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Comparison of total energy intakes estimated by 24-hour diet recall with total energy expenditure measured by the doubly labeled water method in adults

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ABSTRACT

BACKGROUND/OBJECTIVES: The doubly labeled water (DLW) method is the gold standard for estimating total energy expenditure (TEE) and is also useful for verifying the validities of dietary evaluation tools. In this study, we compared the accuracy of total energy intakes (TEI) estimated by the 24-h diet recall method with TEE obtained using the doubly labeled water method.
SUBJECTS/METHODS: This study involved 71 subjects aged 20–49 yrs. Over a 14-day period, three 24-h diet recalls per subject (2 weekdays and 1 weekend day) were used to estimate energy intakes, while TEE was measured using the DLW method. The paired *t*-test was used to determine the significance of differences between TEI and TEE results, and the accuracy of the 24-h recall method was determined by accuracy predictions percentage, root mean square error, and bias.
RESULTS: Average study subject age was 33.4 ± 8.6 yrs. The association between TEI and TEE was positive and significant ($r = 0.463$, $P < 0.001$), and the difference between TEI (2,084.3 ± 684.2 kcal/day) and TEE (2,401.7 ± 480.3 kcal/day) was also significant ($P < 0.001$). In all study subjects, mean TEI was 12.0% (307.5 ± 629.3 kcal/day) less than mean TEE, and 12.2% (349.4 ± 632.5 kcal/day) less in men and 11.8% (266.7 ± 632.5 kcal/day) less in women. Rates of TEI underprediction for all study subjects, men, and women, were 60.5%, 51.4%, and 66.7%, respectively.
CONCLUSIONS: This study shows that 24-h diet recall underreports energy intakes. More research is needed to corroborate our findings and evaluate the accuracy of 24-h recall with respect to additional demographics.

Keywords: Energy metabolism; energy intake; adult

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Conflict of Interest
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INTRODUCTION

Diet is an etiologic and preventative factor of coronary heart disease, diabetes, and cancer, which are all of increasing concern [1-3], and thus, means of accurately determined dietary consumptions are required to evaluate the impacts of diet on health, weight loss, and other lifestyle interventions in which nutrition plays a key role [4]. Total energy intake (TEI) is a determinant of an individual's nutrient requirements and the nutrient content of a diet, and thus, accurate estimates of energy intakes are important [4]. Furthermore, they are essentially required in medical, human biology, sports, and nutrition studies.

Various methods are available for obtaining information about dietary intakes, such as 24-h diet recall and the food frequency questionnaire (FFQ), dietary records, and direct observations [5]. The FFQ is used in large epidemiologic studies of diet and health to assess dietary intakes using long-term eating patterns but is limited because it is difficult for subjects to provide accurate quantitative information about foods consumed. The 24-h diet recall method can be used to estimate the amount of intake per meal based on the type and quantity of meals eaten during the preceding 24 h [5], and thus, this method is used for large-scale nutrition surveys, such as the National Health and Nutrition Examination Survey (NHANES) in Korea and other countries [6]. Nevertheless, because 24-h diet recall also depends on memory, errors occur when it is used to estimate dietary intakes [5,7].

Because these methods rely on information provided by respondents, which may not be accurate, determining the validity of food intake metrics is problematic. Many researchers have tried to identify effective biological markers of food intake in order to evaluate the accuracy of dietary assessments [8]. Goldberg *et al.* [9] proposed applying the principle of energy physiology to derive cut-off values for assessing reported energy intakes, expressed as multiples of the basal metabolic rate, with respect to expected energy expenditures in sedentary individuals. In weight-stable individuals, total energy expenditure, as measured by the doubly labeled water (DLW) method, reflects calorie intake. However, due to the complexity and cost of this method, it is not a practical option for large-scale epidemiological researches [8].

Some dietary assessment methods such as dietary records have been used as reference tools to evaluate the accuracy of 24-h diet recall methods [10]. However, it has been established that reporters often underestimate food intakes in dietary records as evidenced by studies that investigated different groups of subjects such as children and adolescents [11], adults [12], athletes [13], and obese individuals [14]. Therefore, true reporting bias is not detected if both the 24-h diet recall method and dietary records have correlated errors. Alternatively, the DLW method, which is the gold standard for measuring total energy expenditure (TEE) [15,16], can be used to verify the validity of dietary evaluation tools, including 24-h diet recall methods [5]. The DLW method is based on the principle of energy metabolism, namely, that energy expenditure and energy intake are equal when body weight and composition do not change [17,18]. Thus, the DLW method allows true reporting bias to be determined because it is not subject to errors associated with self-reported intakes. However, DLW testing is expensive as costs of ^{18}O and analytical equipment are high and experienced technical experts are required to analyze results.

The accuracy of 24-h diet recall methods for estimating TEI using the DLW method as a reference has been investigated in children [19], adults [20] and the elderly [21] in foreign countries. In Korea, similar studies have been conducted in elderly women and men [22,23], but no such study has been performed on Korean adults. Therefore, we considered a study on the accuracy of the 24-h recall in Korean adults was required since gender and age have been reported to influence the accuracies of 24-h recall methods [22]. Accordingly, we assessed the accuracy of TEI estimated by 24-h diet recall in adults by comparing results with TEE values measured using the DLW method.

SUBJECTS AND METHODS

In a previous study [24], the accuracy of dietary reference intakes equations for determining estimated energy requirements in Korean adults were assessed using the DLW method and the approval was received from Gangneung-Wonju National University Institutional Review Board (approval No. GWNUIRB-2013-3). The subjects of this previous study were also used in this study.

Subjects

This study was conducted on 72 subjects (36 men and 36 women) aged 20–49 yrs selected from the Gangneung region in Gangwon-do Province, Korea. Subjects were recruited through advertisements on the internet and by displaying flyers in the Gangneung region. The following inclusion criteria were applied: i) a body mass index (BMI) ≥ 18.5 kg/m^2 but < 25.0 kg/m^2, ii) non-participation in any weight control program, iii) the absence of any disease affecting energy metabolism and not taking drugs related to thyroid, kidney, and prostate disease, iv) non-athletes or non-involvement in any extreme exercise program, and v) residing in the study area during the study period. Initially, 72 subjects were included, but one man dropped out, and thus, this study was composed of 71 subjects (35 men and 36 women). All subjects signed an informed consent form before participating in the study.

Anthropometric measurements

To determine whether there were changes in body weights during TEE measurements, which were performed over 14 days, using the DLW method, anthropometric measurements were taken on the first and last days of the measurement period. Heights were measured using an automatic extensometer (BSM 330; Biospace Co., Seoul, Korea) with subjects standing upright in light clothes and without shoes. In addition, body weight, body fat (%) and fat-free mass were measured using a body composition analyzer (Inbody 720; Biospace).

24-h dietary survey

We surveyed the TEI of the study subjects using a 24-h diet recall method for 3 non-continuous days (2 weekdays and 1 weekend day) within 2 weeks of DLW measurements. Trained investigators conducted the interviews by applying KHNANES guidelines [23]. On the days, dietary data were collected, meals and drinks consumed by subjects during the preceding 24 h were recorded. The subjects took and recorded photographs of all foods eaten and provided these during interviews to reduce recall bias. Nutritional analysis of the data obtained by 24-h diet recall was performed using CAN-Pro 4.0 software developed by the Korean Nutrition Society (Seoul, Korea).

Total energy expenditure measurement

Manufacture and ingestion of DLW

Total energy expenditure was measured using the DLW method over 14 days. The principle of this method has been explained in detail elsewhere [16]. In brief, the DLW was prepared on a per kilogram of total body weight basis by combining 1.03 g of $H_2^{18}O$ (10% enriched; Taiyo Nippon Sanso, Tokyo, Japan) and 0.07g of ^2H_2O (99.9% enriched; Sigma-Aldrich, St. Louis, MO, USA). Subjects were administered the prepared DLW at a dose of 1.1 g per kg of body weight.

Collection and analyses of urine samples

The urine samples were collected five times (at baseline and on days 1, 2, 13, and 14 after initiating DLW testing). Subjects were requested not to eat or drink for 30 minutes before each urine collection. Subjects were instructed to collect and record details of urine sampling to ensure result accuracy. During mornings when urine samples were collected, subjects discarded the first urine voided after waking up and sampled urine an hour later. Urine samples were stored in a freezer below −20°C before analysis. ^2H and ^{18}O in urine samples were analyzed using an isotopic mass analyzer (Finnigan Delta Plus; Thermo Fisher Scientific, Waltham, MA, USA).

Calculation of energy expenditure by DLW method

Rates of daily emissions of ^2H (k_h) and of ^{18}O (k_o) were obtained and used to compute the rate of carbon dioxide produced (rCO_2) using the formula below [16,21]. A total body water (TBW) percentage of 60% was used in the calculation [16].

$$rCO_2\ (\text{mol/day}) = 0.4554 \times TBW \times (1.007\ k_o - 1.041\ k_h)$$

The food quotient (FQ) formula derived by Black *et al.* [25] was used to calculate the FQ values based on 24-h recall results. The rCO_2 and FQ values obtained were inserted in the Weir equation (modified) [16,26] to calculate total energy expenditures as depicted in the equation below:

$$TEE\ (\text{kcal/day}) = 3.9 \times (rCO_2/FQ) + 1.1 \times rCO_2$$

Statistical analysis

All data collected were processed using IBM SPSS software (version 25.0; IBM Corp., Armonk, NY, USA). Results are presented as means ± SDs, and statistical significance was accepted for P-values < 0.05. The Kolmogorov-Smirnov test was used to test the normality of data distributions and showed all data were normally distributed (P > 0.05). The independent t-test was used to determine the significances of differences between genders. The significances of differences between TEI and TEE results were determined using the paired t-test. To evaluate the accuracy of the 24-h recall method, bias (%), percentage accurate prediction, percentage under prediction, percentage over prediction, and root mean square error (RMSE) were calculated. RMSEs express differences between TEI and TEE as absolute values and were calculated as follows [27].

$$RMSE = \sqrt{\frac{1}{N}\Sigma(TEI - TEE)^2}$$

Accurate prediction was defined as the percentage of subjects with a TEI between 90% and 110% of the TEE, underprediction as a TEI < 90% of the TEE, and overprediction as a TEI > 110% of the TEE [28,29]. The correlation between TEI and TEE was assessed by using Person's correlation coefficients, and a Bland-Altman plot was used to assess the level of agreement between TEE and TEI results.

RESULTS

Subject characteristics

The 71 study subjects had a mean age of 33.4 ± 8.6 yrs and a mean BMI of 22.7 ± 2.7 kg/m^2 (**Table 1**). In terms of age and BMI, no discernible difference was observed between men and women. Men were substantially taller and heavier than women (172.6 ± 5.9 cm and 69.1 ± 7.0 kg vs. 159.4 ± 5.9 cm and 56.5 ± 8.5 kg, respectively). Men (23.2 ± 2.1 kg/m^2) and women (22.2 ± 3.2 kg/m^2) had BMIs in the normal range. On the other hand, men had a lower body fat percentage (18.6 ± 5.1% vs. 30.1 ± 5.6%) and body fat mass (12.9 ± 4.1 vs. 17.3 ± 5.3 kg), but significantly greater fat-free mass (FFM) (56.2 ± 5.8 kg vs. 39.2 ± 4.6 kg).

Comparison between TEI and TEE results and underreporting of energy intake

TEI and TEE results and underreporting of energy intake in adults are summarized in **Table 2**. In men and women, total energy intakes (2,356.6 ± 574.7 and 1,839.3 ± 636.1 kcal/day, respectively) were significantly lower than total energy expenditures (2,705.9 ± 418.0 and 2,106.0 ± 329.4 kcal/day). In addition, for all study subjects, the difference between TEI (2,084.3 ± 686.2 kcal/day) and TEE (2,401.7 ± 480.3 kcal/day) was significant (P < 0.001). However, underreporting of energy intake was not significantly different between men (349.4 ± 632.5 kcal/day) and women (266.7 ± 632.5 kcal/day).

Bias and RMSE between TEI and TEE in men and women were −12.2 ± 21.6% and 714.6 kcal/day and −11.8 ± 32.0% and 678.3 kcal/day, respectively (**Table 3**). For all study subjects, bias and RMSE were −12.0 ± 27.1% and 696.4 kcal/day, respectively. Furthermore, 60.5% of energy intakes were underpredicted, 25.4% were accurately predicted, and 14.1% were overpredicted. On the other hand, the accuracy of the 24-h recall method did not show any significant difference by age group (men and women in their 20s, 30s, or 40s, not included in **Table 3**).

The correlation between TEI and TEE in **Fig. 1** was significant and positive with a correlation coefficient of 0.463 (P < 0.001). The Bland-Altman plot (**Fig. 2**) showed a mean difference

Table 1. Subject characteristics

Variables	Total (n = 71)	Men (n = 35)	Women (n = 36)	P-value[2)]
Age (yrs)	33.4 ± 8.6	33.5 ± 8.8	33.3 ± 8.5	0.909
Height (cm)	165.9 ± 8.9	172.6 ± 5.9	159.4 ± 5.9	<0.001
Body weight (kg)	62.7 ± 10.0	69.1 ± 7.0	56.5 ± 8.5	<0.001
Body mass index (kg/m^2)	22.7 ± 2.7	23.2 ± 2.1	22.2 ± 3.2	0.133
% Body fat[1)]	24.4 ± 7.9	18.6 ± 5.1	30.1 ± 5.6	<0.001
Fat mass (kg)[1)]	15.1 ± 5.2	12.9 ± 4.1	17.3 ± 5.3	<0.001
Fat-free mass (kg)[1)]	47.7 ± 5.2	56.2 ± 5.8	39.2 ± 4.6	<0.001

Values are presented as mean ± SD.
[1)]Measured using an Inbody 720 body composition analyzer.
[2)]Obtained by the independent sample t-test between men and women

Table 2. TEI, TEE, and underreporting of energy intake in adults

Variables	TEI (kcal/day)	TEE (kcal/day)	P-value[1)]	Under-reporting (kcal/day)[2)]
Men (n = 35)	2,356.6 ± 574.7	2,705.9 ± 418.0	< 0.01	349.4 ± 632.5
Women (n = 36)	1,839.3 ± 636.1	2,106.0 ± 329.4	< 0.01	266.7 ± 632.5
Total (n = 71)	2,084.3 ± 684.2	2,401.7 ± 480.3	< 0.001	307.5 ± 629.3*

Values are presented as mean ± SD.
TEI, total energy intake (estimated by the 24-h recall method); TEE, total energy expenditure (measured by the DLW method); DLW, doubly labeled water.
[1)]Obtained by paired t-test between TEI and TEE.
[2)]Under-reporting of energy intake by the 24-h diet recall = TEI − TEE.
*P < 0.001: significantly different by independent t-test between men and women.

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Table 3. Accuracy of 24-h diet recall for estimating energy intakes based on bias, RMSE and accurate predictions (%)

	Bias[1)] (%)	Maximum negative error[2)] (%)	Maximum positive error[3)] (%)	RMSE (kcal/day)	Accurate prediction[4)] (%)	Under prediction[5)] (%)	Over prediction[6)] (%)
Men (n = 35)	−12.2 ± 21.6	62.3	30.5	714.6	34.3	51.4	14.3
Women (n = 36)	−11.8 ± 32.0	56.4	46.3	678.3	19.4	66.7	13.9
Total (n = 71)	−12.0 ± 27.1	62.3	46.3	696.4	25.4	60.5	14.1

Values are presented as mean ± SD.
TEI, total energy intake; TEE, total energy expenditure; RMSE, root mean square error
[1)]Mean percentage error between TEI and TEE.
[2)]The largest underprediction
[3)]The largest overprediction
[4)]Percentages of subjects with a TEI within 10% of the TEE.
[5)]Percentage of subjects with a TEI < 90% of the TEE.
[6)]Percentage of subjects with a TEI > 110% of the TEE.

between TEI and TEE results of −307.5 kcal/day and that the limits of agreement ranged from −1,540.9 to 926.0 kcal/day.

DISCUSSION

In this study, total energy expenditure measured using the DLW method was used to evaluate the accuracy of the 24-h diet recall method, which was conducted on 3 non-consecutive days on adults aged from 20 to 49 yrs. To date, the most accurate reference technique for validating energy intake measurement methods is the DLW method [30]. Until the 1980s, it was difficult to assess the accuracy of dietary surveys, but the development of the DLW technique using isotopes (^2H,^{18}O) to measure energy expenditure made this possible [30]. The DLW technique is based on the principle of energy metabolism, that is, energy intake equals energy expenditure when subjects' body weights are stable [31]. In this study, the average energy intake estimated for all study subjects by the 24-h recall method was 2,084.3 ±

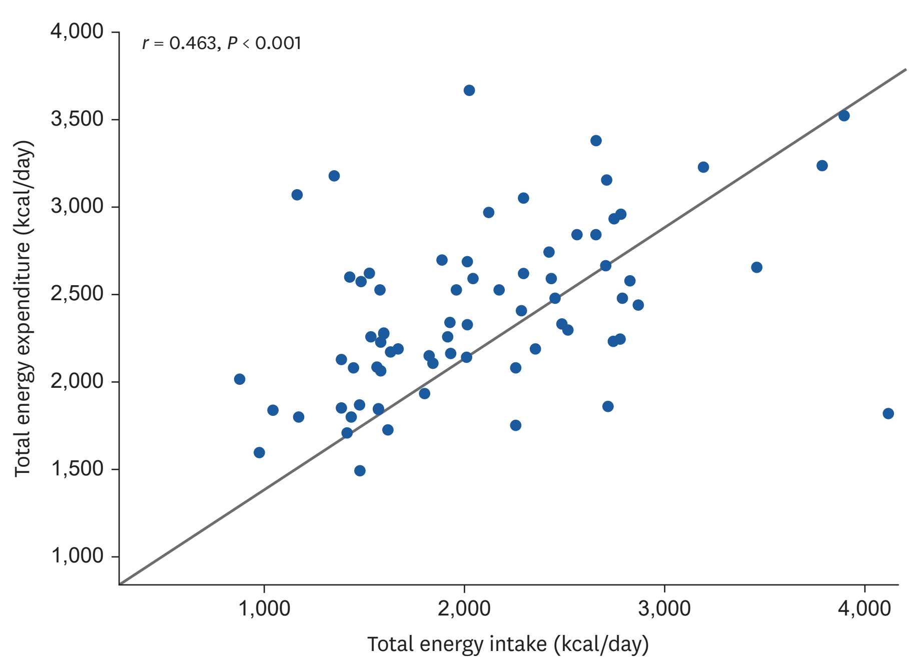

Fig. 1. Correlation between TEE measured by the DLW method and TEI estimated by 24-h diet recall.
DLW, doubly labeled water; TEI, total energy intake; TEE, total energy expenditure.

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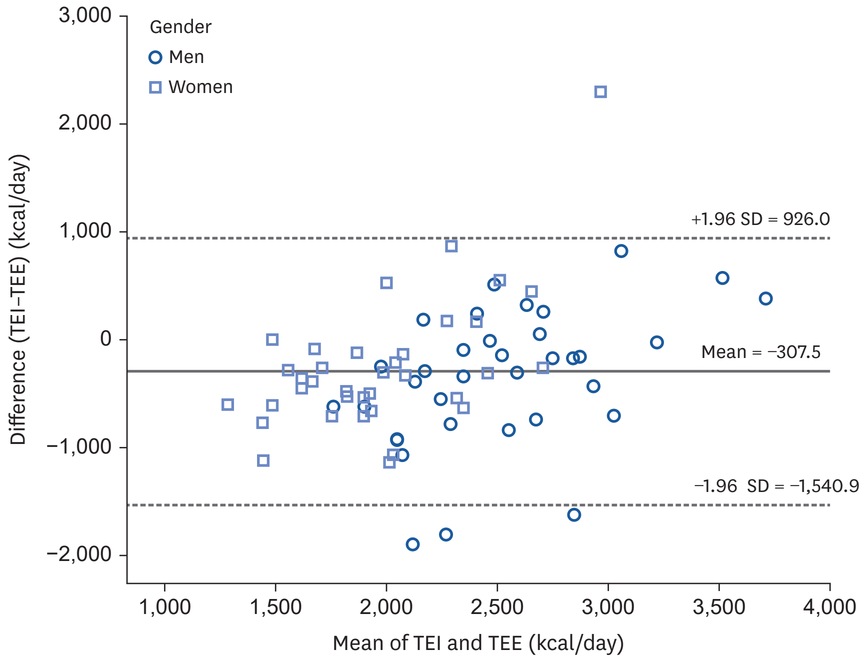

Fig. 2. Bland-Altman plot for TEE measured by the DLW method and TEI estimated by 24-h diet recall.
DLW, doubly labeled water; TEI, total energy intake; TEE, total energy expenditure.

684.2 kcal/day, which was 12.0% lower than that obtained for TEE (2,401.7 ± 480.3 kcal/day, $P < 0.001$). Average energy intake for men was underreported by 12.2% (TEI 2,356.6 ± 574.7 kcal/day and TEE 2,705.9 ± 418.0 kcal/day) and 11.8% underreported for women (1,839.3 ± 636.1 vs. 2,106.0 ± 329.4 kcal/day).

Weighed diet records have been used as a dietary assessment method to estimate energy intakes [10], but this method also underestimated energy intakes as compared with the TEE measured by DLW method [11,12]. For example, 7-day weighed dietary records underestimated energy intakes by 11–27% in the adolescents and 20.5% in adults.

Studies on the accuracy of the 24-h diet recall method for evaluating energy intake have been carried out in various countries on adults [20,32-34], and also found TEI values were lower than TEE values. A study carried out by Subar *et al.* [33] on a group of 261 men and 233 women aged 40–69 yrs reported that TEI was underreported by men and women as compared with TEE by 12.7% and 13.3%, respectively.

Another study by Gemming *et al.* [32] on 40 adults aged 18–64 yrs revealed that TEI was underestimated by 17% in men and 13% in women compared to TEE. In addition, the studies [20,34] on women aged 19-46 yrs reported that TEI values were 17% and 16% lower than TEE values which concurs with our findings.

Previous studies have shown, subject memory is improved by the use of wearable cameras [32], multiple pass 24-h recalls [20,32,34], and a "Forgotten Foods" list [33]. In the present study, subjects took pictures of foods and beverages consumed during the previous day to reduce recall bias. Studies by Biró *et al.* [7] and Salvador Castell *et al.* [10] revealed that recall bias is the largest error associated with estimating energy intakes using the 24-h diet recall method.

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However, a subsequent study that addressed this issue using photographs of food consumed by subjects the previous day found that accuracy of 24-h diet recall was improved [35].

The findings of some studies [36-38] conducted in adults are inconsistent with our findings. A study by Moshfegh *et al.* [36] on 127 women and 94 men aged 30 to 69 reported underreporting of < 1% and 6% for men and women, respectively, when TEI and TEE results were compared. In addition, a study conducted to determine the energy expenditure in underweight adults, that is, 6 men aged 20–32 yrs, reported that TEI results were only 1.3% lower than TEE results [38]. Meanwhile, a study by Sawaya *et al.* [37] on 10 women aged 25 yrs showed that TEI values were 24.7% less than TEE values. Differences between the findings of these studies and our findings may be due to the number of subjects recruited or the number of days of 24-h diet recall. It has been previously reported that the accuracy of the 24-h diet recall method may depend on the number of days and the methods used [39]. Ma *et al.* [4] concluded that accuracy is better when evaluations are conducted for at least 3 days and that weekends should be included to reduce underreporting rates.

According to the studies of Black *et al.* [40] on middle aged women/retired men and Tomoyasu *et al.* [41] on elderly adults to evaluate the accuracy of dietary survey methods with respect to the DLW method, dietary surveys resulted in the underreporting of energy intake by 11% and 20.2% respectively. Johnson *et al.*' study [42] that evaluated the accuracy of the three-day meal recording method in elderly persons reported underreporting in energy intakes in men and women of 12% and 24%, respectively, whereas in another study [43] conducted on elderly persons, the rates were 12% for men and 31% for women. Furthermore, studies conducted in Korea on elderly women [22] and men [23] also reported that TEI underreported TEE by 25.9% and 4.4%, respectively. Although these studies were conducted in the elderly, their results support our findings, which indicates that 24-h dietary recall underreports energy intakes. Some studies have reported that underreporting is positively correlated with age [8,44-46]. However, according to MacDiarmid and Blundell [47], age is associated with characteristics that influence underreporting.

Numerous relatively recent studies have compared self-reporting energy intakes with TEE values obtained using the DLW method. Overall, these studies show energy intakes are generally underreported [30] and underreported by children [19], teenagers [48], underweight adults [38], and the elderly [37]. However, careful analysis of reported underreporting rates [47,49-51] revealed that the following factors cause under-reporting when dietary assessment tools are used, especially the 24-h diet recall method; gender, age, income level, education, irregular meal habits, dietary restraint, emotional status, and smoking.

The findings of a review of 37 published studies by Black *et al.* [51] revealed that younger women were significantly more likely to underreport energy intake than younger men. This may have been caused by the pressure society places on women to look slimmer, which can result in underestimated food records [42]. According to the study of Johnson *et al.* [42], percent body fat was negatively correlated with underreporting of energy intake ($r = -0.42$, $P = 0.001$) in older women, but none of the physiological variables were significantly correlated with underreporting of energy intake in older men.

Dietary restraint (cognitive control of food intake) [52] has also been reported to be a cause of underreporting of dietary intakes [8,47]. According to MacDiarmid and Blundell [47], some subjects explained they did not report all the food they consume because they were “too embarrassed” to report everything eaten. Subjects were asked in a prospective study while completing a dietary assessment tool, if they would alter their diets [47], and it was found that restrained eaters were more likely to change their eating pattern or eat less than non-restrained eaters. Bingham *et al.* [53], who used the Three Factor Eating Questionnaire, reported that inaccurate reporters had considerably higher restraint scores than accurate reporters. Therefore, the underreporting of food intake observed in the present study might have been caused by inaccurate reporters or restrained eaters that failed to report everything they had eaten.

According to Hebert *et al.* [54], although dietary questionnaires are nominally used to detail nutrients consumed, they undoubtedly have psychosocial and psychological impacts, and thus, psychology is needed to understand what motivates accurate or inaccurate reporting and should be considered to improve the accuracies of recall-based evaluations. Thus, the psychological characteristics of subjects and interviewers may become increasingly important when determining the validity of dietary evaluation tools [55].

In conclusion, the present study shows that energy intakes estimated by 24-h diet recall resulted in underestimations in men (12.2%), women (11.8%) and in all study subjects (12%) as compared with DLW-based results.

The present study has several limitations that warrant consideration. First, obesity has been reported to affect the accuracy of the 24-h recall methods adversely [40,50]. However, the number of subjects that could be included in our study was limited by the high cost of DLW method, and increasing the range of subjects' weights beyond the normal weight range would have reduced statistical power for weight-based group analysis to an unacceptable level. Thus, all study subjects were adults with normal weights. Second, our study was conducted on subjects aged 20–49 yrs, which limits generalizations to other age groups. Third, the study subjects resided in Gangwon-do Province, Korea, which means the results may not apply to the whole Korea population.

Nevertheless, we believe the study is meaningful because it provides insight into the accuracy of 24-h diet recall as compared with the DLW method. In addition, trained investigators used 24-h diet recall guidelines used in KHNANES to collect dietary data and photographs were taken before and after meals by subjects the day before interviews to increase recall accuracy.

Additional studies are needed to corroborate our findings, to evaluate the accuracy of 24-h diet recall with respect to additional demographics, and to devise means of improving the accuracy of 24-h diet recall methods based on analyses of the factors that influence its underreporting rates.

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