HHS Public Access

Author manuscript

Epidemiology. Author manuscript; available in PMC 2018 January 19.

Published in final edited form as:

Epidemiology. 2004 November ; 15(6): 738–745.

On the Importance of Using Multiple Methods of Dietary Assessment

Loki Natarajan[*], **Cheryl L. Rock**[*], **Jacqueline M. Major**[*], **Cynthia A. Thomson**[†], **Bette J. Caan**[‡], **Shirley W. Flatt**[*], **Janice A. Chilton**[§], **Kathryn A. Hollenbach**[*], **Vicky A. Newman**[*], **Susan Faerber**[*], **Cheryl K. Ritenbaugh**[‖], **Ellen Gold**[¶], **Marcia L. Stefanick**[**], **Lovell A. Jones**[§], **James R. Marshall**[††], and **John P. Pierce**[*]

[*]Cancer Center, University of California, San Diego, California

[†]Arizona Cancer Center, University of Arizona, Tucson, Arizona

[‡]Division of Research, Kaiser Permanente Medical Group, Inc., Oakland, California

[§]University of Texas, M. D. Anderson Cancer Center, Houston, Texas

[‖]Center for Health Research, Kaiser Permanente Medical Group, Inc., Portland, Oregon

[¶]Department of Epidemiology and Preventive Medicine, University of California, Davis, California

[**]Stanford Center for Research in Disease Prevention, Stanford University, Palo Alto, California

[††]Roswell Park Cancer Institute, Buffalo, New York

Abstract

Background—Plasma carotenoid concentrations reflect intake of vegetables and fruits, the major food sources of these compounds. This study compared the ability of 2 measures of dietary intake (24-hour diet recalls and food frequency questionnaires [FFQs]) to corroborate plasma carotenoid concentrations in a subset of women participating in a diet intervention trial.

Methods—Plasma carotenoid concentrations and dietary intakes, estimated from 24-hour diet recalls and FFQs, were examined at baseline and 1 year later in a subset of 395 study participants (197 intervention and 198 comparison group). We used longitudinal models to examine associations between estimated intakes and plasma carotenoid concentrations. These analyses were stratified by study group and adjusted for body mass index (BMI), plasma cholesterol concentration, and total energy intake. We conducted simulations to compare mean-squared errors of prediction of each assessment method.

Results—In mixed-effects models, the estimated carotenoid intakes from both dietary assessment methods were strongly associated with plasma concentrations of α-carotene, β-carotene, and lutein. Furthermore, modeling the 2 sources of intake information as joint predictors reduced the prediction error.

Correspondence: John P. Pierce, Cancer Prevention and Control Program, Cancer Center, University of California, San Diego, La Jolla, CA 92093-0645. jppierce@ucsd.edu.

Conclusion—These findings underscore the importance of using multiple measures of dietary assessment in studies examining diet–disease associations.

Carotenoids are a group of biologically active compounds found in plants and microorganisms but not synthesized in animals. The presence of these compounds in human tissue reflects the amount provided by the diet, particularly fruits and vegetables.[1] Plasma and peripheral tissue carotenoid concentrations increase in response to habitual intake of carotenoids administered as supplements[2,3] or consumed as carotenoid-rich foods,[4–8] and in response to dietary interventions that successfully promote increased vegetable and fruit intake.[9–14] Nondietary factors known to influence carotenoid concentrations include the molar concentrations of cholesterol-rich lipoproteins,[15] and body size and adiposity, across the usual range that is characteristic of a heterogeneous group.[1]

To assess the success of dietary intervention efforts, it is crucial that accurate and reliable methods be available for measuring indicators of behavioral changes that are targeted by the intervention. The choice of dietary assessment methodology involves consideration of both scientific and practical issues. Approaches involving detailed records or recalls of intake have strengths such as more accurate information and less reliance on long-term memory and subjective judgment.[16] However, large day-to-day variability in food choices could limit the ability of recalls and records to capture usual nutrient intakes, a problem that could be overcome by the use of food frequency questionnaires (FFQ) that assess intake over a longer time span.[17]

Data used in the present analysis were derived from a longitudinal intervention study testing the effect of a diet high in vegetables, fruits, and fiber, and low in fat, on risk for recurrence of breast cancer in women (the Women's Healthy Eating and Living [WHEL] Study).[18] A previously published report[19] using these data noted that both the FFQ and the 24-hour recalls demonstrated significant increases in intake of dietary constituents at 1 year that were targeted by the intervention. However, there were large coefficients of variation in each self-report method suggesting that a multimode approach could be required to accurately assess intake. The case for such an approach would be strengthened if the dietary estimate obtained from each assessment method provided a unique contribution to predicting a biologic marker such as plasma carotenoid concentrations.

In the WHEL Study, plasma concentrations of carotenoids are measured before and during the intervention to establish whether plasma concentrations reflect a change in the dietary intake of vegetables and fruits. In this investigation, we examined the contribution of each dietary intake approach (24-hour recalls and FFQ) to predicting plasma carotenoid concentrations using mixed-effects models. Simulation analyses were conducted to evaluate the prediction error of each approach.

METHODS

Population

Data for the current investigation were obtained from 400 women enrolled in the WHEL Study who completed dietary assessments and blood collections at baseline and 12 months.

The WHEL Study, being conducted at 7 sites, is a randomized, controlled trial of the effectiveness of a high-vegetable, low-fat diet in reducing additional breast cancer events in women treated for stage I, II, or IIIA breast cancer (within 4 years of diagnosis). Between 1995 and 2000, 3088 women, stratified by age, size of tumor, and clinical site, were randomly assigned to either an intensive diet intervention or to a comparison group. The study expects to follow women through 2006. Further details of the study protocol, inclusion and exclusion criteria, data collection, intervention methodology, and other study details are reported elsewhere.[18]

Participants identified for this substudy were a systematic quota sample of the first 400 breast cancer survivors randomized into the WHEL Study. Within each study group (intervention and comparison), we selected the first 100 women with available plasma aliquots and dietary data who were ≤50 years of age at enrollment and the first 100 women who were older than 50 years. Additionally, we limited our analysis to women who had not changed their tamoxifen use from baseline to 12 months, so tamoxifen use remained constant over this time period. (Of the 400 women, 47% had not used tamoxifen at either time point and 53% were on tamoxifen at both time points.) This medication is known to affect plasma cholesterol concentration and thus could have an effect on circulating carotenoid concentrations. Participants in the substudy came from 6 of the clinical sites of the WHEL Study (all except Portland).[18] Five women were subsequently dropped from this analysis as a result of insufficient data.

Participants randomized to the comparison group were advised to consume a diet consistent with current National Cancer Institute dietary recommendations for cancer prevention (5 servings of vegetables and fruits daily, 20 g/day fiber, and ≤30% energy from fat). The diet intervention group was given the following advice on daily consumption: 5 vegetable servings, 3 fruit servings, 16 ounces of vegetable juice, 30 g of fiber, and 15–20% energy from fat. An intensive telephone-based diet counseling program, 12 group cooking classes, and printed materials were used to achieve diet modification in the intervention group. The participants in the comparison group were encouraged to attend 4 cooking classes unrelated to the dietary targets of the intervention and were provided standard dietary guidance materials available from governmental agency sources.

The study protocol involved clinic visits at baseline and at specified time points thereafter. A fasting blood sample was collected, and height and weight were measured using standard procedures. Body mass index (BMI) was calculated as weight (in kg) divided by the square of height (in m). Measurements obtained at baseline (prerandomization) and at 12 months were used in the present study. The Institutional Review Boards of all participating institutions approved procedures for this study, and written informed consent was obtained from all study participants.

Carotenoid Analysis

Plasma carotenoids, including α- and β-carotene, lutein, lycopene, and β-cryptoxanthin, were separated and quantified using a high-performance liquid chromatography (HPLC) method that has been previously described.[20] Zeaxanthin and lutein elute together with this method, so values presented as lutein are assumed to be lutein plus zeaxanthin. Accuracy

was assessed by periodic analysis of National Institute of Standards and Technology Standard Reference Material, and a pooled plasma sample was analyzed with batches of study samples to monitor analytical precision, with day-to-day coefficient of variation <10%. Total plasma cholesterol concentrations were determined with the Kodak Ektachem Analyzer system (Johnson & Johnson Clinical Diagnostics, Rochester, NY)[21] and used in the interpretation of plasma carotenoid data.[1] Standard reference materials from the manufacturer were used to validate analytical precision of these procedures.

Dietary Information

Dietary intakes of carotenoids and energy were assessed using 24-hour diet recalls and the Arizona FFQ. Details regarding these dietary assessment methodologies are described elsewhere.[18,19] Briefly, at each measurement time point, each study participant provided 4 24-hour dietary recalls, including 2 weekdays and 2 weekend days over a 3-week period. For each time point (baseline and 12 months for the purposes of the current investigation), the 4 recall measures were averaged, and this average was used in the analysis. Trained dietary assessors, who were blinded to the intervention or comparison group assignment of the participants, collected these data during telephone interviews. Nutrient calculations were performed using the Nutrition Data System for Research software developed by the Nutrition Coordinating Center, University of Minnesota, Minneapolis, MN (Food and Nutrient Database 31, version 4.03, released November 2000). Carotenoid intakes estimated from the dietary recalls method included food and dietary supplement sources. Participants were queried regarding actual dietary supplement use on the recall days during the telephone interview, and supplement content was quantified using a methodology and dietary supplement database that has been previously described.[22]

Information regarding usual foods consumed and frequency of consumption over the previous 3 months was collected with the aid of a 153-item, semiquantitative, scannable FFQ using age- and gender-specific estimates of portions estimated as small, medium, or large.[23] The database used to quantify nutrient intake from this FFQ was derived from the USDA Food Composition Database and the Nutrient Database for Standard Reference (versions 11–13),[24] and the Continuing Survey of Food Intake by Individuals 1994–1996, 1998.[25] Carotenoid data in the FFQ-linked database were updated from the USDA–NCC Carotenoid Database (1998).[26] In the current investigation, the reported carotenoid intake from the FFQ included both dietary sources and supplement intake. The supplement data used with this method of assessment were based on an inventory of products reported as being used during interviews of the study participants at the baseline and follow-up clinic visits.

Statistical Methods

Graphic techniques were used as an initial step toward modeling the relationships between plasma carotenoid concentrations and estimated dietary intakes. Summary statistics for all the variables of interest were calculated. We assessed the degree of concordance between the 2 intake measures at each time point by examining the distribution (mean, standard deviation) of the difference between intakes estimated by the FFQ and 24-hour recalls. Pearson correlations between the 2 intake measures were also calculated.

The ability of the dietary assessment method (independent variable) to predict plasma carotenoid concentrations (dependent variable) was examined using mixed-effects regression analysis.[27,28] We transformed the carotenoid measures (both plasma concentrations and estimated dietary intakes) by the natural logarithm to improve normality and to stabilize the variance.

We developed separate models for each outcome variable, namely, the plasma carotenoid concentration of interest, as a function of the fixed-effects predictors: 24-hour diet recalls and FFQ estimates of carotenoid intake. For each carotenoid, 3 models were developed: model A with intake estimated by the 24-hour recalls as the predictor, model B with intake reported on the FFQ as the predictor, and model C with both the FFQ and 24-hour recalls as joint predictors. In all models, we included BMI, plasma cholesterol concentration, and reported energy intake as fixed effects because these variables are known or suspected to influence plasma concentrations of carotenoids.[1,15] The analyses were stratified by study group (intervention or comparison). A participant-specific intercept constituted the random-effects parameter. Model parameters (regression coefficients with approximate standard errors for the fixed effects) were estimated and inference was based on standard asymptotic theory for mixed models.[27,28]

To evaluate the performance of the dietary intake instruments, both separately and jointly, we undertook a simulation analysis (200 repetitions) comparing the mean squared error of prediction of the models. A bootstrap sample was generated by resampling (with replacement) from the observed data and for each sample, 3 repeated-measures models were fit similar to those described earlier. We then computed the ratios of the mean squared errors of prediction of model A to model B, model C to model A, and model C to model B. This process of 1) resampling, 2) fitting models A, B, and C, and 3) estimating the ratio of prediction errors was conducted 200 times. The ratio of the mean squared errors for the observed data, as well as summary statistics (mean and empiric 95% confidence intervals), for the 200 bootstrap estimates of this ratio were computed.

RESULTS

Characteristics of the 2 study groups at baseline were evaluated for potential confounding or effect-modifying variables and do not exhibit meaningful differences (Table 1). The degree of agreement between the 2 dietary intake measures was examined by computing the difference between each individual's FFQ and 24-hour recalls score at each time point. If the 2 instruments were interchangeable, then we would expect the distribution of these differences to be tightly centered around zero. However, this is not the case, and in fact, large variability between the measures is evident in Table 2. These differences persisted when the measures were compared at 12 months (data not shown). Furthermore, unadjusted Pearson correlations between the 24-hour recalls and the FFQ (log-transformed) were modest and ranged from 0.34 to 0.59. These results suggest that the 2 measures were not surrogates of each other. We explored this further using mixed-effects models.

The average estimated dietary intakes by the FFQ and 24-hour recalls for this subsample have been reported elsewhere.[19] Data on carotenoids from dietary supplements (in addition

to food-derived carotenoids) were included for each dietary assessment method. Very few participants reported using dietary supplements containing α-carotene (N = 6) or lutein (N = 10). Supplemental formulations containing lycopene or β-cryptoxanthin were generally not available for consumers during the time period of this study. Over 50% of participants (N = 248) obtained some β-carotene from supplements (because this compound is used in many multivitamins and combination formulations). Notably, the amount of β-carotene from supplements did not differ substantially between the 2 study groups at either time point. The median daily intake (interquartile range [IQR]) of β-carotene from supplements according to the FFQ was 3062.5 μg (2020–10000 μg) at baseline and 2000 μg (833–2500 μg) at 12 months. According to the 24-hour recalls, the median daily intake (IQR) of β-carotene from supplements was 1937.5 μg (1200–6300 μg) at baseline and 1500 μg (1200–4500 μg) at 12 months.

Table 3 provides the average plasma concentrations for the 5 carotenoids. The mean plasma concentrations at baseline were similar for participants, regardless of dietary group assignment. The intervention group exhibited a large increase in mean plasma concentrations of α-carotene, β-carotene, and lutein, whereas for the comparison group, the mean plasma concentrations of the 5 carotenoids remained stable across time.

The degree of change promoted by the intervention efforts is also evident in Table 4. In contrast to the comparison group, the intervention group exhibited large increases in plasma concentrations of α-carotene, β-carotene, and lutein, corroborated by differences in estimated intakes of these carotenoids based on both dietary assessment approaches. However, the changes in mean plasma lycopene and beta-cryptoxanthin concentrations were similar for the 2 study groups, although the changes in estimated intakes of these 2 carotenoids in the intervention group was higher than that observed in the comparison group based on the 24-hour diet recalls. Data from the FFQ estimates of intakes suggest a difference in the degree of change in the 2 study groups for all of the carotenoids except beta-cryptoxanthin.

The longitudinal relations between plasma carotenoid concentrations and estimated intakes using FFQ and 24-hour diet recall data were explored in separate models after adjusting for the confounding effects of BMI, energy intake, and plasma cholesterol concentration (Table 5, models A and B). In both study groups, each of these dietary assessment approaches was a strong predictor of the plasma carotenoid concentration, as evidenced by the large F-statistics. The strength of the association (ie, the regression coefficient) differed by study group, with the intervention group exhibiting larger slopes for each dietary assessment approach than the comparison group. (For example, the parameter was 0.32 for the intervention group and 0.16 for the comparison group in the model in which 24-hour diet recalls data [log-transformed] predict plasma β-carotene concentration [log-transformed] [Table 5, model A].) This difference is not surprising because the intervention effort promotes a large change in circulating carotenoids, thus expanding the range of values on which the repeated-measures analysis is based.

A final multivariate model was developed incorporating estimated intake by both the FFQ and 24-hour recalls as joint predictors while adjusting for the confounders and influencing

factors mentioned here. Because the 2 intake instruments exhibit enough deviance from each other so as not to be interchangeable (Table 2), the purpose of this joint model is to assess the contribution of each method, after accounting for the other, and to explore the possibility that each could provide separate information on an individual's dietary intake. An examination of the regression coefficients and associated F-statistics (Table 5, model C) suggests that for the intervention group, both intake measures contributed approximately equally to plasma α-carotene concentrations (the 2 F-statistics are almost equal), whereas the 24-hour recalls were a stronger predictor of plasma β-carotene concentrations and the FFQ captured plasma lutein concentrations better. In the comparison group, these results were almost reversed. The FFQ appeared to be more strongly associated with plasma α- and β-carotene concentrations (because of the higher F-statistic associated with the FFQ coefficient), whereas the 24-hour recalls predicted plasma lutein concentrations. These conclusions are, of course, predicated on the model being correctly specified. Thus, neither dietary instrument clearly dominates the joint model and each appears to contribute independently to the plasma concentrations of α-carotene, β-carotene, and lutein.

The simulation results are presented in Table 6. For both diet groups, we estimated the ratio of the mean-squared errors of prediction for each dietary intake measure (ie, 24-hour recalls, model A, vs. FFQ, model B) when predicting plasma concentrations of α-carotene, β-carotene, and lutein. In each case, these ratios were close to unity. Furthermore, for these carotenoids, the empiric 95% confidence intervals for the bootstrap distribution of the ratio of prediction errors (based on resampling 200 times) straddled 1.0, thus providing further evidence that the prediction errors for the estimated intakes based on 24-hour diet recalls and the FFQ approaches were similar. More interestingly, in most cases, the joint model (model C) exhibited lower observed prediction error than either of the models with each dietary intake method as a separate predictor (models A and B). The 95% confidence intervals for the ratio of prediction errors for model C to each of models A and B did not include 1.0 for α- and β-carotene for the comparison group and for α-carotene for the intervention group. The 24-hour recalls (model A) and the joint model (model C) appear to have comparable prediction error for β-carotene for the intervention group. The results are more ambiguous in the case of lutein as all 3 models appear to have similar errors.

DISCUSSION

The primary goal of a dietary intervention is to promote dietary modification and to habituate participants to a particular dietary pattern. Of utmost importance is the ability to measure accurately the change in diet affected by the intervention efforts. Although dietary assessment approaches such as 24-hour recalls and FFQs are subject to bias and measurement error,[29] they are the primary strategies used to estimate dietary intake and dietary change. Numerous investigations have been undertaken to determine the validity of the many modes of dietary assessment, to compare them with each other, and to quantify the biases and errors inherent in these instruments.[16,19,30–34] In particular, Thomson et al.[19] compared the ability of the FFQ and 24-hour recalls to capture changes in dietary constituents that are targeted by the WHEL Study intervention. In the current investigation, we focused on the ability of these 2 approaches, modeled both separately and jointly, to predict observed plasma carotenoid concentrations as biomarkers of carotenoid intake. Our

work strengthens the findings of Thomson and colleagues[19] by providing the appropriate statistical framework within which to quantify the joint contributions of the 2 assessment methods. We used longitudinal modeling techniques to use all available information to allow for changes over time and to account for intra- and interparticipant variability. In addition, a simulation analysis was conducted to compare the prediction errors of the 2 assessment methods. Our results indicated that both assessment techniques strongly predict plasma concentrations and have comparable prediction errors. Perhaps more importantly, the prediction error of the model with both dietary assessment methods as joint predictors was lower than that of either of the models, which included each assessment method as a separate predictor. Thus, although neither instrument emerged as clearly superior to the other in its ability to reflect plasma carotenoid concentrations, the use of both instruments jointly provided a better fit to the data.

Carotenoids in the diet are not distributed across a widely diverse group of foods; each of these pigments is found in specific categories of foods. For example, alpha-carotene is found primarily in orange vegetables, with negligible amounts occurring in green leafy vegetables.[26] Free-living individuals typically demonstrate large day-to-day variability in the specific foods that are consumed. Because plasma concentrations reflect habitual diet, one might expect the FFQ approach to be superior to 24-hour diet recalls for predicting plasma concentrations, but we found the 2 assessment methods to be comparable. Notably, half of the participants in this study (those in the intervention group) were encouraged to eat phytochemical- and micronutrient-dense vegetables and fruits daily, so their day-to-day variability for carotenoid intakes is likely to be much less than that of the general population.

Plasma carotenoid concentrations exhibit a linear relationship with level of intake within the range of intakes most commonly reported.[1,35,36] In addition to carotenoid intake, factors known to influence plasma carotenoid concentrations include plasma cholesterol concentrations and the size, adiposity, and smoking status[37] of a person who ingests a given dose. Additionally, characteristics of the food matrix, supplement formulation, and concurrent fat and fiber intakes also influence the plasma response to carotenoid intake.[38] A strength of our study is that our analyses were based on mixed-effects models, accounting for interindividual and intraindividual variability, as well as with adjustment for some of the influencing variables discussed here such as plasma cholesterol concentrations, BMI, and reported energy intake. Smoking status was not included in the models because there were too few smokers in this population (3% smokers in the sample of 400).[19]

Admittedly, this investigation had limitations. Dietary data tend to exhibit large variability and inherent biases. Measuring change in the diet with the various dietary assessment approaches can present particular challenges.[39] A primary issue is whether the dietary assessment instrument is sufficiently sensitive to capture information on change in the intervention-related dietary patterns. Repeated measurement of intake or monitoring could, in and of itself, alter the response. Similarly, participants in an intervention could be more likely to report diets in agreement with the goals of the intervention. Both of the dietary assessment methodologies used in the present study demonstrated changes in carotenoid intakes for the intervention group across time that were not shown for the comparison group. Furthermore, dietary intakes estimated with both approaches were independently associated

with plasma concentrations of the carotenoids that are most abundant in the widest range of vegetables: α-carotene, β-carotene, and lutein.[26]

Another issue is that the quality of the food content data for these compounds, especially for the nonprovitamin A carotenoids, still limits the ability to estimate accurately the carotenoid content of foods consumed. Improvements in the carotenoid database have occurred over the past few years,[26,40] but the quality rating for food content data for these compounds remains low for most foods. The actual amount of a carotenoid in a given food is influenced by genotype, plant maturity, climate, and other growing conditions, resulting in substantial inherent variability in the carotenoid content of the foods that are consumed and reported in the dietary assessment.[41] This variability could contribute to our observation of changes in estimated dietary intakes of beta-cryptoxanthin and lycopene that were not corroborated by changes in plasma concentrations of these carotenoids.

In summary, our results indicate that both the 24-hour recalls and the FFQ provide unique information on dietary intake that was associated with plasma carotenoid concentrations. As might be expected, the intervention group exhibited a stronger association between carotenoid intakes as measured by either dietary assessment approach and plasma carotenoid concentrations. The multivariate models illustrate that both instruments, when used jointly, can provide useful and independent information about dietary intake of these compounds. The bootstrap analysis demonstrates that the use of both approaches could lead to lower mean squared error of prediction. Results of this study indicate that relying on only one approach to dietary assessment imparts considerable risk of misclassification, and thus, inaccurate interpretation of data on associations between dietary factors and disease risk. A composite measure of the 2 dietary intake approaches (ie, an appropriately weighted estimate) could be more informative and accurate. Collectively, these results demonstrate the importance of using a multimode approach, in particular the use of more than one dietary assessment method, in obtaining an accurate assessment of dietary intake.

Acknowledgments

The Women's Healthy Eating and Living Study Group: *University of California, San Diego, Cancer Prevention and Control Program, San Diego, CA*: John P. Pierce (Principal Investigator), Cheryl L. Rock, Susan Faerber, Vicky A. Newman, Shirley W. Flatt, Sheila Kealey, Loki Natarajan, Jacqueline M. Major, and Barbara Parker; *Center for Health Research, Portland, OR:* Cheryl K. Ritenbaugh and Mark Rarick; *Kaiser Permanente Northern California, Oakland, CA*: Bette J. Caan and Lou Fehrenbacher; *Stanford University, Palo Alto, CA*: Marcia L. Stefanick and Robert Carlson; *University of Arizona, Tucson and Phoenix, AZ:* James R. Marshall, Cynthia A.Thomson, and James Warnecke; *University of California, Davis, Davis, CA*: Ellen B. Gold and Sidney Scudder; *University of California, San Diego Cancer Center, San Diego, CA*: Linda Wasserman and Kathryn A. Hollenbach; *University of Texas M. D. Anderson Cancer Center, Houston, TX*: Lovell A. Jones and Richard Theriault.

We also thank Dennis Heath and Mila Pruitt for conducting the plasma carotenoid analysis.

This study was supported by NCI grant CA69375; University of California, San Diego General Clinical Research Center NIH grant M01-RR00827; University of California, San Francisco, General Clinical Research Center NIH grant M01-RR00079; Stanford University, General Clinic Research Center NIH grant M01-RR00070; the California Cancer Research Fund grant 99-00548V-10147; and the Walton Family Foundation.

References

1. Rock CL. Carotenoids: biology and treatment. Pharmacol Ther. 1997; 75:185–197. [PubMed: 9504139]

2. Mayne ST, Cartmel B, Silva F, et al. Effect of supplemental beta-carotene on plasma concentrations of carotenoids, retinol, and alpha-tocopherol in humans. Am J Clin Nutr. 1998; 68:642–647. [PubMed: 9734742]

3. Nierenberg DW, Dain BJ, Mott LA, et al. Effects of 4 yr of oral supplementation with beta-carotene on serum concentrations of retinol, tocopherol, and five carotenoids. Am J Clin Nutr. 1997; 66:315–319. [PubMed: 9250109]

4. Haegele AD, Gillette C, O'Neill C, et al. Plasma xanthophyll carotenoids correlate inversely with indices of oxidative DNA damage and lipid peroxidation. Cancer Epidemiol Biomarkers Prev. 2000; 9:421–425. [PubMed: 10794487]

5. Muller H, Bub A, Watzl B, et al. Plasma concentrations of carotenoids in healthy volunteers after intervention with carotenoid-rich foods. Eur J Nutr. 1999; 38:35–44. [PubMed: 10338686]

6. Paiva SAR, Yeum KJ, Cao G, et al. Postprandial plasma carotenoid responses following consumption of strawberries, red wine, vitamin C or spinach by elderly women. J Nutr. 1998; 128:2391–2394. [PubMed: 9868186]

7. Yeum LK, Booth SL, Sadowski JA, et al. Human plasma carotenoid response to the ingestion of controlled diets high in fruits and vegetables. Am J Clin Nutr. 1996; 64:594–602. [PubMed: 8839505]

8. Broekmans WMR, Klopping-Ketelaars IAA, Schuurman CRWC, et al. Fruits and vegetables increase plasma carotenoids and vitamins and decrease homocysteine in humans. J Nutr. 2000; 130:1578–1583. [PubMed: 10827213]

9. Maskerinec G, Chan CLY, Meng L, et al. Exploring the feasibility and effects of a high-fruit and vegetable diet in healthy women. Cancer Epidemiol Biomarkers Prev. 1999; 8:919–924. [PubMed: 10548322]

10. Rock CL, Flatt SW, Wright FA, et al. Responsiveness of serum carotenoids to a high-vegetable diet intervention designed to prevent breast cancer recurrence. Cancer Epidemiol Biomarkers Prev. 1997; 6:617–623. [PubMed: 9264275]

11. Pierce JP, Faerber S, Wright FA, et al. Feasibility of a randomized trial of a high-vegetable diet to prevent breast cancer recurrence. Nutr Cancer. 1997; 28:282–288. [PubMed: 9343838]

12. Le Marchand L, Hankin JH, Carter FS, et al. A pilot study on the use of plasma carotenoids and ascorbic acid as markers of compliance to a high fruit and vegetable dietary intervention. Cancer Epidemiol Biomarkers Prev. 1994; 3:245–251. [PubMed: 8019375]

13. Smith-Warner SA, Elmer PJ, Tharp TM, et al. Increasing vegetable and fruit intake: randomized intervention and monitoring in an at-risk population. Cancer Epidemiol Biomarkers Prev. 2000; 9:307–317. [PubMed: 10750670]

14. Rock CL, Moskowitz A, Huizar B, et al. High vegetable and fruit diet intervention in premenopausal women with cervical intraepithelial neoplasia. J Am Diet Assoc. 2001; 101:1167–1174. [PubMed: 11678487]

15. Clevidence BA, Bieri JG. Association of carotenoids with human plasma lipoproteins. Methods Enzymol. 1993; 214:33–46. [PubMed: 8469147]

16. Buzzard IM, Faucett CL, Jeffery RW, et al. Monitoring dietary change in a low-fat diet intervention study: advantages of using 24-hour diet recalls vs food records. J Am Diet Assoc. 1996; 96:574–579. [PubMed: 8655904]

17. Patterson RE, Kristal AR, Tinker LF, et al. Measurement characteristics of the Women's Health Initiative food frequency questionnaire. Ann Epidemiol. 1999; 9:178–187. [PubMed: 10192650]

18. Pierce JP, Faerber S, Wright F, et al. A randomized trial of the effect of a plant based dietary pattern on breast cancer recurrence: the Women's Healthy Eating and Living (WHEL) Study. Control Clin Trials. 2002; 23:728–756. [PubMed: 12505249]

19. Thomson CA, Giuliano A, Rock CL, et al. Measuring dietary change in a diet intervention trial: comparing food frequency questionnaire and dietary recalls. Am J Epidemiol. 2003; 157:754–762. [PubMed: 12697580]

20. Gamboa-Pinto A, Rock CL, Ferruzzi MG, et al. Cervical tissue and plasma concentrations of α-carotene and β-carotene in women are correlated. J Nutr. 1998; 128:1933–1936. [PubMed: 9808645]

21. Shirey TL. Development of a layered-coating technology for clinical chemistry. Clin Biochem. 1985; 16:147–155.
22. Newman V, Rock CL, Faerber S, et al. Dietary supplement use by women at risk for breast cancer recurrence. J Am Diet Assoc. 1998; 98:285–292. [PubMed: 9508010]
23. Martinez ME, Marshall JR, Graver E, et al. Reliability and validity of a self-administered food frequency questionnaire in a chemoprevention trial of adenoma recurrence. Cancer Epidemiol Biomarkers Prev. 1999; 8:941–946. [PubMed: 10548325]
24. US Department of Agriculture, Agricultural Research Service. USDA Nutrient Database for Standard Reference, Releases 11–13. Nutrient Data Laboratory Home Page. 2001. http://www.nal.usda.gov/fnic/foodcomp. Accessed November 4, 2004
25. Agricultural Research Service, US Department of Agriculture. Design and Operation: The Continuing Survey of Food Intakes by Individuals and the Diet and Health Knowledge Survey, 1994–96. Washington, DC: US Department of Agriculture; 1997.
26. Holden JM, Eldridge AL, Beecher GR, et al. Carotenoid content of US foods: an update of the database. J Food Comp Anal. 1999; 12:169–1996.
27. Diggle, PJ., Liang, KY., Zeger, SL. Analysis of Longitudinal Data. Oxford: Clarendon Press; 1994.
28. Khattree, R., Naik, DN. Applied Multivariate Statistics With SAS Software. 2nd. Cary, NC: SAS Institute Inc; 1999.
29. Black AE, Cole TJ. Biased over- or under-reporting is characteristic of individuals whether over time or by different assessment methods. J Am Diet Assoc. 2001; 101:70–80. [PubMed: 11209588]
30. Freedman LS, Carroll RJ, Wax Y. Estimating the relation between dietary intake obtained from a food frequency questionnaire and true intake. Am J Epidemiol. 2001; 134:310–320.
31. Plummer M, Clayton D. Measurement error in dietary assessment; an investigation using covariance structure models. Parts I & II. Stat Med. 1993; 12:925–948. [PubMed: 8337549]
32. Rosner B, Gore R. Measurement error correction in nutritional epidemiology based on individual foods, with application to the relation of diet to breast cancer. Am J Epidemiol. 2001; 154:827–835. [PubMed: 11682365]
33. Kipnis V, Midthune D, Freedman L, et al. Empirical evidence of correlated biases in dietary assessment instruments and its implications. Am J Epidemiol. 2001; 153:394–403. [PubMed: 11207158]
34. Prentice RL. Measurement error and results from analytic epidemiology:: dietary fat and breast cancer. J Natl Cancer Inst. 1996; 88:1738–1747. [PubMed: 8944004]
35. Parker RS. Absorption, metabolism, and transport of carotenoids. FASEB J. 1996; 10:542–551. [PubMed: 8621054]
36. Parker RS, Swanson JE, You CS, et al. Bioavailability of carotenoids in human subjects. Proc Nutr Soc. 1999; 58:155–162. [PubMed: 10343353]
37. Rock CL, Thornquist MD, Kristal AR, et al. Demographic, dietary and lifestyle factors differentially explain variability in serum carotenoids and fat-soluble vitamins: baseline results from the sentinel site of the Olestra Post-Marketing Surveillance Study. J Nutr. 1999; 129:855–864. [PubMed: 10203561]
38. Van het Hof KH, West CE, Westrate JA, et al. Dietary factors that affect the bioavailability of carotenoids. J Nutr. 2000; 130:503–506. [PubMed: 10702576]
39. Kristal AR, Beresford SA, Lazovich D. Assessment change in diet-intervention research. Am J Clin Nutr. 1994; 59(suppl):185S–189S. [PubMed: 8279421]
40. Ritenbaugh C, Peng YM, Aickin M, et al. New carotenoid values for food improve relationship of food frequency questionnaire intake estimates to plasma values. Cancer Epidemiol Biomarkers Prev. 1996; 5:907–912. [PubMed: 8922299]
41. Beecher, GR., Kahchik, F. Analysis of micronutrients in foods. In: Moon, TE., Micozzi, MS., editors. Nutrition and Cancer Prevention: Investigating the Role of Micronutrients. New York: Marcel Dekker; 1991. p. 103-158.

TABLE 1

Comparison of Population Characteristics by Diet Group at Baseline

	Intervention Group (n = 197) Mean ± SD	**Comparison Group (n = 198) Mean ± SD**
Body mass index (kg/m^2)	27.7 ± 6.6	27.1 ± 6.1
Plasma cholesterol concentration (mmol/L)	5.2 ± 1.2	5.1 ± 1.0
Energy intake (kcal/d)	1729 ± 364	1752 ± 404
Age at randomization (years)	52.7 ± 8.6	52.8 ± 9.8

TABLE 2

Mean Difference Between Estimated Dietary Intakes From Food Frequency Questionnaire and 24-h Recall at Baseline

	Baseline (n = 395)
Dietary Intakes (μg/d)	**Mean (95% CI)**
α-Carotene	−77 (−284 to 130)
β-Carotene	1183 (575 to 1792)
Lutein	988 (658 to 1318)
Lycopene	3510 (2652 to 4369)
β-Cryptoxanthin	40 (−4 to 84)

TABLE 3

Comparison of Plasma Concentrations of Carotenoids at Baseline and 12 mo in Both Diet Groups

	Baseline		12 Months	
Plasma Concentrations (μmol/L)	**Intervention Group (n = 197) Mean ± SE**	**Comparison Group (n = 198) Mean ± SE**	**Intervention Group (n = 197) Mean ± SE**	**Comparison Group (n = 198) Mean ± SE**
α-Carotene	0.21 ± 0.02	0.22 ± 0.01	0.77 ± 0.06	0.22 ± 0.01
β-Carotene	0.88 ± 0.07	1.02 ± 0.08	1.62 ± 0.10	1.05 ± 0.08
Lutein	0.37 ± 0.01	0.39 ± 0.02	0.50 ± 0.02	0.37 ± 0.01
Lycopene	0.75 ± 0.03	0.70 ± 0.03	0.78 ± 0.03	0.70 ± 0.03
β-Cryptoxanthin	0.21 ± 0.01	0.20 ± 0.01	0.21 ± 0.01	0.20 ± 0.01

TABLE 4

Comparison of Average 12-mo Change in Plasma Concentrations and Dietary Intakes of Carotenoids by Diet Group

	Plasma Concentrations (μmol/L)		Dietary Intakes (μg/d)			
			Food Frequency Questionnaire		24-Hour Recalls	
	Intervention Group Mean ± SE	Comparison Group Mean ± SE	Intervention Group Mean ± SE	Comparison Group Mean ± SE	Intervention Group Mean ± SE	Comparison Group Mean ± SE
α-Carotene	0.55 ± 0.05	0.00 ± 0.01	4855 ± 364	120 ± 123	10254 ± 682	−56 ± 191
β-Carotene	0.75 ± 0.09	0.03 ± 0.05	15599 ± 1102	506 ± 380	21482 ± 1319	−407 ± 403
Lutein	0.12 ± 0.01	−0.02 ± 0.01	3388 ± 375	723 ± 269	2686 ± 244	−7 ± 173
Lycopene	0.04 ± 0.03	−0.01 ± 0.03	2398 ± 631	−658 ± 484	10417 ± 1008	−546 ± 456
β-Cryptoxanthin	0.00 ± 0.01	0.01 ± 0.00	69 ± 23	20 ± 16	181 ± 42	−20 ± 45

TABLE 5

Repeated Measures Analysis Modeling Plasma Carotenoid Concentrations

	α-Carotene		β-Carotene		Lutein	
Fixed Effects	**Slope ± SE**	**Type III F-test**	**Slope ± SE**	**Type III F-test**	**Slope ± SE**	**Type III F-test**
Model A						
Intervention						
24-h recalls	0.37 ± 0.02	327.2	0.32 ± 0.03	160.3	0.25 ± 0.04	46.0
Comparison						
24-h recalls	0.12 ± 0.02	38.5	0.16 ± 0.0	15.7	0.15 ± 0.05	10.9
Model B						
Intervention						
FFQ	0.56 ± 0.03	339.5	0.41 ± 0.03	154.1	0.28 ± 0.03	76.2
Comparison						
FFQ	0.27 ± 0.03	73.1	0.26 ± 0.05	22.9	0.11 ± 0.04	6.5
Model C						
Intervention						
24-h recalls	0.22 ± 0.03	72.7	0.20 ± 0.04	29.4	0.12 ± 0.04	8.1
FFQ	0.33 ± 0.04	73.1	0.20 ± 0.05	17.7	0.22 ± 0.04	34.2
Comparison						
24-h recalls	0.09 ± 0.02	25.2	0.13 ± 0.04	9.8	0.13 ± 0.05	7.5
FFQ	0.24 ± 0.03	57.2	0.22 ± 0.05	16.7	0.08 ± 0.04	3.2

The natural log of all measured carotenoid was used in this analysis.

TABLE 6

Ratio of Prediction Errors of Dietary Intake Methods in Predicting Plasma Concentrations

		Intervention Group		Comparison Group	
	Models Compared	Observed Ratio	Simulation* Mean Ratio (95% CI)	Observed Ratio	Simulation* Mean Ratio (95% CI)
α-Carotene	A to B	0.98	0.99 (0.87 to 1.10)	1.09	1.06 (0.99 to 1.24)
	C to A	0.88	0.87 (0.80 to 0.94)	0.82	0.84 (0.74 to 0.87)
	C to B	0.86	0.86 (0.80 to 0.92)	0.89	0.89 (0.84 to 0.95)
β-Carotene	A to B	0.93	0.93 (0.85 to 0.98)	1.03	1.01 (0.97 to 1.09)
	C to A	0.99	0.98 (0.98 to 1.00)	0.93	0.94 (0.87 to 0.96)
	C to B	0.92	0.91 (0.86 to 0.96)	0.96	0.95 (0.92 to 0.99)
Lutein	A to B	1.04	1.03 (0.99 to 1.10)	0.98	0.98 (0.94 to 1.03)
	C to A	0.95	0.95 (0.91 to 0.98)	0.99	0.99 (0.97 to 1.00)
	C to B	0.98	0.98 (0.95 to 1.00)	0.97	0.97 (0.94 to 1.00)

*Based on 200 replicates.

Model A: 24-h recalls predicting plasma concentrations.

Model B: FFQ predicting plasma concentrations.

Model C: 24-h recalls and FFQ predicting plasma concentrations.