Published in final edited form as:
Hypertension. 2014 February ; 63(2): 238–244. doi:10.1161/HYPERTENSIONAHA.113.02218.

MEASUREMENT ERROR CORRECTED SODIUM AND POTASSIUM INTAKE ESTIMATION USING 24-HOUR URINARY EXCRETION

Ying Huang[1], **Linda Van Horn**[2], **Lesley F. Tinker**[1], **Marian L. Neuhouser**[1], **Laura Carbone**[3], **Yasmin Mossavar-Rahmani**[4], **Fridtjof Thomas**[3], and **Ross L. Prentice**[1]

[1]Division of Public Health Sciences, Fred Hutchinson Cancer Research Center, Seattle, WA

[2]Department of Preventive Medicine, Northwestern University, Chicago IL

[3]Department of Preventive Medicine, University of Tennessee Health Sciences Center, Memphis, TN

[4]Department of Epidemiology and Population Health, Albert Einstein College of Medicine, Bronx, NY

Abstract

Epidemiologic studies of the association of sodium and potassium intake with cardiovascular disease risk have almost exclusively relied on self-reported dietary data. Here, 24-hour urinary excretion assessments are used to correct the dietary self-report data for measurement error, under the assumption that 24-hour urine recovery provides a biomarker that differs from usual intake according to a 'classical' measurement model. Under this assumption, dietary self-reports underestimate sodium by 0–15%, overestimate potassium by 8–15%, and underestimates the sodium-to-potassium ratio by about 20% using food frequency questionnaires, 4-day food records, or three 24-hour dietary recalls, in Women's Health Initiative studies. 'Calibration' equations are developed by linear regression of log-transformed 24-hour urine assessments on corresponding log-transformed self-report assessments, and several study subject characteristics. For each self-report method the calibration equations turned out to depend on race and age, and strongly on body mass index. Following adjustment for temporal variation, calibration equations using food records or recalls explained 45–50% of the variation in (log-transformed) 24-hour urine assessments for sodium, 60–70% of the variation for potassium, and 55–60% of the variation for

Correspondence to: Ross L. Prentice, Ph.D., Division of Public Health Sciences, Fred Hutchinson Cancer Research Center, 1100 Fairview Avenue North, P.O. Box 19024, Seattle, WA 98109-1024; phone: 206-667-4264; fax: 206-667-4142; rprentic@whi.org.

Author contributions: Drs. Van Horn, Tinker, Neuhouser, and Prentice planned the analyses, and obtained Women's Health Initiative (WHI) approvals. Dr. Huang served as principal data analyst and contributed to manuscript drafting. Dr. Prentice coordinated the effort, including manuscript drafting. Drs. Tinker, Huang, and Neuhouser investigated and used WHI resources to explore the influence of hypertensive medications on findings. All authors contributed to critical revisions of the manuscript leading to several improvements, for example in the areas of biomarker quality control (Dr. Carbone), statistical model building (Dr. Thomas), alternate data analyses and data interpretation (Dr. Mossavar-Rahmani).

Clinical Trials Registration: ClinicalTrials.gov identifier: NCT00000611

Conflict of Interest
The authors have no conflicts of interest to report.

For a list of all the investigators who have contributed to WHI science, please visit: https://cleo.whi.org/researchers/Documents%20%20Write%20a%20Paper/WHI%20Investigator%20Long%20List.pdf

the sodium-to-potassium ratio. These equations may be suitable for use in epidemiologic disease association studies among postmenopausal women. The corresponding 'signals' from food frequency questionnaire data were weak, but calibration equations for the ratios of sodium and potassium to total energy explained about 35%, 50%, and 45% of log-biomarker variation for sodium, potassium, and their ratio, respectively, following adjustment for temporal biomarker variation, and may be suitable for cautious use in epidemiologic studies.

Keywords

bias (epidemiology); biomarker; calibration equation; dietary assessment; measurement error; postmenopausal women; potassium; sodium

A strong association of high sodium and low potassium intake with elevated blood pressure and hypertension has been established in epidemiologic studies and randomized controlled trials,[1,2] but epidemiologic studies of these associations with cardiovascular disease (CVD) incidence and mortality have been less consistent.[3,4] However, epidemiologic studies of these associations have nearly all relied on self-report dietary data. The accuracy of dietary assessment for these nutrients has been reported to depend on individual characteristics as well as behavioral and environmental factors.[5,6] The limitations of dietary data have stimulated some studies to use 24-hour urinary excretions instead, for sodium and potassium intake estimation. Specifically, the Trials of Hypertension Prevention (TOHP) collaborative group reported a positive association between the urinary sodium-to-potassium excretion ratio and CVD incidence, but there were only 193 incident events, and associations with sodium and potassium separately were not significant.[7] A study among persons with established CVD or diabetes used urinary excretion data, and had a larger number of CVD events, but the relevance to disease risk in healthy populations is unclear.[8]

For reasons of cost, 24-hour urines are typically not collected by all enrollees in large epidemiologic cohort studies. Instead, one can use 24-hour urines in a subsample of moderate size to develop 'calibration' equations that aim to correct the self-report data for random and systematic bias aspects of their measurement error. These equations can then be used to develop calibrated intake estimates throughout study cohorts, for use in disease association analyses.

The regression calibration approach[9–11] just outlined assumes the biomarker consumption estimate, here that based on log-transformed 24-hour urinary recovery, to equal the targeted consumption, which here is defined as usual daily intake over a specified time period, plus error that has mean zero and is independent of the targeted quantity and of other study subject characteristics – a so-called 'classical' measurement error model. This measurement model allows the objective measure to differ considerably from its target, but in a manner that is independent and random among study subjects. With log-transformation, the approach would be little affected if the measurement error mean was allowed to be non-zero to make a provision, for example, for nutrient excretion through sweat or feces.

Note, however, that 24-hour urine excretions are somewhat controversial as individual consumption biomarkers, especially for sodium. For example, within-person correlations for

paired 24-hour urine assessments separated by several months, were 0.50 for potassium, but only 0.30 for sodium in the TONE trial.[5] A controlled human feeding study involving randomly fluctuating sodium consumption found a correlation of 0.55 between 24-hour urine sodium and corresponding actual dietary intake, with improved agreement when using multiple 24-hour urine collections over several days.[12] A recent experiment, involving a constant sodium intake over some months, revealed some important rhythmicities of 24-hour sodium excretion of duration longer than 24 hours, possibly due to with-in person tissue sodium retention variations over time.[13] It seems plausible that these variations are independent and random among study subjects, but data available in this research effort do not allow this assumption to be tested. In addition to a classical measurement model for log-transformed 24-hour urine assessment, the measurement model used here[14] includes a more flexible measurement model for the corresponding self-report data to allow for systematic biases with body mass index[15] and with other factors.

Women's Health Initiative (WHI) resources provide an opportunity to develop calibration equations in the context of postmenopausal women in the United States: Nutrition biomarker studies within WHI cohorts collected 24-hour urine specimens, which were analyzed for sodium and potassium content for this report, and also assessed dietary habits using each of food frequency questionnaires (FFQs), four-day food records (4DFRs), and three 24-hour dietary recalls (24HRs). Twenty-percent reliability subsamples repeated the biomarker protocols about 6 months after the initial application, allowing study of calibration equation improvement with replicate 24-hour urine and dietary data. Calibration equations from these biomarker sub-studies will be presented in this report. A subsequent report will relate the resulting calibrated consumption estimates, using equations developed here, to CVD risks in WHI cohorts.

MATERIALS AND METHODS

Women's Health Initiative cohorts

The design of the WHI Clinical Trial (CT) and Observational Study (OS), and enrollee characteristics at WHI enrollment, have been presented.[16–18] All women were postmenopausal and in the age range 50–79 when enrolled at 40 U.S. clinical centers during 1993–98. The CT enrolled 68,132 women to either or both of the Dietary Modification (DM) trial (48,835 women) or to overlapping postmenopausal hormone therapy trials (27,347 women). The companion WHI OS is a prospective cohort study that enrolled 93,676 postmenopausal women in the age range 50–79 years during 1994–98. The CT and OS cohorts were drawn from essentially the same catchment populations, with substantial overlap in baseline data collection and in outcome ascertainment procedures[19] during cohort follow-up. The WHI food frequency questionnaire[20] was administered at baseline and 1-year in the DM trial, and approximately every three years thereafter during the trial intervention period (ended 4/8/05), and was administered at baseline and 3-years in the OS. A four-day food record was obtained at baseline for women in the DM trial as a part of eligibility determination, and 24-hour dietary recalls (24HRs) were obtained for certain subsets of DM trial participants.

Nutrition Biomarker Sub-studies in the Women's Health Initiative

The data considered here are derived from two nutrition biomarker sub-studies within WHI cohorts. The Nutrient Biomarker Study (NBS), conducted during 2004–2006, included 544 women at 12 WHI clinical centers. It enrolled 50% of women from the DM intervention and 50% from the usual diet comparison group of the DM trial cohort, with few additional eligibility or exclusionary criteria.[21] The NBS aims to evaluate measurement properties of the WHI FFQ, and to correct FFQ consumption estimates for measurement error.

The Nutrition and Physical Activity Assessment Study (NPAAS) enrolled 450 postmenopausal women from the OS, and was conducted during 2007–2009.[22] Women were recruited at 9 WHI clinical centers, 8 of which also participated in the NBS. Black and Hispanic women were oversampled, as were women in the extremes of body mass index (BMI) and relatively younger postmenopausal women. NPAAS was designed to evaluate and compare the measurement properties of the FFQ, 4DFR, and three 24HRs.

Women were excluded from either biomarker study for having any medical condition precluding participation, weight instability, or travel plans during the study period. In both studies a 20% reliability sub-sample repeated the entire study protocol at about 6 months after the original protocol application.

NBS and NPAAS protocol and procedures

The study protocol for both studies involved two clinical center visits separated by a two-week period, along with at-home activities. Detailed descriptions of visit content and schedule have been published.[21,22] Participants collected 24-hour urine on the day prior to the second clinic visit. At the second visit, completeness of the 24-hour urine collections was assessed by self-report of missed or spilled collections and para-aminobenzoic acid. In the NBS sixteen, and in NPAAS seven, urine collections were considered incomplete, and excluded from present analyses. On-line Supplementary Figure S1 provides further detail on the data collection schedule in NBS and NPAAS.

Recovery biomarkers

Specimen handling and quality assurance procedures have been described for NBS[21] and NPAAS.[22] Blinded duplicates (5%) were included in all biomarker assessments. Sodium and potassium urine analyses were performed by ion-selective electrode.[23] For NBS, the assays were conducted by Pharmaceutical Product Development Global Central Labs in Highland Heights, Kentucky, and for NPAAS, at the University of Washington Laboratory Medicine. The coefficients of variation (CV) in the NBS were 11.6% for sodium and 10.7% for potassium based on 32 blind duplicate pairs, and in NPAAS the CVs were 4.3% for sodium and 5.9% for potassium based on 24 and 26 blind duplicate pairs, respectively.

Total energy expenditure during the two-week protocol was estimated by a doubly-labeled (DLW) procedure.[21,22]

Dietary assessment in NBS and NPAAS

Dietary assessment procedures, including the WHI FFQ,[15] 4DFR and 24HRs, as applied in NBS and NPAAS, have been described in some detail.[21,22] Dietary data from each of the three methods were analyzed for nutrient content using the University of Minnesota's Nutrition Coordinating Center's Nutrition Data Systems for Research (NDS-R®).

Statistical methods

Calibration equations were developed that target usual consumption over an approximate 1-year period, for each of sodium, potassium, and the sodium-to-potassium ratio. Additional equations were developed for the corresponding ratios of sodium and potassium to total energy consumption. For each nutritional variable, these equations were developed from linear regression of the log-transformed biomarker assessment on the corresponding log-transformed dietary assessment and other factors. The 'signal' strength from the self-report was judged by its regression coefficient and by the percent of biomarker variation (R^2) in the study sample explained by the self-report assessment. The overall regression R^2 was used to examine the ability of associated calibrated consumption estimates to recover the biomarker variation. Adjusted R^2 values that allow for random variation in the biomarker due to differences between consumption and biomarker values during the 24-hour urine collection period or to consumption variations over time within the overall targeted time period, are calculated by dividing unadjusted R^2 values by the correlation between paired log-transformed biomarker values from the pertinent 20% reliability stubstudy.[22]

Additional calibration equations were developed using only data from the reliability subsamples. These equations arise from linear regression of the average of the paired log-transformed biomarker values on the average of the corresponding paired log-transformed self-report values and other factors. Adjusted R^2 values from these analyses are calculated by multiplying unadjusted R^2 values by $0.5 + 0.5\rho^{-1}$, where ρ is the correlation between paired log-transformed biomarker values from the reliability subsample.

In making these calculations, daily food record and recall estimates were averaged prior to log-transformation. Also, values for log-transformed biomarker and self-report assessments that fall outside the inter-quartile range for the variable by more than twice its width were excluded as outliers.

Calibration equations arising from FFQ assessments from the non-overlapping NBS and NPAAS data sets were compared using likelihood ratio tests based on the combined data set. Bootstrap procedures (10,000 bootstrap samples) were used to compare regression coefficients across dietary assessment instruments. All P-values are two-sided.

The overall WHI protocol, and protocols for NBS and NPAAS, were approved by the Institutional Review Committees of participating institutions, and participating women provided written informed consent for their overall and biomarker study activities.

RESULTS

Table 1 shows the distribution of women enrolled in NBS and NPAAS according to characteristics assessed at the time of biomarker study participation. About two-thirds of the women were overweight or obese. Note the larger fraction of black and Hispanic women in NPAAS compared to NBS.

Table 2 shows geometric means and associated 95% confidence intervals (CIs) for the 24-hour urine measures and for each of the dietary assessments; for sodium, potassium and the sodium-to-potassium ratio. Corresponding statistics are shown on the right side of Table 2 for the ratio of each self-report to the biomarker. Compared to the 24-hour urine measures, sodium is underestimated by 15% (NBS) and 10% (NPAAS) by the WHI FFQ, by 8% using three 24HRs, and by a non-significant 2% using the 4DFR. In comparison, potassium is overestimated by 10% or more by each of the dietary assessment approaches, and the sodium-to-potassium ratio is underestimated by about 20% by each assessment procedure. Also (not shown) in NBS, the FFQ underestimation in sodium was not significantly different between the DM trial comparison arm and the intervention arm, as was also the case for the potassium overestimation. However, the underestimation of sodium-to-potassium ratio was somewhat larger in the NBS intervention arm ($p=0.02$).

On-line Supplementary Table S1 examines whether these 'biases' depend on study subject characteristics, based on linear regression of log(self-report)-log(biomarker) on the listed characteristics. As for energy and protein estimation[21,22] the most influential characteristics were BMI, age and race. Sodium underestimation with the FFQ was considerably larger among black and Hispanic women compared to white women, and was larger among relatively younger women, and among women having a high BMI. Somewhat similar patterns were evident for sodium estimation based on 24HRs, but biases in relation to these factors were not significant for the 4DFR.

There were few clear systematic biases for potassium estimation. Systematic biases were evident with each of the dietary assessment procedures for the sodium-to-potassium ratio. This ratio was underestimated to a greater extent among women with high BMI when using the FFQ, and the underestimation was greater among black and/or Hispanic women with each of the three assessment methods.

Besides age, BMI, and race, other factors such as DM trial randomization (for NBS), dietary supplement use, smoking status, education, and income also have some relationship to reporting bias.

Table 3 presents adjusted R^2 values for the dietary self-report assessments and the overall fitted model from linear regression of log(biomarker) on log(self-report) and other study subject characteristics. The left side of Table 3 gives these adjusted R^2 values based on the initial biomarker and dietary assessments in the two biomarker studies, while the right side of Table 3 provides corresponding information based on the paired biomarker and dietary assessments in the 20% reliability subsample component of these studies.

From the left side of Table 3, one sees that the FFQ sodium assessments explain little of the 24-hour urine sodium variation (adjusted R^2 of 5.3% and 3.5% in NBS and NPAAS respectively), whereas the 4DFR and 24HR assessments provide an explanation or about 20–25% of this variation. The adjusted R^2 values are somewhat larger for potassium, but are still only about 15–20% from the FFQ assessment, compared to 50–60% from food records or recalls. The FFQ adjusted R^2 values for the sodium-to-potassium ratio were about 25%, compared to 40–45% for the 4DFR or 24HRs. Detail on these 'calibration' equations, sufficient to allow intake estimates to be calculated from the dietary self-report data and study subject characteristics, is given in Supplementary Table S2. These show that BMI contributes significantly to sodium calibration when used with any of the three assessment procedures, as did age with the FFQ and 24HR assessments. For potassium, race contributed significantly to the calibration using any of the assessment methods, as did several other variables with the FFQ assessment. Race also contributed to the calibration for the sodium-to-potassium ratio, as did education for each of the self-report assessments, and as did dietary supplement use.

The total regression adjusted R^2 values on the left side of Table 3 support the utility of calibrated consumption estimates from the 4DFR and the 24HRs for each of the three nutritional variables, and possibly also those from FFQs for the sodium-to-potassium ratios.

We compared FFQ calibration equations between NBS and NPAAS. A likelihood ratio test of equality of all coefficients was not significant for sodium (p=0.59), or potassium (p=0.22). The NPAAS sodium-to-potassium ratio calibration equation did not differ from that for the DM comparison group in NBS, whereas this ratio was underestimated to a greater extent in the DM intervention group, than in NPAAS (p=0.02).

Supplementary Figures S2 and S3 show paired log-biomarker and log-self-report values from the 20% reliability subsample of the two biomarker studies. The 24-hour urine correlations between paired values were 0.32 (NBS) and 0.31 (NPAAS) for sodium, 0.46 for potassium, and 0.56 for the sodium-to-potassium ratio, based on the 111 women in the NBS reliability substudy and the 88 women in the NPAAS reliability subsample. The adjusted R^2 values on the right side of Table 3 are based on reliability sub-sample data only, are less precisely estimated because of the much reduced sample sizes. The adjusted R^2 values for the self-report increase when using the replicate 4DFR and 24HR assessments, but improvement is not evident when using FFQs. Total regression adjusted R^2 values are in the 60–80% range using food records or recalls, for each of the three dietary variables. Details of these calibration equations, which would require replicate dietary data for application, are given in Supplementary Table S3.

Supplementary Table S4 augments the calibration equations of Supplementary Table S2 by including interaction terms between the log(self-report) and race. Some moderate interactions were suggested for each of sodium, potassium and their ratio, with weaker self-report signals from minority women, especially for the 4DFR-based equations.

Additional analyses considered whether the use of certain medications may imply needed refinements to the calibration equations of Supplementary Table S2. Participating WHI

women were asked to provide medication information during 2008–2009. For NPAAS women, this inventory mostly took place 1–2 years following their biomarker study participation. There were 56, 53, 101, and 89 NPAAS women who reported use of beta blockers, calcium channel blockers, antihypertensives (including angiotensin II receptor agonists, angiotensin-converting enzyme inhibitors), and diuretics (including sodium channel blockers and potassium-sparing diuretics, aldosterone antagonists), respectively, for an immediately preceding time period in excess of one year. The NPAAS calibration equation analyses were repeated excluding eleven corticosteroid users of more than 1-year duration, and including indicator variables for each of the four 'antihypertensive' categories listed above. The significance levels for testing zero coefficients for the four indicator variables were respectively 0.90, 0.49, 0.54, and 0.78 for sodium; 0.35, 0.98, 0.98, and 0.40 for potassium; and 1.00, 0.71, 0.66, and 0.80 for the sodium-to-potassium ratio.

Supplementary Table S5 shows analyses corresponding to Supplementary Table S2 for sodium and potassium divided by total energy consumption. This involves regression of the log-transformed 24-hour urine measures divided by the DLW estimate of total energy on the corresponding self-report nutrient intake to total energy ratio and the other listed variables. Results were similar to those in Supplementary Table S2 without such energy adjustment, but BMI did not contribute significantly to the sodium calibration. Adjusted R^2 values for FFQ assessments were somewhat larger than those shown on the right side of Table 3 with adjusted R^2 values of 25–45% for sodium/energy, and 45–55% for potassium/energy.

DISCUSSION

The analyses presented here assume that log-transformed 24-hour urine sodium and potassium provide estimates of corresponding log-transformed usual intake (e.g., over a 1-year period) with measurement error that is independent of intake and study subject characteristics, such as BMI, age, race, and education. This assumption cannot be tested with data available in the WHI biomarker studies. For sodium, this assumption has some support from an earlier human feeding study,[12] but tissue retention rythmicities over time periods larger than 24-hours[13] need to be included in the biomarker error component, along with actual consumption variations across 24-hour periods. The rather modest correlations (0.32 in NBS, 0.31 in NPAAS; Supplementary Figures S2 and S3) between log-24-hour urinary sodium between paired urine samples collected at time points separated by about 6 months in time presumably reflect both of these sources of variation. Corresponding correlations were larger for log- transformed 24-hour urinary potassium (0.53 in NBS, 0.46 in NPAAS),

Under this biomarker modeling assumption, simple linear calibration equations are shown here to 'capture' much of the variation in usual daily nutrient consumption in WHI biomarker studies, when these equations use intake estimates from four-day food records or three 24-hour dietary recalls. In fact, the adjusted R^2 values for sodium, potassium, and the sodium-to-potassium ratio (Table 3, left side) are comparable to those for energy and protein[22] using their well-established biomarkers. These adjusted R^2 values can be increased further if replicate 4DFRs or replicate sets of three 24HRs are available with suitable temporal separation (Table 3, right side).

In comparison, the ability of FFQ-based dietary data to explain variations in corresponding 24-hour urine measures is quite limited especially for sodium, and this ability is not improved by using replicate FFQs. This limitation may reflect the ubiquitous nature of sodium in the food supply that may not be adequately captured by a FFQ generic list of non-brand-named foods.[24] Also, the WHI FFQ did not specify sodium-reduced food products within the food list, and did not ask about salt added during cooking or at the table. In spite of these limitations, there was a useful 'signal' from the FQ data for the ratios of sodium and potassium to total energy, and corresponding calibration equations (Supplementary Table S5) can be recommended, along with that for the sodium-to-potassium ratio (Supplementary Table S2) for cautious use in disease association studies.

Cardiovascular disease association studies in WHI cohorts, using calibrated estimates for sodium, potassium, and their ratio are planned for the near future. The question of portability of calibration equations to cohorts beyond that in which they were generated has not received much attention in the nutritional epidemiology literature to date. A pooled nutritional biomarker study involving nutritional biomarker studies in the United States, including NBS and NPAAS, is currently underway, and will examine this topic for energy, protein, sodium, and potassium.

The strengths of this study include the sizeable nutritional biomarker studies, nested within large and well-characterized cohorts of postmenopausal women. Limitations include the single 24-hour urine collection among most of these women, and uncertainty concerning the adequacy of 24-hour sodium and potassium excretion as usual intake biomarkers. In view of this uncertainty, additional developmental work to further develop biomarkers of usual sodium and potassium intake is recommended.

PERSPECTIVES

Hypertension associations with sodium and potassium consumption are well-established, but epidemiologic studies to relate these consumptions to cardiovascular disease risk have been mixed, quite possibly because of their typical reliance on self-reported dietary consumption. Nutrient biomarker studies within Women's Health Initiative cohorts of postmenopausal women are used to develop estimates of sodium and potassium intake and their ratio that aim to correct self-report estimates for measurement error. These calibrated estimates appear to be able to reproduce much of the variation in average daily consumption estimates over about a 1-year period of time, and to be suitable for use in association studies with disease outcomes. Such association studies will be carried out in the near future in the Women's Health Initiative setting, which entails more than 160,000 postmenopausal women who have been followed since the 1990s. These association analyses may help to refine sodium and potassium dietary recommendations, and could help to stimulate needed improvements in the food supply for chronic disease risk reduction.

Acknowledgments

Sources of Funding

This work was partially supported by grants CA119171 and CA53996 from the National Cancer Institute. WHI Program support is provided by the National Heart, Lung, and Blood Institute, National Institutes of Health, U.S.

Department of Health and Human Services [contract HHSN268201100046C]. Decisions concerning study design, data collection and analysis, interpretation of the results, the preparation of the manuscript, or the decision to submit the manuscript for publication resided with committees comprised of WHI investigators that included NHLBI representatives.

References

1. Intersalt Cooperative Research Group. Intersalt: an international study of electrolyte excretion and blood pressure: results for 24 hour sodium and potassium excretion. BMJ. 1988; 297:319–328. [PubMed: 3416162]
2. Whelton PK, He J, Cutler JA, Brancati FL, Appel LJ, Follmann D, Klag MJ. Effects of oral potassium on blood pressure: meta-analysis of randomized controlled clinical trials. JAMA. 1997; 277:1624–1632. [PubMed: 9168293]
3. Strazzullo P, D'Elia L, Kandala NB, Cappuccio FP. Salt intake, stroke, and cardiovascular disease: meta-analysis of prospective studies. BMJ. 2009; 339:b4567. [PubMed: 19934192]
4. Yang Q, Liu T, Kuklina EV, Flanders WD, Hong Y, Gillespie C, Chang MH, Gwinn M, Dowling N, Khoury MJ, Hu FB. Sodium and potassium intake and mortality among US adults. Arch Int Med. 2011; 171:1183–1191. [PubMed: 21747015]
5. Espeland MA, Kumanyika S, Wilson AC, Reboussin DM, Easter L, Self M, Robertson J, Brown WM, McFarlane M. TONE Cooperative Research Group. Statistical issues in analyzing 24-hour dietary recall and 24-hour urine collection data for sodium and potassium intakes. Am J Epidemiol. 2001; 153:996–1006. [PubMed: 11384956]
6. Espeland MA, Kumanyika S, Wilson AC, Wilcox S, Chao D, Bahnson J, Reboussin DM, Easter L, Zheng B. Lifestyle interventions influence relative errors in self-reported diet intake of sodium and potassium. Ann Epidemiol. 2001; 11:85–93. [PubMed: 11164124]
7. Cook NR, Obarzanek E, Cutler JA, Buring JE, Rexrode KM, Kumanyika SK, Appel LJ, Whelton PK. Trials of Hypertension Prevention Collaborative Research Group. Joint effects of sodium and potassium intake on subsequent cardiovascular disease: the trials of hypertension prevention follow-up study. Arch Intern Med. 2009; 169:32–40. [PubMed: 19139321]
8. O'Donnell MJ, Yusuf S, Mente A, Gao P, Mann JF, Teo K, McQueen M, Sleight P, Sharma AM, Dans A, Probstfield J, Schmieder RE. Urinary sodium and potassium excretion and risk of cardiovascular events. JAMA. 2011; 306:2229–2238. [PubMed: 22110105]
9. Prentice RL. Covariate measurement errors and parameter estimation in a failure time regression model. Biometrika. 1982; 69:331–342.
10. Wang CY, Hsu L, Feng ZD, Prentice RL. Regression calibration in failure time regression with surrogate variables. Biometrics. 1997; 53:131–145. [PubMed: 9147589]
11. Carroll, RJ.; Ruppert, D.; Stefanski, LA.; Crainiceanu, C. Measurement Error in Nonlinear Models, a Modern Perspective. 2. Boca Raton, FL: Chapman and Hall/CRC; 2006.
12. Luft FC, Finebert NS, Sloan RS. Estimating dietary sodium intake in individuals receiving a randomly fluctuating intake. Hypertension. 1982; 4:805–808. [PubMed: 7141607]
13. Rakova N, Juttner K, Dahlmann A, Schroder A, Linz P, Kopp C, Rauh M, Goller U, Beck L, Agureev A, Vassilleva G, Lenkova L, Johannes B, Wabel P, Moissl U, Vienken J, Gerzer R, Eckardt K-U, Muller DN, Kirsch K, Morukov B, Luft FC, Titze J. Long-term space flight simulation reveals infradian rhythmicity in human Na+ balance. Cell Metab. 2013; 17:125–131. [PubMed: 23312287]
14. Prentice RL, Sugar E, Wang CY, Neuhouser M, Patterson RE. Research strategies and use of biomarkers in studies of diet and chronic disease. Public Health Nutr. 2002; 5:977–984. [PubMed: 12633522]
15. Rhodes DG, Murayi T, Clemens JC, Baer DJ, Sebastian RS, Moshfegh AJ. The USDA Automated Multiple-Pass Method accurately assesses population sodium intakes. Am J Clin Nutr. 2013; 97:958–964. [PubMed: 23553153]
16. Women's Health Initiative Study Group. Design of the Women's Health Initiative Clinical Trial and Observational Study. Control Clin Trials. 1998; 19:61–109. [PubMed: 9492970]

17. Hays J, Hunt JR, Hubbell FA, Anderson GL, Limacher M, Allen C, Rossouw JE. The Women's Health Iniative recruitment methods and results. Ann Epidemiol. 2003; 13:S18–S77. [PubMed: 14575939]

18. Langer RD, White E, Lewis CE, Kotchen JM, Hendrix SL, Trevisan M. The WHI Observational Study: baseline characteristics of participants and reliability of baseline measures. Ann Epidemiol. 2003; 13:S107–S121. [PubMed: 14575943]

19. Curb JD, McTiernan A, Heckbert SR, Kooperberg C, Stanford J, Nevitt M, Johnson KC, Proulx-Burns L, Pastore L, Criqui M, Daugherty S. WHI Morbidity and Mortality Committee. Outcomes ascertainment and adjudication methods in the Women's Health Initiative. Ann Epidemiol. 2003; 13:S122–S128. [PubMed: 14575944]

20. Patterson RE, Kristal AR, Tinker LF, Carter RA, Bolton MP, Agurs-Collins T. Measurement characteristics of the Women's Health Initiative food frequency questionnaire. Ann Epidemiol. 1999; 9:178–187. [PubMed: 10192650]

21. Neuhouser ML, Tinker L, Shaw PA, Schoeller D, Bingham SA, Horn LV, Beresford SA, Caan B, Thomson C, Satterfield S, Kuller L, Heiss G, Smit E, Sarto G, Ockene J, Stefanick ML, Assaf A, Runswick S, Prentice RL. Use of recovery biomarkers to calibrate nutrient consumption self-reports in the Women's Health Initiative. Am J Epidemiol. 2008; 167:1247–1259. [PubMed: 18344516]

22. Prentice RL, Mossavar-Rahmani Y, Huang Y, Van Horn L, Beresford SA, Caan B, Tinker L, Schoeller D, Bingham S, Eaton CB, Thomson C, Johnson KC, Ockene J, Sarto G, Heiss G, Neuhouser ML. Evaluation and comparison of food records, recalls and frequencies for energy and protein assessment using recovery biomarkers. Am J Epidemiol. 2011; 174:591–603. [PubMed: 21765003]

23. Korzun, W.; Miller, W. Sodium and potassium. In: Pesce, A.; Kaplan, L., editors. Methods in Clinical Chemistry. St. Louis MO: CV Mosby; 1987. p. 86

24. Cogswell ME, Zhang Z, Carriquiry AL, Gunn JP, Kuklina EV, Saydah SH, Yang Q, Moshfegh AJ. Sodium and potassium intakes among US adults: NHANES 2003–2008. Am J Clin Nutr. 2012; 96:647–657. [PubMed: 22854410]

NOVELTY AND SIGNIFICANCE

What is New?

- Equations are developed to correct self-reported intake of sodium, potassium, and their ratio for measurement error in dietary assessment.
- These calibration equations are provided for dietary data from each of food frequency questionnaires, 4-day food records, and (three) 24-hour dietary recalls.

What is Relevant?

- Measurement error in dietary assessment has impeded study of the risk of cardiovascular and other diseases in relation to sodium and potassium consumption.
- This paper shows that the ‘signals’ from certain types of dietary self-report data are sufficiently strong for reliable sodium and potassium consumption estimation, when combined with other readily available study subject data.
- The work provides important infrastructure for research to strengthen dietary recommendations concerning sodium and potassium.

Summary

- Self-report intake data that have been corrected for measurement error can be calculated from the calibration equations presented here, for use full-scale disease association studies among postmenopausal women.
- Analyses of this type from the national Women’s Health Initiative (160,000 women) will be reported separately.

Hypertension. Author manuscript; available in PMC 2015 February 01.

Table 1

Biomarker Study Subject Characteristics at the Time of Participation (Visit 1) in the Nutrient Biomarker Study (NBS) and the Nutrition and Physical Activity Assessment Study (NPAAS) within Women's Health Initiative Cohorts

Biomarker Study		**NBS***		**NPAAS***	
Characteristic	**Category**	**N**	**%**	**N**	**%**
Age (years)	[50,64]	88	16.2	47	10.4
	(64,75]	298	54.8	308	68.4
	(75,91]	158	29	95	21.1
BMI (kg/m^2)	<25	177	32.5	156	34.7
	[25,30)	189	34.7	121	26.9
	≥30	178	32.7	173	38.4
Race/ethnicity	White	448	82.4	288	64.0
	Black	59	10.8	84	18.7
	Hispanic	26	4.8	64	14.2
	Other	11	2	14	3.1
Family Income ($1000)	≥75	94	18.2	117	27.0
	50–74	123	23.8	84	19.4
	35–49	107	20.7	98	22.6
	20–34	60	11.6	43	9.9
	<20	133	25.7	92	21.2
Education	High school/GED or less	102	18.8	64	14.3
	School after High school	207	38.2	157	35.1
	College degree or Higher	233	43.0	227	50.7
Cigarette smoker	No	524	96.5	429	97.5
	Yes	19	3.5	11	2.5
Dietary Suppl. Use	No	84	15.4	219	48.8
	Yes	460	84.6	230	51.2

*Abbreviations: NBS, Nutrient Biomarker Study; NPAAS, Nutrition and Physical Activity Assessment Study

Table 2

Geometric Means and 95% Confidence Intervals (CIs) for this mean, for Sodium, Potassium, and their Ratio from 24-hour Urinary Excretion and from Dietary Self-report Assessments, and (right side) Ratios of Self-report to Biomarker

Data Source	n	Geometric Mean	95% CI		n	Geometric Mean	95% CI	
Sodium (mg)								
Biomarker, NBS*	542	2807.11	2714.91	2902.44				
FFQ, NBS	539	2398.83	2323.17	2476.95	537	0.85	0.82	0.89
Biomarker, NPAAS	395	2638.65	2534.24	2747.36				
FFQ, NPAAS	449	2387.63	2291.12	2488.20	394	0.90	0.85	0.95
4DFR, NPAAS	449	2592.48	2523.65	2663.19	394	0.98	0.94	1.02
24HR, NPAAS	444	2425.89	2361.31	2492.25	389	0.92	0.88	0.96
Potassium (mg)								
Biomarker, NBS	539	2334.31	2267.73	2402.84				
FFQ, NBS	536	2531.53	2457.38	2607.92	531	1.08	1.05	1.12
Biomarker, NPAAS	400	2159.13	2079.03	2242.32				
FFQ, NPAAS	446	2456.48	2366.49	2549.89	397	1.12	1.07	1.18
4DFR, NPAAS	447	2593.20	2523.15	2665.18	398	1.20	1.16	1.24
24HR, NPAAS	443	2432.42	2364.26	2502.55	394	1.12	1.08	1.17
Sodium(mg)/Potassium (mg)								
Biomarker, NBS	539	1.22	1.17	1.26				
FFQ, NBS	544	0.96	0.93	0.98	539	0.79	0.76	0.81
Biomarker, NPAAS	398	1.21	1.16	1.27				
FFQ, NPAAS	450	0.98	0.96	1.01	398	0.82	0.78	0.85
4DFR, NPAAS	450	1.01	0.98	1.04	398	0.82	0.79	0.86
24HR, NPAAS	444	1.00	0.97	1.03	392	0.82	0.79	0.86

*Abbreviations: NBS, Nutrient Biomarker Study; NPAAS, Nutrition and Physical Activity Assessment Study; FFQ, food frequency questionnaire; 4DFR, four-day food record; 24HR, three 24-hour dietary recalls

Table 3

Percent of Biomarker Variation Explained (Adjusted R^2) by Dietary Self-Report and by Overall Regression Calibration Equations for Sodium, Potassium, and the Sodium-to-Potassium Ratio

Number of Assessments	Single 24-hour Urine and Dietary Assessment				Replicate 24-hour Urine and Dietary Assessment			
Biomarker Study	NBS*	NPAAS*	NPAAS	NPAAS	NBS	NPAAS	NPAAS	NPAAS
Dietary Assessment	FFQ*	FFQ	4DFR*	24HR*	FFQ	FFQ	4DFR	24HR
SODIUM								
Dietary Assessment	5.3†	3.5	24.6	19.8	0.6	8.8	34.8	27.0
Total Regression	35.5	32.9	46.9	45.6	67.7	57.8	81.5	75.0
POTASSIUM								
Dietary Assessment	19.7	16.5	57.3	49.8	24.4	11.8	58.6	52.4
Total Regression	35.7	34.2	68.9	60.8	46.2	31.8	71.1	62.3
SODIUM/POTASSIUM								
Dietary Assessment	24.1	25.2	44.9	39.9	29.6	9.6	44.5	42.6
Total Regression	43.3	46.4	58.2	55.9	55.3	49.8	71.4	61.3

*Abbreviations: NBS, Nutrient Biomarker Study; NPAAS, Nutrition and Physical Activity Assessment Study; FFQ, food frequency questionnaire; 4DFR, four-day food record; 24HR, three 24-hour dietary recalls

†Table entries are the adjusted percent of log-transformed biomarker variation explained (adjusted R^2) by the log-transformed dietary assessment, and by the linear regression model overall (total regression).