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The effect of personal characteristics on the validity of nutrient intake estimates using a food-frequency questionnaire

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Abstract

Objective: To assess validity of the Nambour food-frequency questionnaire (FFQ) relative to weighed food records (WFRs), and the extent to which selected demographic, anthropometric and social characteristics explain differences between the two dietary methods.
Design: Inter-method validity study; 129-item FFQ vs. 12 days of WFR over 12 months.
Setting: Community-based Nambour Skin Cancer Prevention Trial.
Subjects: One hundred and fifteen of 168 randomly selected participants in the trial (68% acceptance rate) aged 25–75 years.
Results: Spearman correlations between intakes from the two methods ranged from 0.18 to 0.71 for energy-adjusted values. Differences between FFQ and WFR regressed on personal characteristics were significantly associated with at least one characteristic for 16 of the 21 nutrients. Sex was significantly associated with differences for nine nutrients; body mass index (BMI), presence of any medical condition and age were each significantly associated with differences for three to six nutrients; use of dietary supplements and occupation were associated with differences for one nutrient each. There was no consistency in the direction of the significant associations. Regression models explained from 7% (riboflavin) to 27% (saturated fat) of variation in differences in intakes.
Conclusions: The relative validity of FFQ estimates for many nutrients is quite different for males than for females. Age, BMI, medical condition and level of intake were also associated with relative validity for some nutrients, resulting in the need to adjust intakes estimates for these in modelling diet–disease relationships. Estimates for cholesterol, β-carotene equivalents, retinol equivalents, thiamine, riboflavin and calcium would not benefit from this.

Keywords
Food-frequency questionnaire
Weighed diet records
Relative validity
Dietary assessment

Self-administered food-frequency questionnaires (FFQs) are widely used in epidemiological studies because they allow dietary assessment in large study groups at reasonable cost. Reviews of validity studies for FFQs indicate that measurement error varies with design, how they were developed (e.g. modified from a previous version) and the study population[1–3]. The effects of this error on estimates of intake, on proportions of the study population meeting dietary recommendations, and on analyses investigating the relationship between diet and disease, are well described[2,4,5]. The specific subject characteristics associated with measurement error are less well documented. An understanding of these provides a basis for more appropriate modelling of diet–disease relationships and improved interpretation of dietary data, as well as for evaluating and refining the method for future studies.

The Nambour Skin Cancer Prevention Trial is a field trial conducted in an unselected adult population in Australia. A central objective of the project is to examine the relationship of dietary factors to the development of actinic skin and eye disease[6]. The study reported herein focuses on the measurement characteristics of the self-administered FFQ used to assess usual dietary intakes in the trial. The study compares intake estimates from the FFQ with those based on 12 days of weighed food record (WFR) over a 12-month period for a randomly selected sub-sample of the Nambour study population. We estimate the extent of relative bias and imprecision of intake estimates, and assess the extent to which selected demographic, anthropometric and social characteristics of participants explains any difference between the two dietary methods.

Methods

Subjects

Subjects for this validation study were randomly selected from the 1621 participants of the Nambour Skin Cancer

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Prevention Trial, a community-based randomised trial of the effects of a daily β-carotene supplement and application of sunscreen in the prevention of skin cancer[6,7]. Subjects were aged 25–75 years at commencement of the trial in 1992. A total of 1447 (89%) completed an FFQ in 1992. Of these, a random sample of 168 participants was invited to participate in a dietary study involving WFR over a 12-month period from 1992 to 1993. A total of 115 subjects (68% acceptance rate) completed the WFR study[8].

FFQ

The self-administered semi-quantitative questionnaire was adapted from the FFQ developed by Willett and colleagues[2,9]. The food list was changed to reflect the Australian diet according to the 1983 National Dietary Survey of Adults[10,11] and further revised for the Nambour trial to improve estimates of intake of antioxidant-rich foods (inclusion of major food sources, particularly vegetables and fruits).

The FFQ consisted of 129 food items/groups with a corresponding standard serving size expressed in household or common measures such as 1 slice or 1 tablespoon or 1 cup. Respondents were requested to recall how often, on average, they consumed a given amount of each food during the past 6 months (judged to reflect 'usual' intake in this population). The nine response options ranged from 'never' to '4 + times a day'. For seasonal fruits and vegetables, participants were asked to indicate how often these foods were eaten in season. Additional information queried cooking methods and specific types of oil, margarine, butter and cereals, consumption of visible fat on meat, and frequency of eating fried and takeaway foods. The FFQ also collected information on brand, dosage and frequency of use of dietary supplements. All FFQ data were double-entered, and any discrepancies resolved by reference to the original forms.

WFR

Participants completed two non-consecutive days of WFR every 2 months over a period of 12 months. The initial starting day for data collection was randomly allocated across participants to ensure that each day of the week was equally represented and that records for the sample were spaced evenly over the initial 2-month block. For subsequent blocks, recording days were advanced by one day. Where days specified were unsuitable for participants, alternative days were determined to ensure an overall balance of week and weekend days.

Two-kilogram capacity digital scales in two-gram gradations were provided. Participants were requested to weigh all food and drink consumed during the two recording days and to provide information on recipes and dietary supplements used. A research dietitian collected the food diaries and reviewed the records with the participants to check for errors, omissions or doubtful entries[8]. Coding decisions were made by the research dietitian, who checked all decisions for open-ended questions in the FFQ and checked a random 10% subsample of daily records for the WFR (error rate 0.7%)[8].

Other data

Body weight and height were measured by research staff trained using standard protocols; information on age, sex, education, occupation and medical condition was obtained by interviewer-administered questionnaire[6]. Participants were considered to have a medical condition if they answered 'yes' to any of the conditions listed in the question 'Have you ever been told by a doctor/nurse that you have: glaucoma, gallstones, high cholesterol, high triglycerides, diabetes/high blood sugar, high blood pressure/hypertension, angina, heart attack, stroke, cancer?'

Calculation of nutrient intakes

For the FFQ, consumption frequencies were converted into intake in grams per day by multiplying the standard serving size of each food as specified in the FFQ with the following values for each frequency option: never = 0, less than 1 per month = 0.02, 1–3 per month = 0.07, 1 per week = 0.14, 2–4 per week = 0.43, 5–6 per week = 0.79, 1 per day = 1.0, 2–3 per day = 2.5 and 4 + per day = 4. Gram estimates of daily intakes of fruit and vegetables were further weighted according to the proportion of the year the food is in season in Nambour. Daily nutrient intakes were calculated using software designed for the batch processing of FFQ using food composition tables in Australia as contained in NUTTAB95[12]. Data from WFR were entered using Xyris Diet-1 Software[8,13] and nutrient intakes calculated using NUTTAB95. Average daily nutrient intakes were calculated by summing nutrients from each food consumed per day of WFR and obtaining the average of all weighing days for each individual. Nutrient intakes from dietary supplements were not included in the present analyses.

Exclusions and final sample size for validity analysis

Of the 115 subjects who completed the WFR, 19 were omitted from analyses. Twelve subjects completed less than 10 days of WFR, five omitted responses for more than 10% of items in the FFQ and one female became pregnant early in the study. One male was also excluded because energy intake exceeded inclusion criteria (500–3500 kcal day^{-1} for women, 800–4000 kcal day^{-1} for men[2]). The WFRs of 96 subjects were used in the present study.

Statistical analyses

Mean and standard deviation of nutrient intakes for the total sample and by sex were calculated for each dietary method. As distributions of nutrient intakes did not follow a normal distribution, intakes were log (natural)-transformed.

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In addition, energy-adjusted intakes were calculated using the residual method described by Willett[2].

Validity was assessed in two ways: (1) by comparing the ranking of individuals by nutrient intake; and (2) by quantifying agreement in estimated absolute measures of intake. Spearman rank correlation was used to investigate the association in the ranking for both untransformed, unadjusted nutrient intakes and the log-transformed, energy-adjusted intakes.

Because nutrient intakes will be categorised into quartiles of intake in future diet–disease analyses, log-transformed, energy-adjusted nutrient intakes ($FFQ_{log\text{-}adj}$, $WFR_{log\text{-}adj}$) were classified into quartiles. The proportion of individuals classified in the same quartile by the two methods (exact agreement), the proportion who deviated by one quartile and the proportion of grossly misclassified individuals (disagreement by three quartiles) were calculated.

Agreement in absolute nutrient estimates between the two methods was based on the mean difference between log-transformed energy-adjusted intakes ($FFQ_{log\text{-}adj}$, $WFR_{log\text{-}adj}$) and limits of agreement (LOA) as described by Bland and Altman[14] with the correction for a small sample size ($n < 100$) by Ludbrook[15]. A paired t-test ($P = 0.05$) was used to determine whether the $FFQ_{log\text{-}adj}$ consistently over- or underestimated $WFR_{log\text{-}adj}$ intakes. The LOA provided the range in which 95% of the differences between the dietary methods was expected to lie. The LOA, with correction for small sample size, was calculated as:

$$\text{mean difference} \pm t_{\widehat{n-1,0.05}}\, \text{sd}\sqrt{(1+1/n)},$$

where sd is the standard deviation of the difference between methods, $t_{\widehat{n-1,0.05}}$ is the value of t corresponding to two-sided $P = 0.05$ for $\text{df} = n - 1$ and $\sqrt{(1+1/n)}$ is an adjustment for small sample size. Mean differences and LOA were exponentiated to provide a ratio of the FFQ relative to the WFR in the original scale of measurement for each nutrient. For example, a mean ratio of 1.10 and LOA of 0.85 to 1.40 indicates that, on average, FFQ overestimates WFR by 10% and that 95% of the differences lie from 15% below to 40% above. Thus, the null hypothesis for paired t-tests of means was: exponential mean $(FFQ_{log\text{-}adj} - WFR_{log\text{-}adj}) = 1.0$, $P = 0.05$. In the results presented this is reflected by a 95% confidence interval that does not include 1.0.

To determine whether the difference between methods varied across the range of intakes, the difference between $FFQ_{log\text{-}adj}$ and $WFR_{log\text{-}adj}$ was plotted against the average, $(FFQ_{log\text{-}adj} + WFR_{log\text{-}adj})/2$. A regression line was fitted and the slope was tested for significant deviation from 0 ($P = 0.05$). A negative slope indicates that the difference in (log-transformed energy-adjusted) estimates decreases as the average increases while the opposite holds for positive slopes.

The association between personal characteristics of participants and the difference in nutrient intakes between dietary methods was assessed using multivariate linear regression analyses. Age (in years), sex, body mass index (BMI), education (school-leaving age), occupation (professionals, non-professionals), medical condition (yes, no) and use of dietary supplements (yes, no) were the explanatory variables and the difference in log-transformed, energy-adjusted nutrients was the dependent variable. Average intakes were included in the model if the preliminary analysis (see above) showed that average intakes were significantly associated with the difference in intakes. R^2 was calculated to quantify the extent to which the explanatory variables accounted for total variation in the difference in nutrient intakes.

All analyses were performed using SAS software release 8.2[16].

Results

There were no significant differences between the 96 subjects included in the present analyses and the 1621 Nambour trial participants in terms of age, sex, BMI, education and smoking. There was a significantly higher proportion of users of dietary supplements (45.8%) among participants of the validation study than in the trial population (32.7%). There were slightly more professionals (37.9% vs. 29.2%) and more participants with any medical condition (57.5% vs. 47.7%) in the present study but these were not significant ($P > 0.05$).

The mean and standard deviation of the daily nutrient intakes estimated from the FFQ and WFR are presented in Table 1. The overall (sexes combined) results show that intakes estimated by the FFQ were on average greater than those estimated by WFR. Only starch intake estimates were significantly greater from the WFR compared with the FFQ. The variance was also greater for most nutrients according to the FFQ. When the data were stratified by sex, the results were quite different. For females, the FFQ intakes were significantly greater for energy and almost all other nutrients. For males, only nine of the nutrients were significantly different from the WFR, of which FFQ estimates of five nutrients were significantly lower than the WFR. Differences in variance between the two dietary methods were also more marked amongst females than males, with much larger variability in FFQ than in WFR estimates for females.

Correlations between estimated intakes using the two dietary methods for the overall sample and for sex-specific analyses are presented in Table 2. The most striking differences in Spearman correlations of unadjusted intakes between males and females were for β-carotene equivalents, retinol, vitamin C and iron. For these nutrients, the difference in correlations between sexes was by more than a factor of two. Spearman correlation of retinol equivalents for females was negative. Log-transformation and adjusting the nutrient intakes for energy intake caused some changes, but these were not

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Table 1 Mean intake of nutrients from a semi-quantitative food-frequency questionnaire (FFQ) and 12 days of weighed food record (WFR) kept by a sample of Nambour (rural Queensland) residents aged 25–75 years

	Overall ($n = 96$)				Males ($n = 37$)				Females ($n = 59$)			
	FFQ		WFR		FFQ		WFR		FFQ		WFR	
Nutrient	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Energy (kJ)	8951*	2367	8093	2275	9501	2341	9982	2174	8606*	2336	6909	1358
Protein (g)	99.3*	26.5	83.8	25.3	100.8	26.3	102.0	29.2	98.3*	26.8	72.4	13.3
Total fat (g)	79.5	26.4	76.4	23.6	82.0*	25.4	92.1	23.6	78.0*	27.1	66.6	17.8
Carbohydrates (g)	246.0*	71.2	218.8	63.2	260.0	72.7	265.5	63.5	237.2*	69.4	189. 5	42.1
Alcohol (g)	8.3	14.4	7.3	13.2	15.4	19.7	14.8	18.1	3.9	6.9	2.6	5.0
Fibre (g)	30.9*	11.6	23.7	8.2	30.5	12.7	28.1	10.0	31.1*	10.9	20.9	5. 3
Cholesterol (mg)	309.6	114.4	297.2	107.9	323.2	119.7	348.5	115.8	301.0*	111.2	265.0	89.4
Saturated fat (g)	32.9	12.8	32.4	11.6	34.3*	12.5	38.4	12.9	32.0	13.0	28.6	9.0
Monounsaturated fat (g)	29.3*	10.4	26.6	8.7	30.4	10.0	32.6	8.8	28.6*	10.6	22.9	6.3
Polyunsaturated fat (g)	10.6	3.8	11.0	4.1	10.4*	3.6	13.4	4.1	10.7*	3.9	9.4	3.3
Sugars (g)	138.8*	48.5	106.1	37.0	147.9*	53.9	126.7	41.1	133.0*	44.3	93.2	27.5
Starch (g)	103.9*	31.0	112.0	33.7	109.4*	30.6	138.2	33.2	100.5	30.9	95.6	21.5
β-Carotene equivalents (μg)	9773*	5271	3619	1992	8843*	5062	4295	2655	9705*	5413	3194	1285
Retinol (μg)	766.3	1330.2	720.5	1039.7	628.4	524.4	884.0	1110.3	852.8	1645.5	618.0	988.8
Retinol equivalents (μg)	2259*	1697	1324	1125	2077*	1063	1599	1200	2374*	1995	1151	1048
Vitamin C (mg)	222.8*	117.2	134.3	69.7	225.9*	138.7	163.3	82.9	220.8*	102.8	116.1	53.1
Thiamine (mg)	1.75	0.60	1.64	0.59	1.75*	0.57	1.99	0.68	1.76*	0.62	1.42	0.39
Riboflavin (mg)	2.94*	1.08	2.33	0.84	2.86	0.92	2.74	0.95	2.99*	1.18	2.07	0.65
Niacin (mg)	26.68*	7.96	21.64	7.84	26.76	7.81	26.5	9.19	26.63*	8.13	18.60	4.88
Calcium (mg)	972.8*	395.4	817.3	271.9	976.2	396.3	931.3	299.8	970.7*	398.2	745.7	227.6
Iron (mg)	14.3*	4.3	12.3	3.6	14.3	4.0	14.9	4.1	14.3*	4.4	10.7	2.2
Zinc (mg)	13.5*	4.0	10.8	3.4	13.7	3.9	13.1	4.0	13.3*	4.0	9.3	1.9

SD – standard deviation.
* FFQ significantly different from WFR at the 0.05 level (paired *t*-test performed on log-transformed nutrient intakes).

consistently higher or lower. For females, correlation of retinol equivalents estimates changed from negative to a very weak positive correlation.

Table 3 shows the extent of agreement in allocation by quartiles of log-transformed, energy-adjusted intake for each nutrient, using the two sets of intake data. For all subjects, exact agreement ranged from 26% (retinol) to 49% (alcohol and thiamine). The expected proportion of agreement, assuming random allocation, would be 25%. Exact agreement below 30% was noted only for retinol and

Table 2 Spearman correlation coefficients for nutrient intakes obtained from a semi-quantitative food-frequency questionnaire and the average of 12 days of weighed food record

	Unadjusted intakes			Energy-adjusted†		
Nutrient	Overall	Males	Females	Overall	Males	Females
Energy	0.45	0.42	0.45	–	–	–
Protein	0.40	0.37	0.50	0.45	0.41	0.54
Total fat	0.45	0.54	0.46	0.43	0.56	0.27
Carbohydrates	0.45	0.27	0.52	0.37	0.52	0.27
Alcohol	0.84	0.88	0.74	0.71	0.83	0.53
Fibre	0.39	0.57	0.32	0.49	0.66	0.42
Cholesterol	0.36	0.49	0.31	0.36	0.50	0.31
Saturated fat	0.54	0.64	0.48	0.51	0.65	0.41
Monounsaturated fat	0.44	0.50	0.45	0.39	0.45	0.26
Polyunsaturated fat	0.33	0.33	0.44	0.46	0.38	0.58
Sugars	0.53	0.54	0.50	0.46	0.57	0.39
Starch	0.42	0.34	0.47	0.24	0.33	0.19
β-Carotene equivalents	0.22	0.45	0.05	0.32	0.48	0.24
Retinol	0.26	0.55	0.11	0.19	0.27	0.19
Retinol equivalents	0.08	0.47	−0.23	0.18	0.35	0.07
Vitamin C	0.33	0.61	0.16	0.38	0.63	0.20
Thiamine	0.37	0.47	0.36	0.46	0.67	0.28
Riboflavin	0.48	0.56	0.55	0.58	0.52	0.61
Niacin	0.35	0.42	0.44	0.42	0.54	0.41
Calcium	0.53	0.58	0.53	0.67	0.73	0.61
Iron	0.27	0.16	0.42	0.36	0.47	0.33
Zinc	0.33	0.32	0.43	0.38	0.20	0.50

† Log-transformed nutrient intakes adjusted for energy intakes using the residual method.

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Table 3 Percentage agreement between allocation into quartiles according to nutrient intakes obtained from a semi-quantitative food-frequency questionnaire and the average of 12 days of weighed food record after adjustment for energy intake using the residual method

	Overall ($n = 96$)			Males ($n = 37$)			Females ($n = 59$)		
Nutrient	Exact (%)	±1 quartile (%)	GM† (%)	Exact (%)	±1 quartile (%)	GM† (%)	Exact (%)	±1 quartile (%)	GM† (%)
Protein	41	35	4	38	38	8	42	34	2
Total fat	45	35	6	49	38	3	42	34	8
Carbohydrates	42	27	6	38	30	8	44	25	5
Alcohol	49	40	0	46	49	0	51	34	5
Fibre	33	45	3	46	30	0	25	54	5
Cholesterol	35	38	6	32	43	3	37	34	8
Saturated fat	40	41	3	54	27	0	31	49	5
Monounsaturated fat	42	33	6	43	38	3	41	29	8
Polyunsaturated fat	38	39	7	38	27	13	37	46	3
Sugars	35	41	3	41	38	3	32	42	3
Starch	29	38	7	30	41	5	29	37	8
β-Carotene equivalents	35	41	5	38	38	0	34	42	8
Retinol	26	43	9	22	51	5	29	37	12
Retinol equivalents	28	44	8	27	54	5	29	37	10
Vitamin C	31	45	5	41	34	5	25	46	5
Thiamine	49	31	6	57	35	5	44	29	7
Riboflavin	47	40	2	46	38	3	47	41	2
Niacin	36	41	1	38	41	0	36	41	2
Calcium	49	40	2	62	27	3	41	47	3
Iron	35	40	4	41	38	5	32	41	3
Zinc	38	40	4	30	43	5	42	37	3
Random expected	25	38	13	25	38	13	25	38	13

† Gross misclassification, disagreement by three quartiles.

retinol equivalents. Compared with an expected proportion of 13%, gross misclassification (disagreement by three quartiles) was minimal, ranging from 0% (alcohol) to 9% (retinol). For males, the lowest exact agreements were for retinol and retinol equivalents. These were also found for females, plus fibre, starch and vitamin C. Gross misclassification was greatest for polyunsaturated fats amongst males and retinol amongst females.

Table 4 extends the results of Table 1 in presenting the mean ratio (and 95% confidence interval) of FFQ to WFR and the corresponding LOA. FFQ overestimations by 50% and higher were noted for retinol equivalents, vitamin C and, most notably, β-carotene equivalents, which was overestimated, on average, by 250%. The mean ratio gives an indication of the average difference between the two dietary methods while the limits of agreement provide an indication of the actual range of differences at the individual level. Alcohol, β-carotene equivalents, retinol and retinol equivalents had the widest range of LOA while the macronutrients total fat, carbohydrates and protein had the narrowest.

Regressing average intakes on the difference of intakes between FFQ and WFR showed that differences increased significantly as the averages increased for starch and calcium, and approached significance for total fat and carbohydrates. The difference in niacin estimations decreased significantly as the average niacin intakes increased (Table 4).

Results of multiple regression analyses of selected personal characteristics on the difference in intakes are shown in Table 5. The differences were significantly associated ($P < 0.05$) with at least one personal characteristic for 16 of the 21 nutrients. Sex was significantly associated with nine nutrients. Except for the association with difference in alcohol intake, differences were significantly greater for females than for males. For example, the regression coefficient of 0.213 for fibre indicates that the ratio of fibre intakes estimated by FFQ to WFR is 1.23 times greater (exponential of 0.213) in females compared with males. BMI, presence of any medical condition and age were each significantly associated with the difference in intakes of three to six nutrients, while use of dietary supplements and occupation were associated with differences for one nutrient each. There was no consistency in the direction of the significant associations. The extent to which the regression models explained the variation in differences in intakes ranged from 7% (riboflavin) to 27% (saturated fat).

Discussion

The results show that the bias and imprecision of nutrient intake estimates from the FFQ relative to the WFR estimates are associated with several characteristics of the participants in this population – most frequently sex, but also BMI, age and presence of a medical condition. The extent and implications of this vary by nutrient, and

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Table 4 Agreement in nutrient intakes between a semi-quantitative food-frequency questionnaire (FFQ) and the average of 12 days of weighed food record (WFR) after adjustment for energy intake using the residual method, males and females combined

Nutrient	Mean FFQ/WFR ratio (95% confidence interval)†	95% Limits of agreement	Slope‡	*P*-value
Protein	1.19 (1.15–1.23)	0.86–1.63	0.08	
Total fat	1.03 (1.00–1.06)	0.77–1.38	0.21	×
Carbohydrates	1.12 (1.09–1.15)	0.85–1.47	0.21	×
Alcohol	1.07 (0.86–1.34)	0.12–9.43	0.08	
Fibre	1.29 (1.22–1.37)	0.73–2.28	0.03	
Cholesterol	1.04 (0.98–1.10)	0.59–1.85	0.04	
Saturated fat	1.00 (0.96–1.05)	0.66–1.52	0.09	
Monounsaturated fat	1.09 (1.05–1.13)	0.77–1.54	0.05	
Polyunsaturated fat	0.97 (0.92–1.03)	0.54–1.74	−0.002	
Sugars	1.31 (1.25–1.37)	0.83–2.05	−0.09	
Starch	0.92 (0.88–0.96)	0.61–1.40	0.43	**
β-Carotene equivalents	2.56 (2.25–2.90)	0.73–8.90	−0.09	
Retinol	1.00 (0.83–1.20)	0.16–6.22	0.21	
Retinol equivalents	1.74 (1.53–1.99)	0.48–6.29	−0.13	
Vitamin C	1.65 (1.49–1.82)	0.62–4.42	−0.03	
Thiamine	1.07 (1.02–1.13)	0.63–1.83	−0.04	
Riboflavin	1.26 (1.19–1.34)	0.70–2.28	0.14	
Niacin	1.25 (1.19–1.31)	0.77–2.04	−0.26	*
Calcium	1.16 (1.10–1.22)	0.67–1.99	0.37	***
Iron	1.16 (1.11–1.20)	0.79–1.70	0.14	
Zinc	1.24 (1.19–1.30)	0.83–1.86	−0.0004	

† Exponentiation of the mean difference in log-transformed energy-adjusted nutrient intakes (H_0: exp ($FFQ_{log} - WFR_{log}$) = 1.0, $\alpha = 0.05$).
‡ Slope of the regression of the average of log-transformed energy-adjusted intakes, ($FFQ_{log} + WFR_{log}$)/2, on difference in nutrient intakes, $FFQ_{log} - WFR_{log}$ (H_0: slope = 0, $\alpha = 0.05$).
×, $P < 0.10$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

depend on whether absolute or relative intakes are compared.

Two other recent Australian studies have evaluated FFQs in comparison with WFRs. Hodge *et al.*[17] compared estimates from the FFQ developed by the Anti Cancer Council of Victoria with 7-day WFRs completed by 63 women and found that mean intakes from the two methods were within ± 20% for 21 of 27 nutrients and, in contrast to our findings, showed that the FFQ estimates were just as likely to be lower as higher than the WFR estimates. In a study including both males and females, Ambrosini *et al.*[18] compared an FFQ with four 7-day WFRs in 72 Australian adults. Both studies showed poor agreement for β-carotene equivalents, retinol, vitamin C, all types of fat, cholesterol and calcium – similar, though not identical to the current study. Significantly, results from the study by Ambrosini *et al.*[18] also indicated important differences in FFQ performance between men and women. An important observation was that, unlike our findings, the differences between FFQ- and WFR-reported intakes for women increased significantly with level of intake for most nutrients, whereas only a few nutrients showed this pattern for men.

Spearman correlations between the individual intakes from the two methods ranged from 0.08 to 0.84 for unadjusted, and 0.18 to 0.71 for energy-adjusted values (Table 2, sexes combined), ranges that are generally consistent with those observed in similar studies[19–21]. Energy adjustment resulted in a modest change in most correlations, but there was no trend to higher overall values as reported in some studies[2,20,22]. As with the discussion of absolute differences between methods, the Spearman correlations for males and females separately show important differences. The correlations for males tend to be greater, and for some nutrients there are marked differences. A value of 0.3 is a level where attenuation is so severe that it will be difficult to detect associations[3]. Amongst males, the only correlations below 0.3 were for retinol and zinc, whereas amongst the females each of the following was at that level: protein, total fat, monounsaturated fat, starch, β-carotene equivalents, retinol, retinol equivalents, vitamin C and thiamine.

Percentage agreement between FFQ and WFR in assignment by quartile of intake for each nutrient follows the general pattern of the correlation results, but poor agreement and gross misclassification are not as extensive as suggested by the correlation results. For the overall study group, the extent of exact agreement in this study is slightly lower than for the same nutrients reported by Bingham *et al.*[21], while the extent of gross misclassification is similar with a few exceptions. For the overall study group, agreement for retinol, retinol equivalents and starch is little different from what would be expected from random allocation. The sex-stratified results show similar results for females but slightly stronger agreements for males, a pattern that reflects the observations in the analyses of absolute intakes and correlations.

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Table 5 Factors associated with the difference in log-transformed energy-adjusted intakes of nutrients from a semi-quantitative food-frequency questionnaire (FFQ) and 12 days of weighed food records (WFR), males and females combined: multivariate analyses

	Regression coefficient								
Nutrient (difference FFQ−WFR)	Age†	Sex‡	BMI†	School-leaving age†	Occupation§	Medical condition¶	Use of dietary supplements‖	Average of FFQ & WFR††	R^2
Protein	0.002	0.090*	0.003	0.013	0.006	0.064×	−0.003		0.14
Total fat	−0.001	−0.043	−0.012**	0.014	−0.037	0.060*	−0.007	0.336**	0.22
Carbohydrates	0.001	0.004	0.009*	−0.104	0.035	−0.060*	0.006	0.360**	0.16
Alcohol	−0.009	−0.525*	−0.040	−0.179×	−0.165	−0.207	−0.102		0.10
Fibre	0.002	0.213***	0.015×	−0.038	−0.045	−0.019	−0.103×		0.22
Cholesterol	−0.003	−0.032	0.003	0.038	−0.021	0.078	0.106		0.08
Saturated fat	−0.004*	−0.105*	−0.014*	0.012	0.008	0.102*	−0.020		0.27
Monounsaturated fat	0.000	−0.010	−0.011*	0.009	−0.084*	0.037	−0.043		0.14
Polyunsaturated fat	0.007*	0.125*	−0.007	0.035	−0.041	−0.093	0.057		0.18
Sugars	−0.002	−0.046	0.016**	−0.028	0.048	0.006	0.053		0.15
Starch	0.004×	0.063	−0.001	0.008	0.020	−0.123**	−0.064	0.425**	0.21
β-Carotene equivalents	−0.008	0.270×	0.023	−0.016	−0.243×	0.147	−0.106		0.15
Retinol	−0.014×	0.121	−0.030	0.032	0.055	0.055	0.019		0.15
Retinol equivalents	−0.011*	0.277*	0.012	−0.005	−0.090	0.052	−0.073		0.14
Vitamin C	0.003	0.298**	0.034*	−0.013	−0.092	0.057	−0.043		0.18
Thiamine	0.002	0.093	0.008	−0.001	−0.073	0.008	0.004		0.09
Riboflavin	−0.001	0.053	0.004	−0.010	−0.021	0.117×	0.041		0.07
Niacin	0.002	0.118*	0.006	−0.014	−0.017	0.084	−0.016	−0.324*	0.15
Calcium	0.002	−0.010	0.012×	0.020	0.028	0.072	0.116*	0.369***	0.25
Iron	0.000	0.103*	0.003	−0.006	−0.027	0.019	−0.049		0.10
Zinc	−0.000	0.076×	0.004	0.016	−0.032	0.085*	0.000		0.12

† Continuous variable.
‡ Reference: males.
§ Reference: non-professionals.
¶ Reference: no medical condition.
‖ Reference: does not use dietary supplements.
†† Included only for multivariate models where the average of intakes was significantly associated with the difference in intakes (see Table 4).
Note: due to missing values, $n = 82$.
×, $P < 0.10$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

In the present study only starch, niacin and calcium showed a significant association with level of intake. We have extended this analysis by investigating the association of selected personal characteristics of participants with the differences between FFQ and WFR intakes. Results of the multiple regression analyses confirmed the impact of sex on the differences between FFQ and WFR estimates (significant for nine of 21 nutrients) but also showed that age (three nutrients), BMI (six nutrients), medical condition (five nutrients) and level of intake (five nutrients) were also significantly associated with differences. Together these factors explain over 20% of the variance for total fat, fibre, saturated fat, starch and calcium. Only for cholesterol, β-carotene equivalents, retinol, thiamine, riboflavin and calcium were the differences not associated with at least one of these factors.

The WFR estimates are also subject to error. We have reported previously sex differences in the extent of underreporting for FFQ and WFR in this study group[8]. Using cut-offs based on the ratio of energy intake to basal metabolic rate, as described by Goldberg *et al.*[23], the extent of underreporting was highest amongst women using the WFR, about double that observed for females using the FFQ or for males using either method. In spite of recognised weaknesses, the WFR is still regarded as the method of choice as reference method for dietary validation studies. In an evaluation of seven dietary assessment methods in comparison with several biomarkers of dietary intake, Bingham *et al.*[24] showed that WFRs were consistently more strongly associated with the biological markers than were the other methods, and concluded that WFRs 'remain the most accurate measure of dietary intake'. In their recent review Cade *et al.*[3] also suggest that WFRs should be the first method of choice for validating FFQs, with a major advantage being that the main sources of errors in the two methods are different and thus unlikely to be correlated. Correlated errors lead to overestimation of validity when judged by measures of association such as correlations.

While it could not be directly tested in this study, it seems likely that the treatment of portion sizes in data collection and calculation of nutrient intakes has contributed to the sex differences in underreporting and measures of agreement with the FFQ. In a comparison of the validity of three FFQ formats, Subar *et al.*[25] reported that the Willett instrument tends to underestimate the nutrient intakes of men and overestimate those of women. They attribute it to the same portion sizes being assigned to men and women, as applied in this study. In a recent review of the design, utilisation and validation of FFQs, Cade *et al.*[26] observed that in studies where portion sizes are self-defined there tend to be differences between men

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and women, and further that correlations in validity studies tend to be highest when subjects are able to describe their own portion sizes.

Amongst the nutrients, the levels of agreement for β-carotene equivalents and retinol/retinol equivalents are poorest, a matter of particular concern for some of the intended uses of the FFQ. The food list for this version of the FFQ was modified to include major food sources of antioxidants in the Australian diet, expanding particularly the list of vegetables and fruits. However, levels of agreement between FFQs and other dietary assessment methods have generally been found to be poor for both vegetables and fruits, and β-carotene equivalents and retinol[26,27]. Reasons for this are not well established.

These findings have important implications for modelling of diet–disease relationships. The significant association between personal characteristics and difference for most nutrients raises the possibility of differential bias and misclassification. Adjusting intake estimates for these characteristics will improve the validity of the model. One might expect Willett's method of energy adjustment to partially account for this (e.g. because of the relationship between dietary energy intake and BMI), but our results show that BMI is still related to the difference for several nutrients and that further deliberate statistical adjustment in the diet–disease modelling will be required for most nutrients to account for these effects.

The subjects included in this validity study were randomly selected from the overall study population and they were different only in their use of supplements. Thus these results can be generalised to use of the FFQ in the Nambour study population. In summary, the 129-item FFQ provided reasonable estimates of intakes for most nutrients. However, the measurement errors for many nutrients are quite different for males than for females, and importantly age, BMI, medical condition and level of intake were also shown to be associated with measurement errors, resulting in the need to adjust estimates of nutrient intake for these in modelling of diet–disease relationships. The estimates for cholesterol, β-carotene equivalents, retinol, thiamine, riboflavin and calcium would not benefit from this. Of these, β-carotene equivalents and retinol appear to be most poorly estimated, also having very low Spearman correlations. The estimated relationships for these nutrients will be appreciably attenuated and other measures/markers of nutrient intake should be used to complement the FFQ.

The findings of this study highlight the need to assess validity in a sample that is representative of the overall population in which the FFQ will be used, with a sample size that is large enough to assess differences across subgroups. Most validity studies are conducted in convenience or restricted samples, often single-sex and with unrepresentative health status and educational and occupational backgrounds. Under these conditions it is unlikely that important subgroup differences in measurement characteristics of the FFQ will be detected.

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