denova-Gutierrez et al. 2016; Kusama et al. 2005; Paalanen et al. 2006; Torheim et al. 2001). However, some studies have yielded contradictory results indicating that FFQs underestimate nutrient intake (Ahn et al. 2007; Ogawa et al. 2003).

Thus, we conducted a meta-analysis by summarizing the available evidence to comprehensively assess the FFQs' validity stratified by the reference method type (24HRs and FRs) and performed subgroup analyses to explore the influence of related factors of the validation study on final summary estimates, which provide evidence for a design and optimal validity study. Moreover, we explored whether FFQs tended to overestimate or underestimate nutrient intake to analyze nutrient intake accurately and further clarify FFQ application.

## Materials and methods

### Data sources

A systematic literature search was conducted for articles published between January 2000 and April 1, 2020 on the PubMed and Web of Science databases. The search strategy combined the following keywords: "FFQ," "Food Frequency Questionnaire," "Validation," and "Validity."

### Study selection

The inclusion criteria were as follows: (1) studies describing dietary assessment methods developed for epidemiological purposes; (2) studies needed to validate FFQs against other dietary assessment methods (24HRs and FRs); (3) studies where the purpose was to measure nutrient intake; (4) studies targeting healthy adults (aged ≥18 years); (5) studies where FFQs' validation was measured with the Pearson or Spearman correlation coefficient; and (6) studies published in English. If it was unclear whether an article should be included from an abstract review, the full article was retrieved.

The exclusion criteria for the meta-analysis were as follows: (1) focused on participants with a disease or other particular groups (such as athletes, soldiers, or pregnant women); (2) examined a nutrient–disease relationship; (3) FFQs specific to certain nutrients (folate, vitamins, calcium, fats, proteins, etc.); (4) FFQs specific to food; (4) studies involved in methodological comparison; (5) articles could not be found through web searches; and (6) intervention studies.

### Data extraction

Data were screened and extracted by two trained reviewers regarding authors, titles, publication year, country, population characteristics (size, age, and gender distribution), FFQ characteristics (number of food items, reference periods, administration mode), reference methods' characteristics, and the statistics employed to assess validity between the two methods.

Data indicating correlation and agreement between the FFQs and the reference methods were considered: mean and standard deviations (SDs); Pearson or Spearman correlation coefficients (crude, energy-adjusted, and de-attenuated). The reference methods used to collect dietary information for multiple days and day-to-day variation is the main source of random error of dietary assessment. De-attenuated correlation coefficients were calculated to mitigate the impact of within-individual random errors related to dietary intake assessment (Rosner and Willett 1988).

We extracted these values for energy, vitamins, minerals, and other nutrients.

Vitamins included vitamin A, retinol, vitamin C, vitamin D, vitamin E, vitamin K, thiamin, riboflavin, niacin, pantothenic acid, vitamin B6, folate, and vitamin B12.

Minerals included selenium (Se), magnesium (Mg), calcium (Ca), iron (Fe), iodine (I), zinc (Zn), copper (Cu), potassium (K), phosphorus (P), sodium (Na), and manganese (Mn).

Other nutrients included carbohydrate, protein, fat, plant fat, *trans*-fat, cholesterol, sugar, starch, alcohol, caffeine, water, lycopene, cryptoxanthin, carotene, α-carotene, β-carotene, α-tocopherol, β-tocopherol, daidzein, genistein, fiber, water-soluble fiber, water-insoluble fiber, monounsaturated fatty acid (MUFA), polyunsaturated fatty acid (PUFA), n-3 PUFA, n-6 PUFA, saturated fatty acid, linoleic acid, linolenic acid, total fatty acid (TFA), n-3 fatty acid, n-6 fatty acid, docosahexaenoic acid (DHA), and eicosatetraenoic acid (EPA).

The quality of the different validation studies was evaluated according to the quality score system (Serra-Majem et al. 2009). In this system, the following variables are used for analysis: (1) sample and study sample size; (2) statistics to assess validity; (3) data collection; (4) seasonality; and (5) supplements. According to the scores, we divided the study quality into the following categories: (1) very good (≥ 5.0); (2) good (3.5 ≤ score < 5.0); (3) acceptable (2.5 ≤ score < 3.5); and (4) poor (<2.5). The detailed information is shown in Supplemental Table 1.

### Factors selection for subgroup analysis

In addition, many factors may affect the accuracy of a FFQ such as participant characteristics, adequacy of the reference data, questionnaire design (Serra-Majem et al. 2009). First,

**Table 1.** Summary of the characteristics of included studies.[a]

| Characteristics | Overall | 24-hour recalls | Food records |
|---|---|---|---|
| Number of studies | 130 | 66 | 67 |
| Sample size[b] | 103 (20 – 1623) | 133.5 (40 – 1623) | 96.5 (20 – 468) |
| Men (%)[c] | 39.61 (26.03 – 48.17) | 39.89 (26.66 – 48.48) | 39.31 (27.02 – 47.42) |
| Age (year)[c] | 46.65 (36.80 – 53.60) | 47.70 (36.80 – 53.50) | 46.00 (35.33 – 53.68) |
| Items of FFQ[b] | 126 (18 – 322) | 126 (44 – 322) | 120 (18 – 240) |
| Administration mode of FFQ[d] | | | |
| Interview-administered | 53 (40.77) | 36 (54.55) | 18 (26.87) |
| Self-administered | 54 (41.54) | 20 (30.30) | 36 (53.73) |
| Not available | 23 (17.69) | 10 (15.15) | 13 (19.40) |
| Reference period[d] | | | |
| Previous 12 months | 84 (64.62) | 45 (68.18) | 40 (59.70) |
| <Previous 12 months | 29 (22.31) | 14 (21.21) | 16 (23.88) |
| Not available | 17 (13.08) | 7 (10.61) | 11 (16.42) |
| Type of FFQ[d] | | | |
| Non-quantitative | 7 (5.38) | 4 (6.06) | 3 (4.48) |
| Semi-quantitative | 93 (71.54) | 48 (72.73) | 50 (74.63) |
| Quantitative | 25 (19.23) | 12 (18.18) | 12 (17.91) |
| Not available | 5 (3.85) | 3 (4.55) | 2 (2.99) |
| Quality of studies[d] | | | |
| Very good | 25 (19.23) | 19 (28.79) | 7 (10.45) |
| Good | 75 (57.69) | 38 (57.58) | 36 (53.73) |
| Acceptable | 30 (23.08) | 9 (13.64) | 24 (35.82) |
| Regions[d] | | | |
| Asia | 41 (31.54) | 16 (24.24) | 26 (38.81) |
| Europe | 32 (24.62) | 17 (25.76) | 15 (22.39) |
| Africa | 7 (5.38) | 5 (7.58) | 2 (2.99) |
| South America | 16 (12.31) | 12 (18.18) | 4 (5.97) |
| North America | 26 (20.00) | 16 (24.24) | 12 (17.91) |
| Oceania | 8 (6.15) | N/A | 8 (11.94) |

FFQ, food frequency questionnaire; N/A, not available.
[a]A total of 130 studies were included, and three studies used the two reference methods (24-hour recall and food records) to assess the validity of FFQs.
[b]Values are median (range).
[c]Values are median (interquartile range).
[d]Values are N (%).

for participant characteristics, gender is an important influence on food choice and portion size, which may affect the validity of FFQ (Lee et al. 2016a). Second, the validation studies of FFQ often included multiple assessments of reference methods. Meanwhile, the daily intake of dietary nutrients varies greatly, which means more times of dietary assessment may provide a more accuracy of dietary intake (Henriquez-Sanchez et al. 2009). Third, some questionnaire characteristics have proven to be related to the validity of FFQs, such as FFQ length, and portion size use (Molag et al. 2007). For example, a previous meta-analysis of the validity of FFQs targeting adolescents was performed to investigate their overall accuracy and found interviewer administration mode, reference period of the previous year/6 months and high number of food items might reduce FFQ accuracy (Tabacchi et al. 2016). The accuracy of dietary assessment among adolescents differs from adults because the ability of adolescents to assess dietary information is affected by factors such as motivation to complete evaluations, reporting bias associated with unstructured eating patterns, the level of attention paid to body image, and weight status (Livingstone and Robson 2000; Livingstone, Robson, and Wallace 2004). However, no study has reviewed the complex factors that can affect FFQs' accuracy among adults.

## *Statistical analysis*

To utilize data more effectively, we converted the Pearson correlation coefficient into the Spearman correlation coefficient as the latter was not affected by logarithmic transformation (Rupinski and Dunlap 1996). Because Spearman correlation coefficients are not normally distributed, they were converted by Fisher's r-to-z transformation to obtain approximately normally distributed z values. The transformation of correlation coefficient values (r) to Fisher's z is given by $z = 0.5[\ln(1+r) - \ln(1-r)]$. The standard error of z is $SE = 1/\sqrt{n-3}$ (Muehlbauer, Gollhofer, and Granacher 2015). After Fisher's z transformation, a meta-analysis was used to combine the data (Wilson and Lipsey 2001). Furthermore, we calculated pooled correlation coefficients and 95% confidence intervals (CIs) by the formula to interpret the results: $r = (e^{2z} - 1)/(e^{2z} + 1)$. When two values were available for men and women in one article, a meta-analysis was used to combine the two values, which considered the number of men and women. Then, the combined effect values served as the representative values used to assess.

Standardized mean differences (SMDs) were calculated using nutrient intake levels from FFQs minus those from reference methods. For means and SDs, SMD and 95% CIs were used to show the effective index of quantitative data. If the means and SDs were lacking in some studies, they were calculated in accordance with the median and interquartile range (Wan et al. 2014).

Heterogeneity was obtained by calculating the inconsistency index ($I^2$) (Zamora et al. 2006). Based on the value of $I^2$, heterogeneity was classified as high (>75%), moderate (50%–75%), or low (<25%) (Higgins et al. 2003).

We conducted subgroup analyses according to the following characteristics: (1) the number of administrations of the reference method; (2) sample size; (3) administration modes (interviewer-administered and self-administered); (4) number of food items (<126 and ≥126); (5) reference periods; (6) study quality (very good, good, acceptable, and poor); and (7) population characteristics (gender and region).

Three sensitivity analyses were conducted: (1) If the study lacked important information, or if the periods covered in both assessment methods did not overlap, we excluded these studies and calculated pooled effect estimates. (2) First, we excluded studies where the measurement number of the reference method was above one. Then, we conducted pooled effect estimates on truncated datasets that retained studies with the interval time below 1 week (1 week was the median value of interval time between FFQs and reference methods). (3) We calculated the correlation coefficient adjusted by the scoring system described above (Serra-Majem et al. 2009).

Statistical analysis was performed using STATA 11.0 software package (Stata Corporation, College Station, TX, USA). $P < 0.05$ was regarded as statistically significant.

## Results

### Literature search and selection of studies

Figure 1 shows the results of the literature search and selection. We identified 4,826 articles from two electronic databases. After excluding duplicates, the initial database search yielded a total of 3,535 articles. After exclusions, 130 articles were identified (Ahn et al. 2007; Bae et al. 2010; Barrat et al. 2012; Bautista, Herran, and Pryer 2005; Block et al. 2006; Boucher et al. 2006; Brunner et al. 2001; Cardoso, Tomita, and Laguna 2010; Carithers et al. 2009; Chen et al. 2004; Date et al. 2005; Dehghan, del Cerro, et al. 2012; Dehghan, Ilow, et al. 2012; Dehghan, López Jaramillo, et al. 2012; Dehghan et al. 2013; Deschamps et al. 2009; Flagg et al. 2000; Fregapane and Asensio-Garcia 2000; Goulet et al. 2004; Hartwell and Henry 2001; Hebden et al. 2013; Henn et al. 2010; Zhang and Ho 2009; Iqbal et al. 2009; Ishihara et al. 2009; Ishihara et al. 2003; Jaceldo-Siegl et al. 2010; Jackson et al. 2001; Jackson et al. 2013; Jackson et al. 2011; Jain et al. 2003; Johansson et al. 2002; Teixeira et al. 2011; Ke et al. 2005; Kesse-Guyot et al. 2010; Kim, Chan, and Shore 2002; Kim et al. 2011; Kumanyika et al. 2003; Kusama et al. 2005; Labonte et al. 2012; Lassale et al. 2009; Lee et al. 2002, 2006; Liu et al. 2013; Lyu et al. 2007; Cardoso et al. 2001; MacIntyre, Venter, and Vorster 2001; Malekshah et al. 2006; Marques-Vidal et al. 2011; Masson et al. 2003; Messerer, Johansson, and Wolk 2004; Mirmiran et al. 2010; Na and Lee 2012; Nath and Huffman 2005; Fornés, Stringhini, and Elias 2003; Ogawa et al. 2003; Paalanen et al. 2006; Pakseresht and Sharma 2010a; Pakseresht and Sharma 2010b; Pakseresht et al. 2011; Park et al. 2012; Roddam et al. 2005; Rodriguez et al. 2002; Schröder et al. 2001; Sevak et al. 2004; Shai et al. 2005; Shu et al. 2004; Sudha et al. 2006; Takachi et al. 2011; Toft et al. 2008; Tokudome et al. 2005; Tseng and Hernandez 2005; Tsubono et al. 2001; Tsugane, Kobayashi, and Sasaki 2003; Turconi et al. 2010; van Dongen et al. 2011; Villegas et al. 2007; Yang et al. 2010; Zhuang et al. 2012; Affret et al. 2018; Beck et al. 2020; Bizjak, Jenko, and Korousic Seljak 2014; Buscemi et al. 2015; Cantin et al. 2016; Collins et al. 2014; Denova-Gutierrez et al. 2016; El Kinany et al. 2018; Elorriaga et al. 2015; Fallaize et al. 2014; Feng et al. 2016; Garcia Rodriguez et al. 2019; Gunes et al. 2015; Hamdan et al. 2014; Hollis et al. 2017; Jayawardena et al. 2016; Kato et al. 2017; Khalesi et al. 2017; Kim et al. 2015; Kristal et al. 2014; Lee and Park 2016; Leon Guerrero et al. 2015; Lin et al. 2017; Macedo-Ojeda et al. 2013; Mahajan et al. 2013; Mannato et al. 2015; Zapataa et al. 2015; Maruyama et al. 2015; Marventano et al. 2016; Maryam Nouri and Mohajeri 2017; Sauvageot, Guillaume, and Adelin 2013; Palacios et al. 2015; Rabic, Sindik, and Missoni 2014; Sam, Skeaff, and Skidmore 2014; Sam et al. 2020; Selem et al. 2014; Silva-Jaramillo, Neutzling, and Drehmer 2015; Silva et al. 2013; Sluik et al. 2016; Talegawkar et al. 2015; Tayyem et al. 2014; Tijerina and Tur 2020; van Dongen et al. 2019; Verger et al. 2017; Villena-Esponera et al. 2017; Whitton et al. 2017; Ye et al. 2016; Yokoyama et al. 2016; Yuan et al. 2017; Zack et al. 2018; Zang et al. 2019).

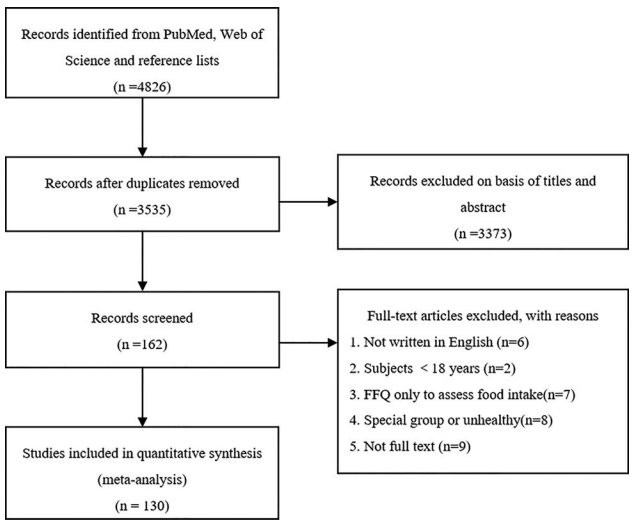


**Figure 1.** Flow diagram for selection of articles.

### Study characteristics

The characteristics of the included studies are shown in Table 1 (detailed information is shown in Supplemental Table 2). The median (range) sample size per study was 103 (20–1,623), with a total of 21,494 participants. Among these studies, the median participant age was 46.65, and the percentage of men was 39.61. Most studies were conducted in Asia ($n = 41$), followed by Europe ($n = 32$), North America ($n = 26$), South America ($n = 16$), Oceania ($n = 8$), and Africa ($n = 7$). The median of the (range) FFQ items validated in the studies was 126 (18–322). Regarding the FFQ administration mode, 53 studies were interview-administered, 54 studies were self-administered, and the remaining 23 studies were not

**Table 2.** Pooled effect estimates (95% CI) and heterogeneity of the correlation coefficients between FFQs and 24-hour recalls for energy and macronutrients.

| | Crude | | | Energy-adjusted | | | De-attenuated | | |
|---|---|---|---|---|---|---|---|---|---|
| Nutrients | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ |
| Energy | 0.473 (0.415, 0.526) | 61 | 94.0 | N/A | N/A | N/A | 0.493 (0.439, 0.544) | 34 | 87.5 |
| Carbohydrate | 0.473 (0.432, 0.512) | 60 | 86.2 | 0.454 (0.409, 0.497) | 44 | 83.2 | 0.549 (0.502, 0.593) | 41 | 87.1 |
| Protein | 0.404 (0.369, 0.438) | 61 | 77.9 | 0.357 (0.313, 0.399) | 45 | 78.8 | 0.549 (0.502, 0.593) | 43 | 83.2 |
| Fat | 0.437 (0.394, 0.480) | 55 | 86.6 | 0.424 (0.375, 0.469) | 44 | 85.0 | 0.503 (0.451, 0.551) | 39 | 87.7 |
| Plant fat | 0.234 (0.157, 0.307) | 4 | 9.4 | 0.244 (-0.01, 0.468) | 2 | 88.1 | 0.480 (0.221, 0.675) | 2 | 89.0 |
| Trans-fat | 0.282 (0.099, 0.447) | 3 | 68.0 | 0.266 (0.163, 0.364) | 3 | 70.1 | 0.497 (0.451, 0.540) | 2 | 0 |
| Cholesterol | 0.402 (0.357, 0.446) | 39 | 76.7 | 0.385 (0.341, 0.428) | 32 | 74.3 | 0.489 (0.435, 0.538) | 27 | 81.3 |
| Sugar | 0.498 (0.387, 0.595) | 8 | 81.2 | 0.512 (0.438, 0.580) | 7 | 56.4 | 0.644 (0.534, 0.732) | 6 | 80.3 |
| Starch | 0.427 (0.334, 0.512) | 1 | N/A | 0.376 (0.279, 0.466) | 1 | N/A | 0.772 (0.724, 0.813) | 1 | N/A |
| Alcohol | 0.721 (0.670, 0.765) | 17 | 83.1 | 0.742 (0.688, 0.788) | 12 | 80.5 | 0.735 (0.649, 0.802) | 8 | 87.6 |
| Water | 0.472 (0.401, 0.536) | 6 | 0 | 0.435 (0.354, 0.509) | 3 | 0 | 0.492 (0.320, 0.633) | 1 | N/A |
| Fiber | 0.435 (0.395, 0.473) | 50 | 76.2 | 0.449 (0.405, 0.491) | 40 | 81.9 | 0.483 (0.432, 0.531) | 34 | 84.3 |
| Soluble fiber | 0.472 (0.141, 0.708) | 2 | 89.3 | 0.528 (0.488, 0.566) | 3 | 0 | 0.620 (0.534, 0.694) | 2 | 74.7 |
| Insoluble fiber | 0.481 (0.403, 0.551) | 4 | 70.1 | 0.478 (0.414, 0.538) | 3 | 0 | 0.555 (0.449, 0.647) | 3 | 84.5 |
| MUFA | 0.377 (0.324, 0.428) | 31 | 74.1 | 0.390 (0.339, 0.440) | 27 | 80.3 | 0.517 (0.429, 0.595) | 24 | 93.9 |
| PUFA | 0.316 (0.266, 0.363) | 34 | 69.4 | 0.343 (0.290, 0.392) | 27 | 77.4 | 0.411 (0.338, 0.481) | 26 | 89.8 |
| SFA | 0.427 (0.380, 0.472) | 41 | 78.5 | 0.461 (0.407, 0.512) | 33 | 85.9 | 0.536 (0.472, 0.594) | 31 | 91.0 |
| Linoleic acid | 0.357 (0.244, 0.459) | 4 | 60.9 | 0.377 (0.323, 0.427) | 3 | 13.0 | 0.626 (0.467, 0.746) | 2 | 93.6 |
| Linolenic acid | 0.465 (0.122, 0.708) | 3 | 91.9 | 0.329 (0.254, 0.400) | 3 | 47.7 | 0.500 (0.404, 0.585) | 2 | 77.0 |
| Oleic acid | 0.491 (0.289, 0.650) | 2 | 89.8 | 0.317 (0.265, 0.366) | 2 | 0 | 0.481 (0.393, 0.560) | 2 | 71.5 |
| EPA | N/A | N/A | N/A | 0.479 (0.315, 0.615) | 2 | 91.6 | 0.578 (0.535, 0.618) | 1 | N/A |
| DHA | N/A | N/A | 41.6 | 0.474 (0.350, 0.581) | 2 | 85.5 | 0.610 (0.491, 0.707) | 1 | N/A |
| TFA | 0.410 (0.205, 0.580) | 1 | N/A | N/A | N/A | N/A | 0.459 (0.262, 0.619) | 1 | N/A |
| n-3 fatty acid | N/A | N/A | N/A | 0.330 (0.242, 0.413) | 1 | N/A | 0.463 (0.361, 0.554) | 2 | 74.5 |
| Caffeine | 0.770 (0.676, 0.840) | 2 | 81.5 | 0.772 (0.665, 0.849) | 2 | 85.4 | 0.787 (0.709, 0.846) | 2 | 76.5 |
| Lycopene | 0.220 (0.093, 0.341) | 1 | N/A | 0.192 (0.062, 0.314) | 1 | N/A | 0.277 (0.152, 0.394) | 1 | N/A |
| Cryptoxanthin | 0.375 (0.257, 0.482) | 1 | N/A | 0.394 (0.278, 0.499) | 1 | N/A | 0.571 (0.476, 0.653) | 1 | N/A |
| Daidzein | 0.500 (0.307, 0.654) | 1 | N/A | 0.520 (0.331, 0.669) | 1 | N/A | 0.632 (0.471, 0.752) | 1 | N/A |
| Genistein | 0.380 (0.165, 0.560) | 1 | N/A | 0.420 (0.212, 0.592) | 1 | N/A | 0.551 (0.370, 0.693) | 1 | N/A |

N, number of studies; CI, confidence interval; $I^2$, inconsistency index; N/A, not available.

available. For the reference period, 84 studies analyzed 12-month FFQ validity, 84 validation studies used the FFQ to collect dietary information for less than 12 months. For the type of FFQ, the numbers of non-quantitative FFQ, semi-quantitative FFQ and quantitative FFQ involved in the study was 7, 93 and 25, respectively. According to the summary score described by Serra-Majem et al. (Serra-Majem et al. 2009), we classified studies as very good ($n = 25$), good ($n = 75$) or acceptable ($n = 30$). The score of each study involved, according to the scoring system, is shown in Supplemental Table 3. In addition, reference methods of the studies included 24HRs ($n = 66$) and FRs ($n = 67$). Three studies used the two reference methods (24HRs and FRs) to assess the validity of FFQs (Kumanyika et al. 2003; Lyu et al. 2007; Yuan et al. 2017).

## Pooled correlation coefficients and SMDs for energy and macronutrients

Pooled effect estimates and heterogeneity of correlation coefficients between FFQs and 24HRs for energy and macronutrients are shown in Table 2. The pooled crude correlation coefficients varied from 0.220 (lycopene) to 0.770 (caffeine), with a median value of 0.375. Most nutrients were above 0.3, except for plant fat (0.234), trans-fat (0.282), and lycopene (0.220). The energy-adjusted and de-attenuated correlation coefficients varied from 0.192 to 0.772 (median = 0.407) and from 0.277 to 0.787 (median = 0.536), respectively. As shown in Table 3, crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and FRs ranged from 0.173 to 0.735 (median = 0.373), from 0.240 to 0.704 (median = 0.426), and from 0.104 to 0.792 (median = 0.5205), respectively. Moreover, 16 of 27 nutrients assessed by 24HRs had lower correlation coefficients than studies using FRs.

For the SMDs (Table 4), we found that all the nutrients were overestimated by FFQs in comparison with those of the 24HRs (SMD > 0), except for alcohol (SMD = −0.033, $P_z = 0.833$) and plant fat (SMD = −0.194, $P_z = 0.736$). Compared with the 24HRs, the FFQs overestimated the consumption of 17 of 32 nutrients.

## Pooled correlation coefficients and SMDs for micronutrients

As shown in Table 5, the pooled crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs ranged from 0.278 for Mn to 0.701 for I (median = 0.397), from 0.233 for Mn to 0.846 for I (median = 0.368), and from 0.047 for Mn to 0.632 for α-carotene (median = 0.4635), respectively. All the pooled crude correlation coefficients of micronutrients were greater than 0.3, except for Mn (0.278). As shown in Table 6, pooled crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and FRs ranged from 0.234 for α-tocopherol to 0.493 for pantothenic acid (median = 0.371), from 0.189 for I to 0.554 for pantothenic acid (median = 0.396), and from 0.135 for I to 0.600 for vitamin K (median = 0.471), respectively. Additionally, most micronutrient values were higher than 0.3, except for vitamin E (0.287), α-tocopherol (0.234), and β-tocopherol (0.240). Moreover, studies using 24HRs as the reference method had higher correlation

**Table 3.** Pooled effect estimates (95% CI) and heterogeneity of the correlation coefficients between FFQs and food records for energy and macronutrients.

| | Crude | | | Energy-adjusted | | | De-attenuated | | |
|---|---|---|---|---|---|---|---|---|---|
| Nutrients | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ |
| Energy | 0.397 (0.356, 0.437) | 55 | 74.4 | N/A | N/A | N/A | 0.412 (0.304, 0.511) | 17 | 92.4 |
| Carbohydrate | 0.434 (0.386, 0.479) | 52 | 82.5 | 0.492 (0.452, 0.531) | 37 | 78.6 | 0.564 (0.504, 0.620) | 22 | 88.4 |
| Protein | 0.347 (0.318, 0.375) | 55 | 44.2 | 0.364 (0.330, 0.396) | 41 | 60.8 | 0.455 (0.409, 0.498) | 21 | 69.8 |
| Fat | 0.374 (0.341, 0.407) | 50 | 57.4 | 0.423 (0.393, 0.451) | 38 | 57.0 | 0.498 (0.450, 0.542) | 20 | 75.4 |
| Plant fat | 0.355 (0.207, 0.487) | 5 | 55.6 | 0.373 (0.220, 0.507) | 2 | 0 | 0.181 (-0.16, 0.489) | 1 | N/A |
| Trans-fat | 0.278 (-0.09, 0.583) | 2 | 82.8 | 0.560 (0.375, 0.701) | 1 | N/A | 0.104 (-0.10, 0.303) | 1 | N/A |
| Cholesterol | 0.408 (0.359, 0.455) | 35 | 69.5 | 0.428 (0.385, 0.469) | 29 | 69.4 | 0.498 (0.438, 0.553) | 15 | 80.3 |
| Sugar | 0.490 (0.419, 0.556) | 13 | 57.5 | 0.543 (0.473, 0.606) | 8 | 69.9 | 0.618 (0.525, 0.697) | 2 | 84.5 |
| Starch | 0.408 (0.343, 0.469) | 6 | 33.5 | 0.400 (0.345, 0.451) | 5 | 0 | N/A | N/A | N/A |
| Alcohol | 0.735 (0.683, 0.780) | 27 | 90.7 | 0.704 (0.656, 0.747) | 20 | 89.7 | 0.792 (0.741, 0.834) | 7 | 88.2 |
| Water | 0.536 (0.373, 0.667) | 2 | 0 | 0.461 (0.359, 0.552) | 3 | 69.8 | 0.438 (0.339, 0.527) | 3 | 67.5 |
| Fiber | 0.367 (0.323, 0.408) | 45 | 66.1 | 0.486 (0.444, 0.526) | 35 | 76.3 | 0.542 (0.488, 0.591) | 19 | 81.8 |
| Soluble fiber | 0.380 (0.312, 0.446) | 5 | 19.1 | 0.496 (0.435, 0.551) | 8 | 59.0 | 0.544 (0.478, 0.605) | 6 | 59.2 |
| Insoluble fiber | 0.396 (0.330, 0.458) | 5 | 14.1 | 0.527 (0.470, 0.580) | 8 | 58.6 | 0.575 (0.507, 0.637) | 6 | 65.4 |
| MUFA | 0.372 (0.329, 0.413) | 34 | 62.5 | 0.389 (0.350, 0.426) | 29 | 64.5 | 0.423 (0.360, 0.482) | 14 | 77.5 |
| PUFA | 0.351 (0.300, 0.399) | 34 | 72.3 | 0.345 (0.305, 0.383) | 28 | 63.6 | 0.400 (0.347, 0.450) | 14 | 66.4 |
| n-3 PUFA | 0.272 (0.214, 0.329) | 7 | 0 | 0.323 (0.283, 0.363) | 10 | 50.0 | 0.418 (0.344, 0.486) | 6 | 59.0 |
| n-6 PUFA | 0.247 (0.162, 0.329) | 6 | 43.5 | 0.335 (0.274, 0.393) | 9 | 49.7 | 0.370 (0.260, 0.471) | 5 | 78.2 |
| SFA | 0.464 (0.423, 0.502) | 38 | 67.0 | 0.480 (0.444, 0.515) | 33 | 68.8 | 0.529 (0.481, 0.575) | 17 | 73.9 |
| Linoleic acid | 0.384 (0.156, 0.573) | 4 | 79.9 | 0.321 (0.123, 0.494) | 3 | 65.8 | 0.532 (0.458, 0.598) | 1 | N/A |
| Linolenic acid | 0.505 (0.126, 0.756) | 3 | 93.3 | 0.312 (0.039, 0.541) | 2 | 82.6 | 0.551 (0.480, 0.616) | 1 | N/A |
| Oleic acid | 0.358 (0.276, 0.435) | 3 | 5.2 | 0.454 (0.380, 0.521) | 2 | 0 | 0.542 (0.469, 0.607) | 1 | N/A |
| EPA | 0.373 (0.192, 0.529) | 3 | 48.6 | 0.255 (0.100, 0.397) | 2 | 0 | 0.512 (0.210, 0.724) | 1 | N/A |
| DHA | 0.367 (0.155, 0.547) | 3 | 61.7 | 0.240 (0.084, 0.384) | 2 | 0 | 0.462 (0.147, 0.692) | 1 | N/A |
| TFA | 0.298 (0.231, 0.363) | 3 | 0 | 0.415 (0.236, 0.566) | 3 | 85.9 | 0.544 (0.463, 0.615) | 2 | 0 |
| n-3 fatty acid | 0.173 (0.040, 0.299) | 2 | 0 | N/A | N/A | N/A | 0.162 (-0.04, 0.355) | 1 | N/A |
| n-6 fatty acid | 0.331 (0.010, 0.589) | 2 | 72.1 | N/A | N/A | N/A | N/A | N/A | N/A |
| Caffeine | 0.498 (0.120, 0.749) | 4 | 93.7 | 0.524 (0.114, 0.781) | 3 | 94.6 | 0.734 (0.581, 0.836) | 2 | 81.1 |
| Lycopene | 0.327 (0.237, 0.411) | 6 | 47.4 | 0.329 (0.247, 0.405) | 6 | 37.5 | 0.529 (0.408, 0.630) | 2 | 52.8 |
| Cryptoxanthin | 0.220 (-0.05, 0.463) | 2 | 90.3 | 0.428 (0.309, 0.533) | 4 | 85.6 | 0.459 (0.354, 0.553) | 5 | 82.8 |
| Daidzein | 0.565 (0.407, 0.690) | 3 | 81.7 | 0.601 (0.544, 0.653) | 5 | 61.1 | 0.677 (0.611, 0.734) | 4 | 69.2 |
| Genistein | 0.554 (0.400, 0.678) | 3 | 80.4 | 0.594 (0.537, 0.645) | 5 | 59.6 | 0.658 (0.601, 0.708) | 4 | 56.6 |

N, number of studies; CI, confidence interval; $I^2$, inconsistency index; N/A, not available.

**Table 4.** Pooled effect estimates (95% CI) and heterogeneity of standardized mean differences for energy and macronutrients.

| | 24-hour recall | | | | Food record | | | |
|---|---|---|---|---|---|---|---|---|
| Nutrients | SMD[a] | N | $I^2$ | $P_z$ | SMD[a] | N | $I^2$ | $P_z$ |
| Energy | 0.287 (0.262, 0.313) | 54 | 96.5 | <0.001 | 0.073 (0.040, 0.106) | 57 | 96.9 | <0.001 |
| Carbohydrate | 0.430 (0.404, 0.457) | 52 | 96.9 | <0.001 | 0.106 (0.074, 0.139) | 56 | 97.4 | <0.001 |
| Protein | 0.342 (0.315, 0.369) | 51 | 96.7 | <0.001 | 0.051 (0.020, 0.083) | 57 | 95.2 | <0.01 |
| Fat | 0.111 (0.083, 0.138) | 50 | 98.2 | <0.01 | −0.084 (−0.117, −0.052) | 55 | 94.9 | <0.001 |
| Plant fat | −0.194 (−0.293, −0.096) | 4 | 99.4 | 0.736 | −0.177 (−0.272, −0.083) | 9 | 96.4 | <0.001 |
| Trans-fat | 0.283 (0.208, 0.358) | 4 | 97.5 | 0.082 | 0.386 (0.192, 0.579) | 3 | 88.0 | <0.001 |
| Cholesterol | 0.288 (0.252, 0.325) | 33 | 95.3 | <0.001 | −0.184 (−0.223, −0.144) | 39 | 93.6 | <0.001 |
| Sugar | 0.242 (0.144, 0.339) | 7 | 95.0 | 0.559 | 0.409 (0.348, 0.469) | 14 | 80.1 | <0.001 |
| Starch | 0.390 (0.235, 0.546) | 1 | N/A | <0.001 | 0.262 (0.184, 0.340) | 6 | 96.3 | <0.001 |
| Alcohol | 0.092 (0.035, 0.149) | 16 | 96.5 | 0.833 | −0.002 (−0.042, 0.039) | 31 | 72.8 | 0.938 |
| Water | 0.220 (0.121, 0.318) | 5 | 96.1 | 0.158 | 0.127 (0.039, 0.215) | 5 | 94.1 | <0.01 |
| Fiber | 0.450 (0.416, 0.483) | 43 | 97.3 | <0.001 | 0.078 (0.041, 0.115) | 50 | 96.3 | <0.001 |
| Soluble fiber | 0.707 (0.623, 0.792) | 2 | 99.2 | 0.434 | −0.200 (−0.267, −0.133) | 9 | 94.0 | <0.001 |
| Insoluble fiber | 0.726 (0.650, 0.802) | 3 | 99.1 | 0.326 | −0.351 (−0.419, −0.284) | 9 | 96.4 | <0.001 |
| MUFA | 0.451 (0.412, 0.491) | 29 | 95.8 | <0.001 | 0.076 (0.038, 0.113) | 38 | 95.8 | <0.001 |
| PUFA | 0.449 (0.411, 0.487) | 31 | 93.7 | <0.001 | 0.038 (0.001, 0.075) | 38 | 94.0 | 0.045 |
| n-3 PUFA | N/A | N/A | N/A | N/A | −0.091 (−0.156, −0.027) | 10 | 96.0 | <0.01 |
| n-6 PUFA | N/A | N/A | N/A | N/A | −0.029 (−0.094, 0.036) | 9 | 92.4 | 0.379 |
| SFA | 0.250 (0.215, 0.286) | 35 | 94.1 | <0.001 | 0.070 (0.034, 0.106) | 43 | 94.4 | <0.001 |
| Linoleic Acid | 0.759 (0.680, 0.838) | 4 | 97.0 | 0.013 | −0.179 (−0.297, −0.062) | 4 | 93.5 | <0.01 |
| Linolenic Acid | 0.180 (0.103, 0.257) | 3 | 92.1 | 0.222 | −0.163 (−0.287, −0.04) | 3 | 98.6 | 0.010 |
| Oleic acid | 0.641 (0.560, 0.722) | 2 | 95.9 | <0.01 | 0.100 (−0.022, 0.223) | 3 | 98.2 | 0.108 |
| EPA | 0.288 (0.216, 0.359) | 3 | 99.3 | 0.308 | −0.387 (−0.57, −0.203) | 4 | 89.3 | <0.001 |
| DHA | 0.459 (0.388, 0.530) | 3 | 99.1 | 0.112 | −0.395 (−0.581, −0.21) | 4 | 93.3 | <0.001 |
| TFA | N/A | N/A | N/A | N/A | 0.147 (0.044, 0.250) | 4 | 97.6 | <0.01 |
| n-3 fatty acid | 0.691 (0.601, 0.781) | 1 | N/A | N/A | −0.022 (−0.213, 0.168) | 2 | 95.0 | 0.820 |
| n-6 fatty acid | N/A | N/A | N/A | N/A | −0.393 (−0.643, −0.143) | 1 | N/A | <0.01 |
| Caffeine | 0.044 (−0.076, 0.164) | 2 | 0 | 0.470 | 0.054 (−0.065, 0.174) | 4 | 97.9 | 0.371 |
| Daidzein | N/A | N/A | N/A | N/A | 0.261 (0.189, 0.334) | 6 | 0 | <0.001 |
| Genistein | N/A | N/A | N/A | N/A | 0.239 (0.166, 0.311) | 6 | 0 | <0.001 |
| Lycopene | 0.095 (−0.089, 0.280) | 1 | N/A | 0.312 | −0.135 (−0.225, −0.044) | 4 | 90.6 | <0.01 |
| Cryptoxanthin | 0.138 (−0.047, 0.323) | 1 | N/A | 0.143 | 0.276 (0.207, 0.345) | 6 | 95.1 | <0.001 |

SMD, standardized mean difference; CI, confidence interval; N, No. of studies; $I^2$, inconsistency index; $P_z$, $P$ for Z test; N/A, not available.
[a]SMDs were calculated by means of nutrient intakes from FFQ minus that from reference methods.

**Table 5.** Pooled effect estimates (95% CI) and heterogeneity of the correlation coefficients between FFQs and 24-hour recalls for micronutrients.

| | Crude | | | Energy-adjusted | | | De-attenuated | | |
|---|---|---|---|---|---|---|---|---|---|
| Nutrients | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ |
| Vitamin A | 0.347 (0.261, 0.427) | 30 | 93.4 | 0.295 (0.237, 0.351) | 25 | 76.6 | 0.326 (0.259, 0.389) | 23 | 78.8 |
| Retinol | 0.414 (0.313, 0.506) | 17 | 91.9 | 0.390 (0.275, 0.495) | 12 | 83.9 | 0.521 (0.397, 0.626) | 9 | 87.7 |
| Vitamin C | 0.396 (0.340, 0.450) | 51 | 90.6 | 0.398 (0.348, 0.445) | 42 | 85.0 | 0.472 (0.421, 0.521) | 37 | 85.9 |
| Vitamin D | 0.419 (0.288, 0.533) | 19 | 96.4 | 0.371 (0.304, 0.435) | 20 | 84.6 | 0.458 (0.371, 0.538) | 18 | 91.3 |
| Vitamin E | 0.418 (0.320, 0.506) | 30 | 95.8 | 0.328 (0.245, 0.407) | 22 | 90.0 | 0.416 (0.356, 0.473) | 19 | 80.4 |
| Vitamin K | 0.488 (0.244, 0.675) | 3 | 97.7 | 0.278 (0.008, 0.509) | 2 | 81.7 | 0.413 (-0.13, 0.767) | 2 | 95.7 |
| Thiamin | 0.433 (0.358, 0.501) | 31 | 92.5 | 0.364 (0.307, 0.419) | 24 | 82.3 | 0.495 (0.439, 0.547) | 23 | 84.0 |
| Riboflavin | 0.448 (0.383, 0.508) | 27 | 89.1 | 0.393 (0.329, 0.453) | 21 | 84.3 | 0.499 (0.428, 0.564) | 20 | 88.7 |
| Niacin | 0.410 (0.352, 0.465) | 18 | 79.6 | 0.353 (0.296, 0.408) | 15 | 74.6 | 0.483 (0.415, 0.546) | 14 | 85.0 |
| Pantothenic acid | 0.431 (0.210, 0.610) | 3 | 95.1 | 0.518 (0.289, 0.691) | 3 | 96.0 | 0.549 (0.356, 0.696) | 3 | 94.9 |
| Vitamin B6 | 0.435 (0.276, 0.571) | 14 | 94.8 | 0.397 (0.303, 0.483) | 12 | 90.4 | 0.510 (0.430, 0.582) | 12 | 88.0 |
| Folate | 0.392 (0.317, 0.461) | 35 | 92.7 | 0.393 (0.344, 0.438) | 32 | 78.5 | 0.465 (0.401, 0.524) | 27 | 87.8 |
| Vitamin B12 | 0.358 (0.284, 0.428) | 18 | 79.2 | 0.337 (0.263, 0.408) | 16 | 81.2 | 0.421 (0.331, 0.504) | 14 | 86.5 |
| Carotene | 0.388 (0.252, 0.509) | 8 | 94.2 | 0.292 (0.210, 0.370) | 6 | 51.9 | 0.379 (0.237, 0.505) | 5 | 83.3 |
| α-Carotene | 0.375 (0.257, 0.482) | 1 | N/A | 0.356 (0.235, 0.464) | 1 | N/A | 0.632 (0.546, 0.704) | 1 | N/A |
| β-Carotene | 0.355 (0.286, 0.419) | 15 | 74.1 | 0.376 (0.302, 0.445) | 13 | 80.5 | 0.486 (0.367, 0.588) | 10 | 92.6 |
| α-tocopherol | N/A | N/A | N/A | 0.325 (0.171, 0.462) | 3 | 86.7 | 0.321 (0.259, 0.379) | 2 | 0 |
| β-tocopherol | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Se | 0.430 (0.345, 0.507) | 7 | 83.2 | 0.495 (0.324, 0.635) | 5 | 90.2 | 0.441 (0.328, 0.542) | 3 | 21.5 |
| Mg | 0.381 (0.310, 0.448) | 17 | 85.4 | 0.462 (0.396, 0.524) | 16 | 85.7 | 0.537 (0.466, 0.602) | 14 | 87.7 |
| Ca | 0.430 (0.382, 0.476) | 53 | 88.2 | 0.439 (0.395, 0.482) | 46 | 83.4 | 0.520 (0.474, 0.562) | 36 | 83.8 |
| Fe | 0.387 (0.344, 0.428) | 46 | 80.8 | 0.357 (0.319, 0.394) | 41 | 71.5 | 0.462 (0.411, 0.510) | 34 | 85.0 |
| I | 0.701 (-0.278, 0.966) | 3 | 99.3 | 0.762 (0.432, 0.999) | 2 | 99.6 | 0.277 (0.077, 0.456) | 1 | N/A |
| Zn | 0.346 (0.294, 0.396) | 25 | 77.5 | 0.336 (0.265, 0.404) | 21 | 86.7 | 0.430 (0.364, 0.493) | 21 | 84.9 |
| Cu | 0.325 (0.219, 0.424) | 5 | 56.4 | 0.344 (0.232, 0.448) | 4 | 82.4 | 0.390 (0.191, 0.558) | 3 | 93.0 |
| K | 0.389 (0.300, 0.472) | 21 | 92.7 | 0.394 (0.340, 0.445) | 16 | 74.6 | 0.454 (0.388, 0.515) | 14 | 79.0 |
| P | 0.397 (0.332, 0.458) | 22 | 86.4 | 0.397 (0.344, 0.448) | 16 | 75.5 | 0.513 (0.454, 0.569) | 15 | 82.3 |
| Na | 0.449 (0.331, 0.553) | 23 | 96.5 | 0.279 (0.193, 0.363) | 16 | 89.6 | 0.471 (0.393, 0.542) | 17 | 89.8 |
| Mn | 0.278 (-0.105, 0.590) | 2 | 90.8 | 0.233 (-0.112, 0.528) | 2 | 88.5 | 0.047 (-0.150, 0.250) | 1 | N/A |

N, number of studies; CI, confidence interval; $I^2$, inconsistency index; N/A, not available.

**Table 6.** Pooled effect estimates (95% CI) and heterogeneity of the correlation coefficients between FFQs and food records for micronutrients.

| | Crude | | | Energy-adjusted | | | De-attenuated | | |
|---|---|---|---|---|---|---|---|---|---|
| Nutrients | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ | Correlation coefficient | N | $I^2$ |
| Vitamin A | 0.312 (0.248, 0.373) | 27 | 73.5 | 0.286 (0.255, 0.317) | 17 | 76.6 | 0.331 (0.267, 0.394) | 10 | 61.6 |
| Retinol | 0.373 (0.329, 0.416) | 20 | 51.0 | 0.373 (0.329, 0.416) | 27 | 51.0 | 0.500 (0.348, 0.627) | 6 | 87.8 |
| Vitamin C | 0.418 (0.378, 0.457) | 48 | 73.7 | 0.442 (0.404, 0.477) | 41 | 76.0 | 0.493 (0.436, 0.546) | 21 | 82.4 |
| Vitamin D | 0.383 (0.312, 0.449) | 17 | 67.6 | 0.394 (0.349, 0.437) | 15 | 55.7 | 0.520 (0.452, 0.582) | 10 | 81.7 |
| Vitamin E | 0.287 (0.227, 0.344) | 29 | 74.9 | 0.319 (0.266, 0.370) | 23 | 75.0 | 0.339 (0.269, 0.407) | 10 | 75.5 |
| Vitamin K | 0.464 (0.346, 0.567) | 6 | 64.1 | 0.510 (0.443, 0.573) | 8 | 77.4 | 0.600 (0.505, 0.680) | 8 | 91.2 |
| Thiamin | 0.343 (0.307, 0.378) | 38 | 51.5 | 0.298 (0.258, 0.337) | 32 | 63.6 | 0.334 (0.256, 0.408) | 16 | 83.5 |
| Riboflavin | 0.416 (0.367, 0.464) | 38 | 78.9 | 0.429 (0.383, 0.473) | 32 | 76.7 | 0.451 (0.391, 0.507) | 16 | 73.9 |
| Niacin | 0.326 (0.284, 0.367) | 30 | 59.3 | 0.296 (0.258, 0.333) | 25 | 51.6 | 0.360 (0.281, 0.433) | 15 | 83.0 |
| Pantothenic acid | 0.493 (0.347, 0.615) | 5 | 70.6 | 0.554 (0.489, 0.613) | 10 | 58.5 | 0.573 (0.497, 0.640) | 5 | 68.1 |
| Vitamin B6 | 0.361 (0.314, 0.407) | 27 | 58.9 | 0.385 (0.339, 0.430) | 23 | 67.3 | 0.439 (0.374, 0.499) | 14 | 80.6 |
| Folate | 0.371 (0.325, 0.415) | 36 | 69.0 | 0.446 (0.403, 0.486) | 29 | 75.5 | 0.480 (0.421, 0.535) | 17 | 82.1 |
| Vitamin B12 | 0.426 (0.358, 0.491) | 21 | 75.5 | 0.373 (0.328, 0.416) | 18 | 54.5 | 0.476 (0.419, 0.531) | 9 | 70.6 |
| Carotene | 0.340 (0.303, 0.377) | 11 | 90.0 | 0.363 (0.320, 0.404) | 10 | 18.9 | 0.373 (0.283, 0.456) | 4 | 14.5 |
| α-Carotene | 0.420 (0.306, 0.521) | 5 | 76.8 | 0.418 (0.363, 0.471) | 9 | 66.9 | 0.491 (0.415, 0.561) | 7 | 82.6 |
| β-Carotene | 0.359 (0.309, 0.406) | 17 | 56.4 | 0.396 (0.357, 0.433) | 18 | 55.7 | 0.471 (0.419, 0.520) | 12 | 71.6 |
| α-tocopherol | 0.234 (0.129, 0.334) | 4 | 0 | 0.457 (0.405, 0.506) | 4 | 12.3 | 0.461 (0.404, 0.514) | 5 | 27.4 |
| β-tocopherol | 0.240 (0.035, 0.425) | 1 | N/A | 0.339 (0.237, 0.434) | 3 | 68.4 | 0.370 (0.268, 0.463) | 4 | 69.4 |
| Se | 0.354 (0.262, 0.439) | 9 | 73.0 | 0.301 (0.258, 0.342) | 10 | 40.1 | 0.331 (0.270, 0.389) | 6 | 60.1 |
| Mg | 0.451 (0.385, 0.513) | 23 | 82.1 | 0.505 (0.451, 0.554) | 20 | 82.4 | 0.513 (0.427, 0.590) | 10 | 89.2 |
| Ca | 0.453 (0.416, 0.488) | 49 | 70.4 | 0.490 (0.456, 0.523) | 39 | 73.2 | 0.524 (0.475, 0.570) | 21 | 79.0 |
| Fe | 0.349 (0.314, 0.384) | 50 | 58.7 | 0.419 (0.382, 0.455) | 36 | 72.9 | 0.466 (0.423, 0.507) | 20 | 67.6 |
| I | 0.346 (0.087, 0.561) | 2 | 46.2 | 0.189 (0.072, 0.300) | 3 | 71.4 | 0.135 (0.071, 0.198) | 3 | 0 |
| Zn | 0.371 (0.313, 0.426) | 24 | 70.4 | 0.338 (0.294, 0.380) | 20 | 58.9 | 0.419 (0.327, 0.503) | 12 | 89.7 |
| Cu | 0.336 (0.247, 0.419) | 10 | 73.1 | 0.429 (0.346, 0.505) | 11 | 86.4 | 0.490 (0.414, 0.560) | 9 | 85.5 |
| K | 0.400 (0.349, 0.448) | 36 | 79.7 | 0.455 (0.416, 0.492) | 28 | 70.8 | 0.514 (0.451, 0.573) | 14 | 84.0 |
| P | 0.447 (0.401, 0.489) | 28 | 68.8 | 0.478 (0.450, 0.505) | 23 | 37.7 | 0.536 (0.486, 0.583) | 15 | 74.2 |
| Na | 0.381 (0.306, 0.451) | 31 | 88.5 | 0.356 (0.309, 0.401) | 25 | 73.6 | 0.396 (0.335, 0.455) | 16 | 79.1 |
| Mn | 0.410 (0.254, 0.546) | 6 | 87.0 | 0.521 (0.434, 0.597) | 7 | 86.8 | 0.560 (0.476, 0.633) | 7 | 87.4 |

N, number of studies; CI, confidence interval; $I^2$, inconsistency index; N/A, Not available.

coefficients than studies using FRs for 15 of 27 micronutrients.

As shown in Table 7, we found that most micronutrients estimated by the FFQs were higher than those assessed by 24HRs, except for vitamin K (SMD = −0.005, $P_z$ = 0.696), niacin (SMD = −0.061, $P_z$ = 0.210), carotene (SMD = −0.217, $P_z$ = 0.605), and Se (SMD = −0.009, $P_z$ = 0.580). Further, we found that most vitamins were overestimated

**Table 7.** Pooled effect estimates (95% CI) and heterogeneity of standardized mean differences for micronutrients.

| | 24-hour recall | | | | Food record | | | |
|---|---|---|---|---|---|---|---|---|
| Nutrients | SMD[a] | N | $I^2$ | $P_z$ | SMD[a] | N | $I^2$ | $P_z$ |
| Vitamin A | 0.197 (0.161, 0.232) | 25 | 98.1 | <0.001 | 0.259 (0.204, 0.315) | 27 | 97.7 | <0.001 |
| Retinol | 0.001 (−0.04, 0.042) | 15 | 94.9 | 0.965 | 0.363 (0.315, 0.412) | 23 | 96.1 | <0.001 |
| Vitamin C | 0.399 (0.371, 0.427) | 44 | 98.8 | <0.001 | 0.310 (0.277, 0.342) | 55 | 97.1 | <0.001 |
| Vitamin D | 0.247 (0.204, 0.29) | 17 | 96.1 | <0.001 | 0.082 (0.030, 0.134) | 20 | 91.0 | <0.01 |
| Vitamin E | 0.293 (0.262, 0.324) | 26 | 98.4 | 0.001 | 0.106 (0.064, 0.148) | 32 | 95.8 | <0.001 |
| Vitamin K | −0.005 (−0.16, 0.149) | 2 | 95.2 | 0.696 | 0.104 (0.035, 0.172) | 8 | 91.7 | <0.01 |
| Thiamin | 0.170 (0.139, 0.200) | 30 | 95.2 | <0.001 | 0.064 (0.027, 0.101) | 43 | 95.8 | <0.01 |
| Riboflavin | 0.199 (0.167, 0.231) | 25 | 95.7 | <0.001 | 0.076 (0.039, 0.112) | 43 | 95.4 | <0.001 |
| Niacin | −0.061 (−0.096, −0.025) | 17 | 97.8 | 0.210 | 0.284 (0.245, 0.324) | 34 | 96.3 | <0.001 |
| Pantothenic acid | 0.410 (0.332, 0.488) | 2 | 98.6 | 0.106 | 0.220 (0.141, 0.300) | 6 | 94.0 | <0.001 |
| Vitamin B6 | 0.381 (0.336, 0.426) | 15 | 96.0 | <0.001 | 0.182 (0.138, 0.225) | 31 | 92.5 | <0.001 |
| Folate | 0.471 (0.440, 0.502) | 33 | 98.5 | <0.001 | 0.162 (0.125, 0.198) | 42 | 96.2 | <0.001 |
| Vitamin B12 | 0.660 (0.606, 0.715) | 16 | 97.9 | <0.001 | 0.150 (0.101, 0.200) | 23 | 90.2 | <0.001 |
| Carotene | −0.217 (−0.263, −0.170) | 7 | 96.8 | 0.605 | 0.219 (0.157, 0.281) | 10 | 94.1 | <0.001 |
| α-carotene | 0.492 (0.305, 0.679) | 1 | N/A | <0.001 | 0.122 (0.060, 0.183) | 8 | 89.0 | <0.001 |
| β-carotene | 0.658 (0.601, 0.715) | 9 | 89.1 | <0.001 | 0.221 (0.174, 0.267) | 23 | 98.2 | <0.001 |
| α-tocopherol | 0.008 (−0.099, 0.114) | 2 | 82.6 | 0.924 | −0.139 (−0.219, −0.060) | 7 | 95.2 | <0.01 |
| Se | −0.009 (−0.056, 0.037) | 7 | 98.4 | 0.580 | 0.066 (0.009, 0.124) | 13 | 94.7 | 0.024 |
| Mg | 0.438 (0.403, 0.473) | 19 | 98.5 | <0.001 | 0.359 (0.317, 0.400) | 28 | 91.6 | <0.001 |
| Ca | 0.403 (0.375, 0.431) | 45 | 98.2 | <0.001 | 0.071 (0.039, 0.103) | 54 | 95.8 | <0.001 |
| Fe | 0.314 (0.285, 0.342) | 40 | 98.1 | <0.001 | −0.024 (−0.057, 0.009) | 51 | 96.3 | 0.150 |
| I | 0.309 (0.168, 0.450) | 2 | 92.8 | 0.143 | −0.500 (−0.586, −0.413) | 5 | 86.0 | <0.001 |
| Zn | 0.291 (0.258, 0.324) | 22 | 0 | <0.001 | 0.224 (0.181, 0.268) | 30 | 93.9 | <0.001 |
| Cu | 0.502 (0.435, 0.570) | 6 | 89.2 | <0.001 | 0.158 (0.102, 0.214) | 12 | 96.2 | <0.001 |
| K | 0.595 (0.562, 0.628) | 23 | 98.8 | <0.001 | 0.258 (0.222, 0.294) | 42 | 97.9 | <0.001 |
| P | 0.456 (0.423, 0.490) | 23 | 98.1 | <0.001 | 0.195 (0.153, 0.237) | 33 | 97.6 | <0.001 |
| Na | 0.192 (0.159, 0.225) | 22 | 98.1 | <0.01 | −0.090 (−0.128, −0.051) | 37 | 96.9 | <0.001 |
| Mn | 0.532 (0.367, 0.697) | 1 | N/A | <0.001 | 0.027 (−0.038, 0.093) | 8 | 94.8 | 0.411 |

SMD, standardized mean difference; CI, confidence interval; N, No. of studies; $I^2$, inconsistency index; $P_z$, $P$ for Z test; N/A, not available.
[a]SMDs were calculated by means of nutrient intakes from FFQ minus that from reference methods.

by FFQs compared with the intake levels drawn from the FRs (SMD > 0), except for α-tocopherol (SMD = −0.139), Fe (SMD = −0.024), I (SMD = −0.5), and Na (SMD = −0.09). However, no significant difference was identified in vitamin K, Fe, and α-tocopherol ($P > 0.05$).

### Agreement of correlation coefficients and SMDs

The agreement of the correlation coefficients and SMDs for energy and nutrients are present in Figure 2 (24HRs) and Figure 3 (FRs). We found that the pooled correlation coefficients between FFQs and 24HRs were above 0.30 and SMDs were below 0.50 for energy and most nutrients, except for plant fat and cryptoxanthin (correlation coefficient < 0.30 and SMD < 0.20). The pooled correlation coefficients between FFQs and 24HRs were above 0.30 and SMDs were below 0.50 for energy and most nutrients, except n-3 fatty acid, n-3 PUFA, n-6 PUFA, vitamin E (correlation coefficient < 0.30 and SMD < 0.20).

### Subgroup analysis using 24HRs as the reference method

#### Subgroup analysis according to study design

The subgroup analysis according to measurement times (cut-off point = 3 times) is shown in Supplemental Table 4. We found that the pooled crude, energy-adjusted, and de-attenuated correlation coefficients of long-term 24HRs (>3) were greater than those of short-term 24HRs (1–3) for 70.73% (29/41), 73.17% (30/41), and 58.97% (23/39) of nutrients, respectively. Additionally, 83.33% (45/54) and 92.59% (50/54) of nutrients measured by FFQs were higher than in short-term and long-term 24HRs (Supplemental Table 5).

The results of the subgroup analysis by sample size are shown in Supplemental Table 6. The pooled crude, energy-adjusted, and de-attenuated correlation coefficients of the studies conducted in a large sample size (>103) were higher than the studies with a small sample size (≤ 103) for 29 of 44 nutrients, 23 of 44 nutrients, and 16 of 37 nutrients, respectively. As shown in Supplemental Table 7, FFQs provided a higher estimation for 51 of 55 nutrients and 38 of 39 nutrients for studies with large and small sample sizes, respectively.

As indicated in Supplemental Table 8, the pooled crude correlation coefficients between interviewer-administered FFQs and 24HRs were higher than self-administered FFQs for 31 of 40 nutrients. The energy-adjusted and de-attenuated validity correlations of interviewer-administered FFQs were higher than self-administered FFQs for 12 of 41 nutrients and 7 of 37 nutrients, respectively. Compared to 24HRs, self-administered and interviewer-administered FFQs were overestimated (SMD > 0) for 47 of 52 and 38 of 45 nutrients, respectively (Supplemental Table 9).

Regarding the quality of studies (Supplemental Table 10), the medians (range) of the pooled crude, energy-adjusted, and de-attenuated correlation coefficients were 0.414 (0.259, 0.801), 0.3985 (0.233, 0.847), and 0.4915 (0.259, 0.814) for very good level; 0.401 (0.130, 0.785), 0.3645 (0.113, 0.796), and 0.485 (0.047, 0.802) for good level; and 0.360 (0.107, 0.736), 0.410 (0.124, 0.680), and 0.496 (0.228, 0.683) for acceptable level, respectively. The FFQs overestimated most

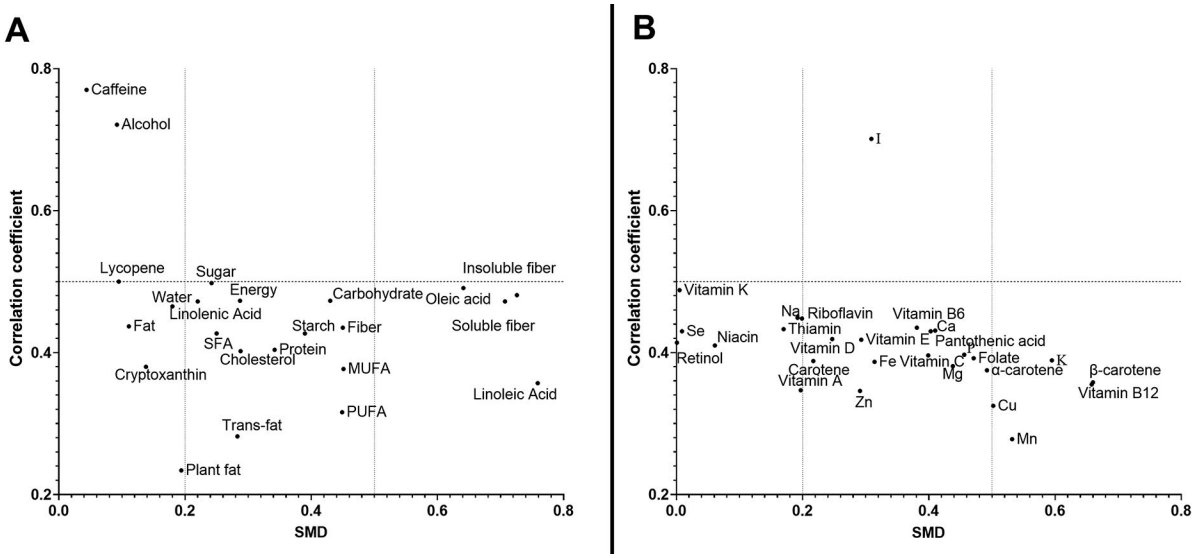


**Figure 2.** The agreement of the pooled correlation coefficients and standardized mean differences (SMDs) when 24-hour recalls were used as reference methods. A: for energy and macronutrients; B: for micronutrient.

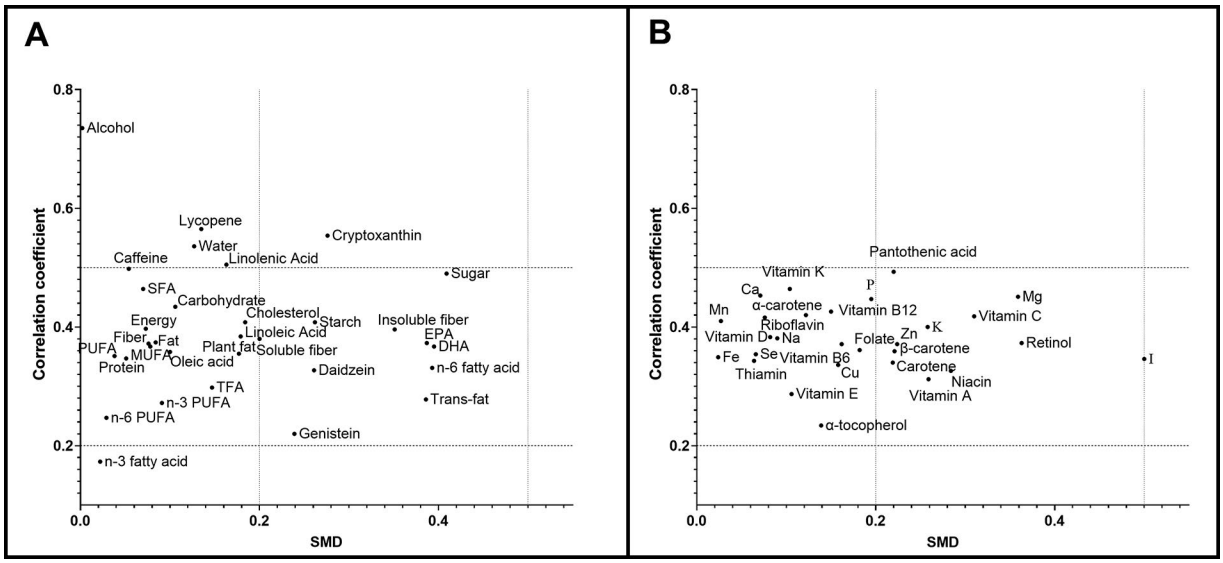


**Figure 3.** The agreement of the pooled correlation coefficients and standardized mean differences (SMDs) when food records were used as reference methods. A: for energy and macronutrients; B: for micronutrient.

nutrient intake levels (87.09% for very good level, 96.23% for good level, and 89.29% for acceptable level), which are presented in Supplemental Table 11.

### *Subgroup analysis according to the FFQ characteristics*

Concerning items of FFQs (Supplemental Table 12), the long FFQs had higher correlation coefficients than the short FFQs for 74.41% (32/43) of crude nutrients, 69.77% (30/43) of energy-adjusted nutrients, and 73.50% (25/34) of de-attenuated nutrients. As shown in Supplemental Table 13, 51 of 54 nutrients and 36 of 42 nutrients assessed by long FFQs and short FFQs tended to be of higher value than those assessed by 24HRs.

Stratifying by reference periods (Supplemental Table 14), we found that the correlation coefficients between 12-month FFQs (compared to less than 12 months) and 24HRs were higher for 23 of 39 crude nutrients, 12 out of 35 energy-adjusted nutrients, and 26 of 32 de-attenuated nutrients. As shown in Supplemental Table 15, 12-month FFQs and less than 12-month FFQs tended to overestimate the intake levels of most nutrients (92.15% of nutrients for 12 months, 91.89% of nutrients for less than 12 months).

### *Subgroup analysis according to the population characteristics*

The results of the subgroup analysis according to gender are shown in Supplemental Table 16. We found that pooled crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs were higher among men than women for 37 of 41 nutrients, 29 of 35 nutrients, and

15 of 33 nutrients, respectively. As shown in Supplemental Table 17, most nutrient intake levels were overestimated by FFQs among the women (45 of 47 nutrients) and men (25 of 39 nutrients).

We conducted the stratified analysis according to different regions. As shown in Supplemental Table 18–20, we found that the medians (range) of pooled crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs were 0.571 (0.336–0.992), 0.454 (0.133–0.988), and 0.4355 (0.141–0.669) for Asia; 0.341 (0.12–0.739), 0.299 (0.019–0.759), and 0.377 (0.029-0.772) for Africa; 0.399 (0.076–0.723), 0.473 (0.056–0.737), and 0.494 (0.047–0.734) for Europe; 0.382 (0.155–0.77), 0.390 (0.112–0.772), and 0.534 (0.277–0.796) for North America; and 0.404 (0.135–0.594), 0.306 (0.172–0.476), and 0.452 (0.239–0.649) for South America. Additionally, 30 of 38 nutrients, 31 of 33 nutrients, 34 of 38 nutrients, 46 of 49 nutrients, and 26 of 28 nutrients evaluated using FFQs were higher than those using 24HRs in Asia, Africa, Europe, North America, and South America, respectively (Supplemental Table 21).

### *Subgroup analysis using FRs as reference methods*

#### *Subgroup analysis according to study design*

The results of the subgroup analysis stratified by the number of repeated measurements of FRs (cut-off point = 7) are shown in Supplemental Table 22. The crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and short-term FRs (1–7), rather than long-term FRs (≥ 7), were higher for 35 of 52 nutrients, 26 of 52 nutrients, and 33 of 47 nutrients, respectively. In addition, compared with the long-term and short-term FRs, the number of nutrients (SMD > 0) overestimated by FFQs was 45 (58 nutrients) and 24 (57 nutrients), respectively (Supplemental Table 23).

We found that crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and FRs among a large sample size, rather than a small sample size, were higher for 13 of 51 nutrients, 27 of 52 nutrients, and 35 of 50 nutrients, respectively (Supplemental Table 24). As shown in Supplemental Table 25, FFQs provided a higher estimation of 24 of 55 nutrients and 39 of 60 nutrients for large and small sample sizes, respectively.

As shown in Supplemental Table 26, pooled crude, energy-adjusted, and de-attenuated correlation coefficients of self-administered FFQs were higher than those of interviewer-administered FFQs for 89.58% (43/48), 88.37% (38/43), and 73.68% (28/38) of nutrients, respectively. As shown in Supplemental Table 27, the self-administered and interviewer-administered FFQs overestimated 27 of 56 nutrients and 38 of 49 nutrients (SMD > 0) compared with the FRs, respectively.

The results of the subgroup analysis based on study quality are shown in Supplemental Table 28. We found that the pooled crude, energy-adjusted, and de-attenuated correlation coefficients ranged from 0.095 to 0.964, from 0.081 to 0.542, and from 0.104 to 0.756 for very good levels; from 0.170 to 0.964, from 0.135 to 0.723, and from 0.135 to 0.787 for good levels; and from 0.029 to 0.759, from 0.019 to 0.759, and from 0.143 to 0.891 for acceptable levels. Subsequently, we found that 30 of 38, 24 of 60, and 44 of 51 nutrient intake levels assessed by FFQs were higher than the FRs (SMD > 0) for very good, good, and acceptable levels, respectively (Supplemental Table 29).

#### *Subgroup analysis according to the FFQ characteristics*

Regarding the FFQs' items (Supplemental Table 30), we found that the long FFQs (item > 126) had higher crude, energy-adjusted, and de-attenuated correlation coefficients than the short FFQs (item ≤ 126) for 77.19% (44/57), 70% (35/50), and 75.51% (37/49) of nutrients, respectively. In addition, short FFQs (25/59) and long FFQs (48/60) tended to report that nutrient intake levels were higher than the FRs; these results are presented in Supplemental Table 31.

Stratifying by reference periods (Supplemental Table 32), we found that 12 of 43 crude nutrients, 17 of 36 energy-adjusted nutrients, and 18 of 28 de-attenuated nutrients that were assessed by 12-month FFQs, compared to less than 12-month FFQs, had higher correlation coefficients, respectively. Thirty of 58 nutrients by 12-month FFQs and 45 of 48 nutrients evaluated by less than 12-month FFQs were lower than those by FRs (Supplemental Table 33).

#### *Subgroup analysis according to the population characteristics*

As shown in Supplemental Table 34, the correlation coefficients for 26 of 48 crude nutrients, 34 of 50 energy-adjusted nutrients, and 27 of 49 de-attenuated nutrients among the men were higher than those among the women. As shown in Supplemental Table 35, most nutrient intake estimated from FFQs was higher than those from the FRs in the three groups (38 of 56 nutrients for the total population, 40 of 56 nutrients for women, 13 of 52 nutrients for men).

We found that the ranges of crude, energy-adjusted, and de-attenuated correlation coefficients were 0.076–0.730, 0.135–0.693, and 0.135–0.787 for Asia; 0.207–0.581, 0.230–0.709, and 0.181–0.891 for Europe; 0.095–0.774, 0.254–0.754, and 0.104–0.827 for North America; 0.029–0.765, 0.019–0.759, and 0.287–0.755 for South America; and 0.170–0.677, 0.229–0.715, and 0.406–0.650 for Oceania. Further, the range for crude correlation coefficient was 0.140–0.599 for Africa. These data are presented in Supplemental Table 36–38. In addition, most nutrients were overestimated by FFQs in the six different regions above (Supplemental Table 39).

## Sensitivity analyses

First (Supplemental Table 40 and 41), we excluded studies that lack available information ($n = 50$) or studies in which the periods covered by the two evaluation methods do not overlap ($n = 28$). After removing these studies, we calculated pooled estimates and found that the crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs varied from 0.076 to 0.772, 0.047 to 0.760, and 0.047

to 0.769, respectively. Moreover, the medians of the correlation coefficients (range) between FFQs and FRs were 0.368 (0.240–0.769) for crude values, 0.429 (0.135–0.746) for energy-adjusted values, and 0.505 (0.135–0.810) for de-attenuated values. We also found that pooled correlation coefficients between FFQs and the reference methods (24HRs and FRs) were consistent with the previous results.

Second, there were 8 studies for 24HRs and 17 studies for FRs found after excluding studies in which the repetition of the reference method was above one. Then, we conducted sensitivity analyses on truncated datasets that retained the studies with an interval time below 1 week (6 studies for 24HRs and 11 for FRs), which are shown in Supplemental Table 42 and 43. We found that the crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs ranged from 0.019 to 0.434, from 0.120 to 0.455, and from 0.141 to 0.561. The correlation coefficients between FFQs and FRs ranged from 0.223 to 0.616 and were higher than the previous results of the meta-analysis for most nutrients (35 of 42 nutrients).

Third, the results of the pooled estimates were adjusted by the quality of these studies, which are presented in Supplemental Table 44 and 45. We observed that the crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and 24HRs ranged from 0.220 to 0.767, 0.191 to 0.861, and 0.047 to 0.783, respectively. The ranges of crude, energy-adjusted, and de-attenuated correlation coefficients between FFQs and FRs were 0.175–0.739, 0.174–0.698, and 0.104–0.789, respectively. The results were consistent with the correlations calculated without the scoring system.

## Discussion

In this study, we conducted a meta-analysis to evaluate the relative validity of FFQs for healthy adults and performed subgroup analyses to find ways to improve the validation study. We found that when 24HRs and FRs were used as reference methods to assess the validity of FFQs, the validity coefficients of FFQs were roughly from 0.4 to 0.7 and 0.3 to 0.6, respectively. Further, we found several factors affecting the correlation coefficients between FFQs and reference methods (24HRs and FRs), such as the number of administrations of the reference method, sample size, administration mode, the number of items, reference periods, and gender. In addition, we found that the estimated energy and nutrient intake levels derived from the FFQs were higher than those derived from the reference methods.

We found that the range (median) of correlation coefficients for FFQs and 24HRs was 0.220–0.770 (0.416), and that for FFQs and FRs was 0.173–0.735 (0.373). The results were consistent with a previous study (Tabacchi et al. 2016) in which the range of pooled correlation coefficients was 0.29–0.52 in adolescents (slightly lower than that of the present study). The reason could be that most adolescents do not cook. Thus, adolescents may know little about cookbooks and its ingredients, leading to some information not being recorded on the dietary record sheet (Yum and Lee 2016). In the present study, relatively low correlation coefficients were observed between FFQs and the two reference methods for n-3 fatty acid, n-6 fatty acid, α-tocopherol, β-tocopherol, PUFA, n-6 PUFA, n-3 PUFA, trans-fat, vitamin E, TFA, vitamin A, DHA, EPA, and Zn, which indicated relatively low agreement. Most of these nutrients were fat-related. The low correlations between FFQs and reference methods might have been linked to the lack of the type of fat reported on the FRs or recalls for every meal (Palacios et al. 2015). In addition, some nutrients (such as Zn in oysters) are found in high concentrations in infrequently consumed foods, which may account for the low correlations (Egami et al. 1999; Hollis et al. 2017). Additionally, the highest coefficient was found for alcohol with both reference methods in this study. It suggested that alcohol mainly derived from alcoholic drinks and was less variable, which was easier for respondents to recall use or not (Munger et al. 1992).

Moreover, the focus of this study was the validity of FFQs stratified by the reference method type. We found that correlations of most nutrient intake were lower for FFQs validated against 24HRs rather than FRs. This may be because, while FFQs and 24HRs shared some similar sources of errors—including reliance on memory, the conceptualization of portion sizes, and distortion of reported diet—FRs did not. (Leon Guerrero et al. 2015; Zulkifli and Yu 1992). We also observed higher heterogeneity with the 24HRs than with the FRs. A probable explanation was that 24HRs depend on the recent memory of the participants and the capacity of interviewers to describe food intake, which can affect the accuracy of dietary intake levels.

In addition, subgroup analyses were conducted according to three aspects: study design, characteristics of the FFQs, and characteristics of the population.

First, regarding the design of the validation study, we conducted subgroup analyses according to the number of administrations of the reference method, sample size, and FFQ administration mode. We found that correlation coefficients between FFQs and short-term 24HRs (less than 3 days) were lower than those between FFQs and long-term 24HRs for most nutrients. This is because FFQs focus on usual and long-term dietary intake (Pranger et al. 2019), while 24HRs report dietary intake for a certain number of days. Short-term 24HRs are a poor descriptor of an individual's usual dietary intake because of the daily variability in the food and nutrient intake, which is common of most people (Willett 2013). Thus, short-term 24HRs may not be sufficient to estimate the usual energy and nutrient intake, which limits the correlation between FFQs and short-term 24HRs (Silva et al. 2013). However, correlation coefficients between FFQs and long-term FRs (more than 7 days) were lower than those with the short-term FRs. An FR is an open-ended tool performed several times per day for a fixed period and thereby puts a higher burden on daily life for weighing and recording food intake (Zhuang et al. 2012). The completion of FRs depended on the participants' motivation, awareness of food intake, and literacy, in comparison with 24HRs (Dehghan, del Cerro, et al. 2012). Thus, increasing FRs might induce lower participant motivation and even alter their diet. The use of long-term FRs, rather than 24HRs

might lead to measurement errors. To some extent, the deviation from the true dietary intake reduced the correlations between FFQs and long-term FRs (Willett 2013). Thus, the reference methods' characteristics and the actual situation (such as research funding and level of literacy of participants) should be considered when researchers design as FFQ presents similar source of error to 24HRs.

We additionally excluded studies that where the period covered in both assessment methods did not overlap and conducted a sensitivity analysis. The pooled correlation coefficients between FFQs and the reference methods (24HRs and FRs) were consistent with the previous results. To comprehensively analyze the real changes in diet and minimize the effect of seasonal dietary intake variation on the dietary assessment (Willett 2013), it is recommended to collect 1-year dietary data, and the time of the reference method is best to cover the reference period of FFQs.

Then, we found that the correlation coefficients between FFQs and 24HRs were lower for most nutrients with a smaller sample size. Because a small sample size may limit representativeness, which induces large differences in within-person nutrient intake (Xu, J Dibley, and D'Este 2004). The de-attenuated correlations between FFQs and FRs were found to be higher among a large sample size. The use of a larger sample size could reduce day-to-day variations in nutrient intake and better reflect significant correlation (Nath and Huffman 2005), and partly explain the high correlations between FFQs and FRs after the elimination of the within-person variability in large samples. However, a large sample size might lead to a loss of follow-up and a heavy burden (time and cost) on participants and investigators, especially when multiple record data are collected. Thus, it is recommended that the sample size should consider the actual situation of researchers on the premise of meeting the statistical efficiency.

Regarding the administration mode of FFQs, we found that FFQs with a self-administered mode had higher correlation coefficients than interviewer-administered mode, which indicated that self-administered mode could be considered an effective administration approach. Even though an FFQ with a self-administered mode is burdensome for individuals, especially with low educational background and old age, it is cost-efficient and has a relatively higher correlation coefficient (Turconi et al. 2010). Thus, it is recommended that the FFQs should be self-administered and reviewed by trained interviewers after completion to improve the quality of information (Leon Guerrero et al. 2015).

Subsequently, we conducted sensitivity analyses on truncated datasets that retained the studies with interval time below 1 week and found that the results were higher for most nutrients. The FFQs and reference methods in these validation studies may have been administered in close succession, which sensitizes study participants regarding their dietary intake. Therefore, participants may be able to answer the dietary record more accurately, thereby resulting in an artificial improvement in the validity of the FFQ.

Second, to improve the validity study of FFQs, we conducted subgroup analyses of the validity coefficient of an FFQ according to its characteristics. We found that correlations between long FFQs and reference methods (24HRs and FRs) were higher than those for the short FFQs for energy and most nutrients, which is because a long FFQ would likely cover most of the food consumed. However, long FFQs can be burdensome and require higher commitment and effort from individuals, which may lead to an increase in the number of non-responders and missing data (Cade et al. 2004; Yokoyama et al. 2016). Accuracy may further decline because it takes more time to complete a longer FFQ, which induces potential biases, especially for participants with low education levels (Cade et al. 2004). Thus, considering that an FFQ with more items can cover greater dietary information but lead to more non-responders and missing data, pilot studies should be conducted to explore a reasonable length of an FFQ that can achieve higher accuracy.

Furthermore, higher validity correlations were found in FFQs with a shorter reference period. The reason could be that a shorter reference period has lower recall bias level. However, due to the different dietary habits in seasons, the FFQ was often used to recall food intake in 1 year to obtain a complete view of the regular diets of each participant and assess the nutrition–disease association accuracy (Shrestha et al. 2017). Thus, the different dietary habits across seasons should be considered in FFQs.

Third, we conducted subgroup analyses according to the population characteristics to assess the effects of these variables on the validity correlation of FFQs. We found that the correlation coefficients between FFQs and reference methods for energy and most nutrients were weaker among women than men. This result was in line with a previous study (Tsugane, Kobayashi, and Sasaki 2003). It is easier for men to respond to the questionnaire because they are not as interested in and keen about their dietary habits as women. Thus, the dietary diversity is lower in men than in women, which indicates the validity of FFQs for men better than for women for energy and most nutrients (Tsugane, Kobayashi, and Sasaki 2003). The gender differences might be owed in part to disparities in consumption amounts, food choices, and portion size used (Lee et al. 2016). Another possible reason for this is that women are more concerned about their body weight and tend not to accurately answer the precise amount of food consumed (Zhuang et al. 2012).

Furthermore, we found that FFQs, as compared to FRs or 24HRs, overestimate nutrient intake as well as energy, which is similar to the results of subgroup analysis. One of the reasons may be that the FFQs record dietary intake over a long period while 24HRs or FRs provide information on recent food intake (Dehghan, Ilow, et al. 2012; van Dongen et al. 2011). For example, some food items from the FFQ were not consumed during the days when the 24HRs or FRs were performed. Another reason is that FFQs cannot provide precise portion sizes for food group intake at the individual level. Therefore, an FFQ is a reliable tool for ranking individuals according to dietary intake, but FFQ data may not be as accurate to assess the adequacy of

individuals' dietary intake. In addition, some investigators have used biomarkers to evaluate validity of dietary assessment instruments (Schatzkin et al. 2009). Two classes of biomarker have been identified: recovery and concentration biomarkers (Freedman et al. 2010). Recovery biomarkers reflect the balance between intake and excretion of a specific chemical component on an absolute scale over a short period (Keogh, White, and Rodwell 2013).These exist only for energy, protein, potassium, and sodium, which found underestimated by using FFQs (Freedman et al. 2014, 2015). Concentration biomarkers, which are correlated with, but not unbiased for, intake of certain nutrients, because they are influenced by other factors such as absorption, metabolism, and individual characteristics (Keogh, White, and Rodwell 2013). The comprehensive analysis of FFQ validation using biomarkers needs further study.

The present study is the first meta-analysis that explored the validity of FFQs and their influencing factors in adults. Moreover, compared with previous reviews (Lee et al. 2016; Tabacchi et al. 2016), this review's strength is that more studies were combined to assess the effects and more nutrients were evaluated to verify the validity of the FFQ, which makes our results reliable, effective, and more statistically powerful. Meanwhile, we evaluated whether FFQs overestimate or underestimate energy and nutrient intake compared to reference methods to provide further and deeper understanding in using FFQs.

However, some limitations should be considered. First, additional factors can affect the results, which were not analyzed in the present meta-analysis, such as education levels, age, smoking and drinking history, physical activity. For example, a study on the effect of education on the validity of adult FFQs found that a group with higher educational levels showed a tendency for better estimation of the evaluated nutrients (Crispim et al. 2006). For a younger and overweight population, it may be difficult to accurately assess nutrient intake (Paalanen et al. 2006). However, these details were not provided in most included studies. Future studies could consider these participant characteristics when assessing dietary intake. Second, we did not take portion sizes into account when analyzing validity. As is known, fitted portion sizes using recent reference data from a random sample of study participants improved the quantitative assessment of food and nutrient intake, compared with predefined portion sizes based on experience (Nothlings et al. 2007). However, insufficient information regarding fitted or predefined portion sizes was provided in the analyzed articles. Third, some articles published before the year 2000 have influenced our results. Fourth, we excluded studies of FFQ used to analyze specific nutrients in the study. The purpose of the study is to assess the FFQs used to evaluate the overall diet, while the FFQs specific to certain nutrients or foods were used to estimate specific nutrients. Due to different research purposes, the validation studies target specific nutrition could not be included. The validity of FFQ for specific nutrients may need to be further analyzed. Fifth, as all included articles were observational studies, various uncontrollable confounding factors may have affected their results. Sixth, we restricted to studies using Pearson or Spearman correlation coefficients in the study. Bland-Altman analyses and cross-classification analyses were used to assess the validity of FFQ. For cross-classification analyses, participants were divided into categories according to their intakes, and weighted kappa statistic was used to assess the consistency. However, individuals in different studies were divided into different categories—some are quartiles (Ye et al. 2016; Zack et al. 2018) and some are tertiles (De Keyzer et al., 2013; Hemiö et al. 2014; Hollis et al. 2017). Thus, the weighted kappa statistics in different studies cannot be combined. The Bland-Altman method that plots the individual differences between two methods against the mean of the methods gives a visual comparison of assessment (Cade et al. 2002). The effect values of Bland-Altman analysis cannot be extracted and merged.

## Conclusion

We found that the validity correlation of FFQs on energy and most nutrient intake ranged approximately from 0.4 to 0.7 and from 0.3 to 0.6 for 24HRs and FRs, which were used as reference methods in healthy adults, respectively. The results indicated that an FFQ was a valid tool to measure the overall dietary intake in epidemiological studies. Subsequently, it is recommended that the sample size, the characteristics of reference methods, and the actual situation of the study should be considered comprehensively when designing the validation study. Moreover, the results of the subgroup analyses showed that FFQs with a self-administered mode, more items, and shorter reference period improved the validity correlations. Furthermore, the use of FFQs may result in an overestimation of dietary consumption compare to reference methods (e.g., FRs and 24HRs). In comparison to other dietary assessment methods, FFQs can be less accurate in estimating daily nutrient intake. Thus, FFQs should be used with caution for individual dietary guidance.

## Disclosure statement

The authors declare that they have no competing interests.

## Data availability statement

The data supporting the results can be found in Supplemental Tables 1–45.

## Funding

This work was supported by the National Key R&D Program of China under Grant 2017YFC0907402 to Yuhong Zhao; the National Natural Science Foundation of China under Grant 81903302 to Yang Xia; the China Postdoctoral Science Foundation under Grant 2018M641753 to Yang Xia; and the 345 Talent Project of Shengjing Hospital of China Medical University under Grant M0294 to Yang Xia.

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