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## Comparability and repeatability of methods for estimating the dietary intake of the heterocyclic amine contaminant 2-amino-1-methyl-6-phenylimidazo[4,5*b*]pyridine (PhIP)

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Inconsistent risk estimates for dietary heterocyclic amine (HCA) exposure and cancers may be due to differences in exposure assessment methods and the associated measurement error. We evaluated repeatability and comparability of intake estimates of the HCA 2-amino-1-methyl-6-phenylimidazo[4,5*b*]pyridine (PhIP) among two food frequency questionnaire (FFQ) collections, three diary collections, and three measurements of urinary PhIP and its metabolites in 36 non-smokers in Baltimore, Maryland, during 2004–2005. Collections spanned ~9 months. Method repeatability was characterised with intraclass correlation coefficients (ICCs). Comparability among methods was assessed with Spearman correlation coefficients. Within-subject variability in PhIP intake was comparably high across all methods (ICCs of 0.20, 0.30, and 0.15 for FFQ, diary, and creatinine-adjusted urinary PhIP, respectively). Mean diary-based PhIP intake and mean urinary PhIP concentration were strongly correlated when restricting the analysis to participants with at least one non-zero diary-based estimate of PhIP intake ( $n = 15$ ,  $r = 0.75$ ,  $p = 0.001$ ), but not in the full study population ( $n = 36$ ,  $r = 0.18$ ,  $p = 0.28$ ). Mean PhIP intake from the FFQ was not associated with that either based on the diary or urinary PhIP separately, but was modestly correlated with a metric that combined the diary- and biomarker-based approaches ( $r = 0.30$ ,  $p = 0.08$ ). The high within-subject variability will result in significantly attenuated associations if a single measure is used to estimate exposure within an epidemiologic study. Improved HCA assessment tools, such as a combination of methods or validated biomarkers that capture long term exposure, are needed.

**Keywords:** heterocyclic amines; biomonitoring; meat; food frequency questionnaire; PhIP

### Introduction

Epidemiologic evidence linking dietary intake of heterocyclic amines (HCAs) with cancers of the colon (Augustsson et al. 1999; Sinha et al. 2001; Nowell et al. 2002; Butler et al. 2003; Gunter et al. 2005; Shin et al. 2007; Wu et al. 2010), breast (Delfino et al. 2000; Sinha et al. 2000), pancreas (Anderson et al. 2005; Li et al. 2007), and prostate (Cross et al. 2005) is inconsistent, possibly due to differences in exposure assessment methods and the associated measurement error (Norat and Riboli 2001; Butler et al. 2003; Cantwell et al. 2004; Alaejos et al. 2008; Cross et al. 2011; Turesky and Le 2011). The standard method for assessing dietary HCA intake in epidemiologic studies of cancer combines meat intake information from food frequency questionnaires (FFQs) with a database of mean concentrations of HCAs measured in cooked meats (Kazerouni et al. 2001; Sinha et al. 2005;

Keating et al. 2007). Strengths of this method include low participant burden and the ability to provide an estimate of usual intake of HCAs, typically over the previous year. Possible limitations include imperfect recall of usual intake, recall bias (in retrospective studies), and differing accuracy of reporting of meat intake information by gender, social desirability (the tendency to respond to questions in a manner to avoid embarrassment or present oneself favourably), or body mass index (Scagliusi et al. 2009). In addition, the FFQ may poorly represent individual-level exposure because HCA concentrations in meats vary with many aspects of cooking that may not be included in the FFQ or HCA database, such as pre-cooking in the microwave, frequency of flipping meat, concentrations of precursors, or use of marinades (Sinha and Rothman 1997; Salmon 2000; Skog 2002). Despite the importance of exposure classification in epidemiologic evaluation of

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PhIP and reliance of the FFQ for this purpose, little is known of its reliability and comparability with other methods.

Diet diaries offer another strategy for classifying exposure. An advantage of diet diaries is that they do not rely on recall, but accuracy of recording may differ by the same individual characteristics as FFQs (Scagliusi et al. 2009). Furthermore, the number of collection days required to obtain accurate estimates of usual intake increases with increasing intra-individual variability in intake of the target food items. Increasing the number of days of diary collection decreases compliance (Willett 1998). Like FFQs, diaries must be paired with measured values of mean concentrations of HCAs to obtain individual-level estimates of intake. As with FFQs, there has been little previous work examining the comparability of diary-based estimated HCA intake with other methods.

Biomarkers reflect the body burden from exposure without the measurement error introduced from self-reported dietary intake (Cantwell et al. 2004). HCA biomarkers likely have high specificity for the dietary route, because diet is the major source of HCA exposure (Sugimura et al. 2004). Urinary concentration of one of the most mass-abundant HCAs, 2-amino-1-methyl-6-phenylimidazo[4,5*b*]pyridine (PhIP) and its metabolites, is sensitive to increases in dietary PhIP as demonstrated in controlled feeding studies (Reistad et al. 1997; Stillwell et al. 1997; Kulp et al. 2000; Friesen et al. 2001; Strickland et al. 2002). Urinary PhIP and its metabolites have been detected at background levels in populations on unrestricted diets (Ushiyama et al. 1991; Kidd et al. 1999). One of the limitations of urinary PhIP for estimating long-term exposure indicative of cancer risk is its short half-life (less than 12 h) (Boobis et al. 1994; Turteltaub et al. 1999). Although multiple days of urine samples can be used to estimate usual exposure, such as diaries, this can present issues of participant burden and compliance. While longer-term HCA biomarkers (e.g. DNA, hemoglobin, albumin adducts, hair levels) are more likely to capture the more relevant exposure period in epidemiologic studies of cancer, these methods are not yet adequately sensitive, reliable, or feasible for such studies (Magagnotti et al. 2000; Turesky and Le 2011).

Recognising the importance of HCA exposure classification for evaluating linkages with cancer and the limited availability of evaluative data, we conducted a multi-day, multi-method study comparing repeated measures from an FFQ, diary and urinary biomarker, using PhIP as a representative compound.

## Materials and methods

### *Study design*

Details on the study design have been presented previously (Deziel et al. 2011). In brief, 36 participants

(24 women, 12 men) were included in this study. They were recruited between October 2004 and October 2005 from controls in a case-control study of colorectal adenoma at the Johns Hopkins University and included residents of urban, suburban, and rural areas in Maryland, Virginia, and Pennsylvania. Smokers, people who lived with smokers and people with potential for substantial exposure to smoke during occupational or recreational activities were excluded to minimise potential for non-dietary exposure to HCAs. Smoking status was based on self-report and verified with urinary cotinine.

### *Data and sample collection*

At entry (baseline) and approximately 9 months later (follow-up), participants completed a meat-specific FFQ that included photographs and questions about meat intake, cooking method and degree of doneness (Sinha et al. 2005). At 1, 5 and 9 months after baseline, participants completed 1-day diet diaries. Participants recorded in the diaries all food items eaten that day as well as cooking method and degree of doneness for meats consumed (Cantwell et al. 2004). At the end of the same day that the diary was completed, participants collected urine samples that included the last urine void of the evening through and including the first morning void. Due to availability of overnight courier services and laboratory personnel, diary completion and urine collection were restricted to days other than Friday or Saturday. Participants stored the urine specimens in insulated shippers with frozen ice packs and returned them via overnight courier with the completed diaries on the day of the first morning void. When received, the urine samples were aliquotted, and stored at  $-80^{\circ}\text{C}$ . After all collections were complete, the samples were transferred to a  $-20^{\circ}\text{C}$  freezer until analysis (total maximum storage time 2.5 years).

### *Assessment of meat and PhIP intake from FFQs and diaries*

Daily intake of meat (g/day) was assessed from the meat-specific FFQs and diet diaries. The FFQ responses were entered into a database with validation checks. The diet diaries were coded and analysed using Nutrition Data System for Research© v. 2006 (Schakel et al. 1988). The daily number of servings of each type of meat (hamburger, steak, bacon, sausage, pork chop, chicken) from each FFQ was multiplied by the number of grams of that type of meat per serving and summed to obtain the total number of grams of meat consumed daily. For the diet diaries, the number of servings of meat consumed, including main dishes and side dishes, was multiplied by the grams per serving and summed.

Daily intake of PhIP (ng/day) was estimated using the meat-specific FFQs and diet diaries coupled with the NCI Computerized Heterocyclic Amines Resource for Research in Epidemiology of Disease (CHARRED) v.1.7 (Sinha 2002). Daily intake of each type of meat cooked via a particular method and to a particular degree of doneness from the FFQs or diet diaries was multiplied by the corresponding measured concentration of PhIP in the CHARRED database. To obtain total PhIP intake (ng/day), the daily intakes of PhIP for each combination of meat type, cooking method and degree of doneness were summed. If a type of meat reported on a diary was not available in the CHARRED database, it was coded as the most similar meat according to the CHARRED conversion manual (National Cancer Institute 2006). Because data on concentrations of fish were not available in CHARRED and, therefore, we could have underestimated PhIP intake in fish eaters, analyses were conducted with and without participants who consumed fish that was broiled, grilled or fried, cooking methods known to form PhIP (Sugimura et al. 2004).

#### *Assessment of urinary PhIP*

Urine samples were analysed for total PhIP (parent compound and deconjugated metabolites) by high performance liquid chromatography with laser-induced fluorescence detection (HPLC-LIF). In developing the method, urine samples were spiked with PhIP standard (Toronto Research Chemicals, North York, Ontario, Canada) to confirm retention time. The identity of the PhIP peak was confirmed by pooling peaks from multiple HPLC runs and using synchronous fluorescence spectroscopy to compare the fluorescence spectrum of the pooled sample to the PhIP standard (Strickland et al. 2001). The HPLC-fluorescence method was previously found to be in good agreement with gas chromatography–mass spectrometry (Strickland et al. 2001).

Total PhIP was measured to improve method sensitivity and to obtain our best estimate of intake. Prior to analysis, samples were acid-hydrolysed to deconjugate PhIP from glucuronic acid or sulphate and processed with solid phase extraction and immunoaffinity chromatography as previously described (Strickland et al. 2001). Immunoaffinity columns were filled with 0.4 ml CNBr-activated Sepharose 4B (Sigma, St. Louis, MO, USA) coupled with monoclonal antibody 4F5 that recognises PhIP (Kidd et al. 1999). Five  $\mu$ l of the immunopurified sample were injected into an HPLC system (flow rate of 5  $\mu$ l/min) consisting of a Rheodyne injector with a 5- $\mu$ l loop, Agilent 1100 series pumps, a Picometrics Zetalif laser-induced detector (P/N1701-201) with a Series

56 helium-cadmium Omnichrome laser (325 nm). Separation was achieved with a Zorbax SB C<sub>18</sub> (5  $\mu$ m) 150  $\times$  0.5 mm column. The sample was eluted using a linear gradient of acetonitrile (ACN) and water (25–30% ACN over 20 min) followed by column cleaning steps. Area under the peak was determined by manually integrating the peaks (retention time 13.6–13.9 min) using ChemStation Software Rev. A.08.04 (Agilent Technologies, Germany).

To determine the method limit of detection (LOD), urine specimens containing little or no measurable PhIP were spiked with a PhIP standard solution (Toronto Research Chemicals, Inc.) to achieve final concentrations of 2 pg/ml ( $n=6$ ), 4 pg/ml ( $n=10$ ), and 8 pg/ml ( $n=10$ ). These spiked concentrations were selected to be in the range of one to five times the expected LOD. The LOD was calculated by multiplying the standard deviation of the spiked samples by the Student's  $t$ -value corresponding to 99% confidence and  $n-1$  degrees of freedom. The limit of detection (LOD) was determined to be 3 pg/ml based on the standard deviation at 2 pg/ml concentration. The coefficient of variation of the entire method (extraction and analysis) was 17% at 4 pg/ml and 20% at 8 pg/ml.

#### *Assessment of urinary creatinine*

All urine specimens were analysed for creatinine concentration by Hagerstown Medical Laboratories (Hagerstown, MD, USA). Then, 500  $\mu$ l aliquots were evaluated using an automated colorimetric process based on a modified Jaffé reaction using a Dade Behring analyser (Dade Behring, Newark, DE, USA) (Larsen 1972). The LOD was 5 mg/dl.

#### *Statistical analysis*

Both parametric and non-parametric techniques were used in this study. PhIP intake variables were natural log-transformed for all parametric analyses. To avoid losing data during natural logarithm transformation due to a relatively high prevalence of intake values of zero or below the LOD, values of zero for PhIP intake based on the diary or FFQ were assigned a value of 0.1 ng based on half the reported LOD for measuring PhIP (0.2 ng/g) in 1 g of food (Kazerouni et al. 2001). Urinary PhIP concentrations below the detection limit were substituted with LOD/2. For non-parametric analyses, values of zero PhIP intake based on the diary and FFQ were retained as zeros, and LOD/2 was substituted for urinary PhIP values below the LOD.

The repeatability of the HCA intake estimates from the three methods (FFQ, diary and urinary PhIP) was determined by calculating the intraclass correlation coefficient (ICC) with within-subject ( $\sigma_{WS}^2$ ) and between-subject ( $\sigma_{BS}^2$ ) variance components obtained

from mixed-effects models with natural logarithm-transformed PhIP intake as the outcome variable and no fixed effects included. A uniform correlation structure was used to account for the repeated collections on the same subject. To examine the impact of imperfect reliability of the measurement of PhIP intake on the assessment of risk in a hypothetical case-control study, a hypothetical observed odds ratio ( $OR_{obs}$ ) was calculated assuming a single sample was used to estimate PhIP intake and assuming a true odds ratio ( $OR_{tr}$ ) of 2.0 (Equation (1)) (Alaejos et al. 2008; Rappaport and Kupper 2008):

$$OR_{obs} = \exp[\ln OR_{tr} / (1 + \sigma_{WS}^2 / \sigma_{BS}^2)] \quad (1)$$

The relationships among PhIP intake estimates from the three methods (FFQ, diary and urinary PhIP) were evaluated using non-parametric techniques. Spearman correlation coefficients were computed among meat or PhIP intake estimated using the mean intake from the FFQs, diet diaries and creatinine-adjusted and unadjusted urinary PhIP. Due to the high prevalence of zero values for PhIP intake from the diary, Spearman correlation coefficients were assessed for all participants as well as for a subset of those who had a diary-based PhIP intake estimate greater than zero for at least one time point. We used Spearman correlation coefficients to evaluate the relationship between the longer-term FFQ-based mean PhIP intake and a metric that combined the two shorter-term methods, urinary PhIP and diary-based PhIP intake. Because the two shorter-term measures have different units (pg/ml and ng/day, respectively), we standardised the variables [(variable-mean)/standard deviation] and added them together before assessing the correlation with the FFQ. We also examined whether there were observable differences in PhIP intake based on urinary PhIP concentrations or diaries across tertiles of FFQ subgroups using a non-parametric trend test for comparison. All analyses were conducted with Stata 11 (Statacorp; College Station, TX, USA ©2007).

## Results

PhIP intakes estimated from each of the three methods are summarised in Table 1. The median (of the individual mean values) PhIP intake for the FFQ and diary methods were 32 (range: 0–368 ng/day) and 0 ng/day (range: 0–630 ng/day), respectively. The diary was relatively insensitive to detecting PhIP intake (20%) relative to the FFQ (96%). The median creatinine unadjusted and adjusted urinary PhIP concentration (of individual mean values) from the three collection periods were 3.42 pg/ml (range: < LOD to 35.6 pg/ml) and 7.23 ng/g (range: < LOD to 37.4 ng/g), respectively. PhIP was detectable in 56% of the urine samples.

The within-subject variability in intake estimates for all three methods far exceeded the between-subject variability, yielding ICCs less than 0.5 (Table 2). The FFQ was administered twice 9 months apart and, of the three methods, was the most reliable for estimating PhIP intake, though modest (ICC = 0.30, 95% confidence interval [−0.02, 0.57]); Spearman correlation between two FFQs = 0.50,  $p = 0.02$ ). The urinary biomarker, which was measured three times over 9 months, was the least reliable method of PhIP intake (ICC = 0.01, 95% confidence interval [−0.16, 0.23]). However, the reliability improved substantially with creatinine-correction (ICC = 0.15, 95% confidence interval [−0.04, 0.38]). These low ICCs indicate that use of a single collection of any of these metrics in a case-control study would substantially attenuate the observed OR (Table 2). For example, using a single FFQ to estimate PhIP intake in a study population in which the true OR is 2.0, the observed OR would be 1.2.

Examining the associations across all three methods, the mean diary PhIP intake and the mean urinary PhIP concentration achieved significance only when restricting the analysis to those with at least one non-zero intake estimate from the diary ( $n = 15$ ,  $r = 0.75$ ,  $p = 0.001$ ; Figure 1b). No association was observed when all participants were included ( $n = 36$ ,  $r = 0.18$ ,  $p = 0.28$ ; Figure 1a). Fifteen of the 21 participants (71%) with diary-based mean PhIP intake of zero had measurable urinary PhIP at one or more time points (Figure 1a). Mean PhIP intake estimated from the FFQ was not correlated with mean urinary PhIP levels ( $r = 0.20$ ,  $p = 0.23$ ) nor mean PhIP intake estimated using the diary ( $r = 0.17$ ,  $p = 0.32$ ), but was modestly correlated with a metric that combined urinary and diary-based PhIP ( $r = 0.30$ ,  $p = 0.08$ ) (Table 3). Meat consumption (diary and FFQ reported) was not associated with mean urinary PhIP concentrations. We also looked for associations across methods by aggregating the individual-level data into tertiles with no positive trend data evident (Table 4). Analysis with and without participants who consumed fish that was broiled, grilled or fried did not yield appreciable differences in results, so all fish eaters were retained in the analyses. Correlations were of similar magnitude and statistical significance with creatinine-adjusted PhIP and, therefore, only correlations with unadjusted PhIP are presented.

## Discussion

We used a repeated measures design to evaluate the repeatability and comparability of three different methods for assessing dietary exposure to HCA: FFQ, diary and the urinary biomarker PhIP. We observed relatively high within-subject variability in

Table 1. Estimated mean PhIP intake among 36 participants.

Intake metric	# of Collections	% >0 or LOD <sup>a</sup>	Minimum	Median	IQR	Maximum
PhIP intake from baseline FFQ (ng/day)	1	97	0	26	(12, 90)	229
PhIP intake from follow-up FFQ (ng/day)	1	94	0	33	(13, 91)	508
Mean PhIP intake from FFQ <sup>b</sup> (ng/day)	2	96	0	32	(15, 101)	368
Mean PhIP intake from diaries <sup>b</sup> (ng/day)	3	20	0	0	(0, 69)	630
Mean urinary PhIP <sup>b</sup> (pg/ml)	3	56	1.06	3.42	(2.19, 6.36)	35.6
Mean creatinine adjusted urinary PhIP <sup>b</sup> (ng/g)	3	56	1.12	7.23	(2.46, 17.0)	37.4

Notes: <sup>a</sup>Percentage of all individual collections that were either greater than zero or the limit of detection (LOD).

<sup>b</sup>We took the mean of the repeated measures for each intake metric and calculated the distribution of the means.

FFQ, food frequency questionnaire; IQR, inter-quartile range; LOD, limit of detection; PhIP, 2-amino-1-methyl-6-phenylimidazo[4,5*b*]pyridine.

Table 2. Intraclass correlation coefficients (ICC) and associated potential attenuation of odds ratios in a hypothetical case-control study.

Intake metric <sup>a</sup>	ICC <sup>d</sup> (95% CI)	OR <sub>obs</sub> if OR <sub>tr</sub> = 2.0 <sup>e</sup>
FFQ (ng/day) <sup>b</sup>	0.30 (−0.02, 0.57)	1.23
Diary (ng/day) <sup>b</sup>	0.20 (0.00, 0.42)	1.15
Urinary PhIP concentration (pg/ml) <sup>c</sup>	0.01 (−0.16, 0.23)	1.01
Creatinine adjusted urinary PhIP concentration (ng/g) <sup>c</sup>	0.15 (−0.04, 0.38)	1.11

Notes: LOD, limit of detection; OR<sub>obs</sub>, observed odds ratio; OR<sub>tr</sub>, true odds ratio;  $\sigma_{BS}^2$ , between-subject variance;  $\sigma_{WS}^2$ , within-subject variance.

<sup>a</sup>All variables natural log-transformed.

<sup>b</sup>Values of zero were assigned 0.1, corresponding to 1 g of food at 1/2 the LOD for PhIP detection in food (0.2 ng/g).

<sup>c</sup>Values below the detection limit were assigned 1/2LOD.

<sup>d</sup>ICC =  $\sigma_{BS}^2 / (\sigma_{BS}^2 + \sigma_{WS}^2)$ .

<sup>e</sup>OR<sub>obs</sub> =  $\exp[\ln OR_{tr} / (1 + \sigma_{WS}^2 / \sigma_{BS}^2)]$ .

the repeated collections for all methods and relatively weak agreement among the different methods. The current study raises important methodological considerations for future studies.

We observed PhIP intake estimates that were lower compared to those of controls in previous case-control studies that used the same methods. For example, estimated PhIP intake from the baseline (median = 26 ng/day; mean = 60 ng/day) and follow-up (median = 33 ng/day; mean = 75 ng/day) FFQs were lower than intake reported in controls in North Carolina (mean = 86.7 ng/day, *n* = 611) (Butler et al. 2003); Maryland (mean = 78.1 ng/day, *n* = 165) (Cantwell et al. 2004); Los Angeles, Seattle, Detroit, and Iowa (median = 73.8 ng/day) (Cross et al. 2006); and California (median = 92 ng/day) (Delfino et al. 2000). The lower intakes observed in the current study may be due to differences in season of ascertainment (Subar et al. 1994) or the exclusion of Fridays and Saturdays from our collection days, since meat intake tends to be higher on the weekends (Haines et al. 2003).

Similar to the FFQ-based estimates, the mean estimated PhIP intake from the diary in our study (85 ng/day) was lower than the previously reported

mean intake based on the diary (264 ng/day) (Cantwell et al. 2004). In addition to our exclusion of Fridays and Saturdays, this difference may also be due in part to the larger number of diaries collected by Cantwell et al. (12 days) relative to the current study (3 days). Owing to the large within-subject variability, the true long-term PhIP intake is likely not well-represented by 3 days of diary collections.

The concentrations of urinary PhIP in our study population were within the range of previously reported results. The mean urinary PhIP concentration in our study (5.5 pg/ml) was 80% lower than the mean observed in pre-feed levels in a controlled feeding study (30.4 pg/ml) in which participants were asked to refrain from eating charbroiled, smoked or fried meat, suggesting our study group had low well-done meat consumption (Strickland et al. 2001, 2002). However, the geometric mean (4.1 ng/g), range (<LOD to 10.4 ng/g), and percent of samples above the LOD (56%) of creatinine-adjusted urinary PhIP concentrations in our study were somewhat higher than those reported for Caucasian participants on unrestricted diets in a prior study in Los Angeles (geometric mean = 1.18 ng/g, range = <LOD to 14.7 ng/g,

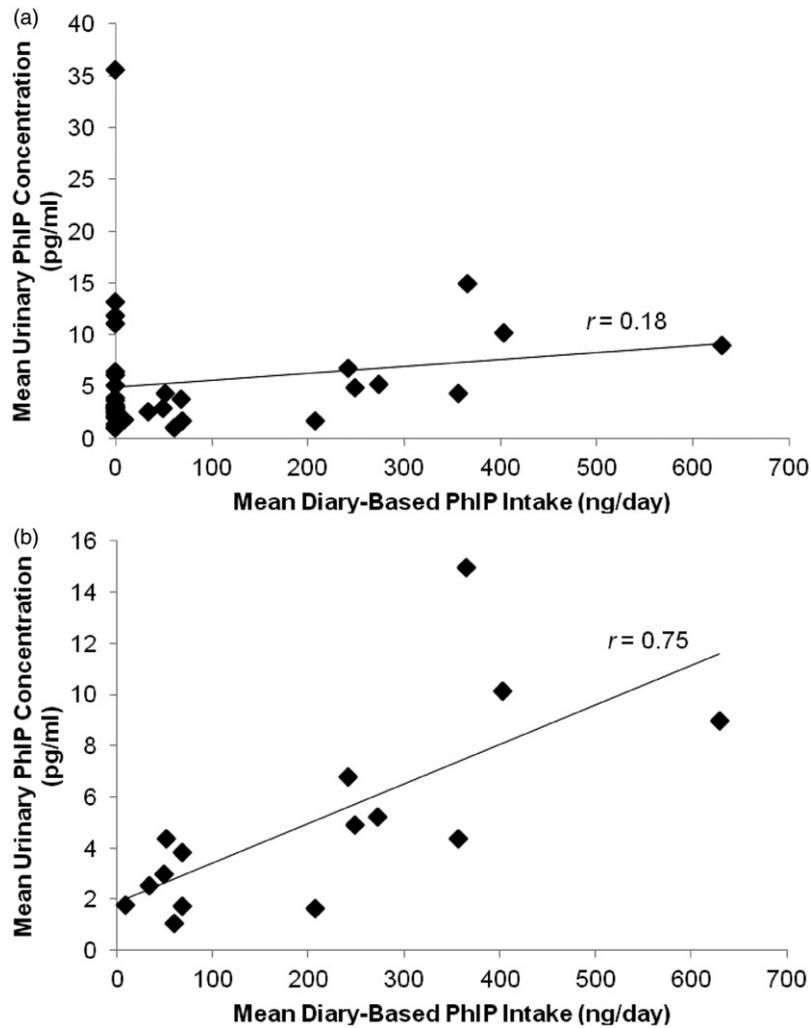


Figure 1. Correlation between diary-based PhIP intake and urinary PhIP concentration in all participants ( $n=36$ ,  $r=0.18$ ,  $p=0.28$ ) (a) and those with mean PhIP intake greater than zero ( $n=15$ ,  $r=0.75$ ,  $p=0.001$ ) (b).

Table 3. Spearman’s correlation coefficients ( $r$ ) between mean FFQ-based PhIP intake, mean urinary PhIP, mean diary-based PhIP intake, and urine and diary-based methods combined ( $n=36$ ).

	FFQ PhIP	
	$r$	$p$ -value
Urinary PhIP	0.20	0.23
Diary-RD	0.17	0.32
Combined metric <sup>a</sup>	0.30	0.08

Note: <sup>a</sup>Combined metric = [(Individual Estimate - Overall Mean)/Overall Standard Deviation]<sub>diary</sub> + [(Individual Estimate - Overall Mean)/Standard Deviation]<sub>urine</sub>.

and % > LOD = 21%) (Kidd et al. 1999). The median (0.43 ng) and range (0.080–23 ng) of the mass of PhIP excreted in our approximately 8–12-h samples were similar to the median (0.31 ng) and range (0.12–2.0 ng)

reported in 24-h urine samples in 10 healthy volunteers in Japan who were on unrestricted diets (Ushiyama et al. 1991).

We observed high within-subject variability in the PhIP intake estimates across all methods (ICC of 0.20, 0.30, and 0.15 for FFQ, diary, and creatinine-adjusted biomarker, respectively), which will substantially attenuate observed ORs if a single measurement is used in an epidemiologic study. The ICC of 0.30 for PhIP intake based on the FFQ was similar to the ICC of 0.36 reported for two dietary interviews asking about fried meat intake over the prior year, administered 4–7 years apart (Knekt et al. 1994). We previously assessed the repeatability of the urinary biomarker 1-hydroxypyrene glucuronide (1-OHPG), an indicator of exposure to the dietary carcinogens polycyclic aromatic hydrocarbons (PAHs), in the same study population (Deziel et al. 2011). The repeatability was higher for 1-OHPG concentration (ICC = 0.37) than that of PhIP (ICC = 0.01), possibly because PAHs

Table 4. Median urinary PhIP and diary based PhIP intake by tertiles of PhIP intake (low, medium, high) based on FFQs.

	Low (median = 13 ng/day)	Medium (median = 32 ng/day)	High (median = 129 ng/day)	<i>p</i> -value (trend) <sup>a</sup>
Median of mean urinary PhIP (pg/ml)	2.89	3.39	4.63	0.11
Median of mean creatinine adjusted urinary PhIP (ng/g)	3.66	11.4	12.8	0.18
Median of mean diary-based PhIP intake (ng/day)	0	4.72	0	0.63

Note: <sup>a</sup>Non-parametric test for trend across ordered groups.

are found in a wider variety of foods. In contrast to the current study, we previously observed that creatinine-adjustment decreased the repeatability of the 1-OHPG concentration (ICC=0.15 for creatinine-adjusted 1-OHPG). These contradictory findings add to the discussion about the utility of and approach for creatinine adjustment (Barr et al. 2005). The large within-subject variability in consumption of PhIP-containing foods highlights the challenges in dietary exposure assessments and provides justification for the use of a repeated measure approach or development and use of longer-term biomarkers, such as protein adducts or hair PhIP (Kobayashi et al. 2007; Bessette et al. 2009).

We did not observe an association between any of the three exposure methods examined separately when the full study population was considered. A previous study observed a modest correlation between FFQ and diary-based estimates of PhIP intake (Pearson's  $r=0.22$ , 95% confidence interval: 0.07–0.36) (Cantwell et al. 2004). Two studies were identified that compared an FFQ against biomarker measurements. In a study of 129 men, Kidd et al. (1999) observed that the odds of having detectable urinary PhIP was not different in individuals with higher frequencies of intake of various meats compared to those with lower frequency of intake. This study only used a single urine sample to compare with the biomarker, and the FFQ did not ask participants to report on meat cooking method or degree of doneness. Kobayashi et al. (2007) observed a Spearman correlation coefficient of 0.47 ( $p=0.036$ ) between PhIP intake based on an FFQ and PhIP measured in hair among 20 volunteers.

We did observe a modest association between mean PhIP intake based on the FFQ and a metric that combined PhIP intake based on the diary and urinary PhIP measurements. If the biomarker-based and survey-based methods to assessing PhIP intake are indeed capturing different time periods or sources of exposure, using HCA biomarkers in combination with survey-based methods could potentially reduce some of the uncertainty in HCA intake estimates in epidemiologic studies (Freedman et al. 2010). For example, Peters et al. (2003) used urine mutagenicity in combination with an FFQ and observed a stronger

relationship with cancer risk than when using either method alone.

We did not observe correlations between meat intake and urinary PhIP, though we had observed an association between meat intake and urinary 1-OHPG concentration in our previous analysis of PAHs (Deziel et al. 2011). This may be because PhIP formation is more specific to meat preparation methods that involve direct and/or efficient transfer of heat, such as broiling, grilling or frying at high temperatures and/or long cooking times (Skog 2002). We expected a positive correlation between diary-based PhIP and urinary PhIP measurements in the full study population because these two methods reflected a similar time period. Furthermore, we observed such a correlation for the PAH benzo[*a*]pyrene in our previous analysis in this population (Deziel et al. 2011). We observed several participants with diary-based PhIP intake of 0 ng/g, but detectable urinary PhIP concentrations at concurrent collections. There are many plausible explanations for the lack of correlation. Firstly, the diary and database may not capture all foods contributing to exposure. While we focused only on meats, there have been some reports in the literature that certain non-meat foods, such as smoked cheeses (Naccari et al. 2009), beer (Manabe, Suzuki et al. 1993), and wine (Manabe, Suzuki et al. 1993), contain HCA, though their contribution to total exposure is likely minimal.

Secondly, in addition to only including meat-based foods, the FFQ, diary and database did not include information on factors related to cooking preparation that can influence the concentrations of PhIP in food. For example, increasing the frequency of flipping meat during cooking can reduce the formation of PhIP (Salmon et al. 2000). Use of marinades may increase or decrease the formation of PhIP, depending on the components of the marinade, contributing to increased variability in HCA concentrations in foods (Busquets et al. 2006).

Thirdly, it is possible that the biomarker is capturing non-dietary exposures. PhIP has been isolated in non-dietary environmental samples, such as tobacco smoke (Manabe et al. 1991), cooking smoke (Thiebaud et al. 1995), and diesel exhaust (Manabe, Kurihara et al. 1993). The relative contribution of these other sources

to total exposure is likely minimal. Furthermore, our selection criteria aimed to exclude people with potentially high exposure to these other sources.

Finally, inter-individual differences in toxicokinetics may account for some of the variability in the relationship between PhIP intake estimated from the diaries relative to PhIP urine levels. For example, in two controlled feeding studies, participants consuming the same preparation of cooked meat had urinary PhIP concentrations that varied 2.7-fold (Strickland et al. 2002) and 4.2-fold (Reistad et al. 1997). Additionally, since urinary PhIP is actually reflecting the balance of activation and detoxification pathways, the levels of excretion of PhIP conjugates may be affected by other dietary constituents, such as the amount of fruits and vegetables consumed (Murray et al. 2001; Walters et al. 2004).

Strengths of this study encompassed the multiple methods included and the repeated measures design. However, we were limited by a relatively small sample size, the infrequent consumption of PhIP containing foods, and the low detection rates of urinary PhIP. Our study could have been strengthened by incorporating a more robust analytical technique, such as liquid chromatography–tandem mass spectrometry, potentially yielding increased detection rates in our urine samples and an improved ability to compare methods. Also, additional diary and urine collections may be needed to make a fair comparison, given the episodic nature of PhIP consumption. We recognise the collection and analysis of duplicate diet samples as another strategy for directly measuring PhIP dietary exposure; however, this approach was not feasible in the context of the current investigation due to cost and participant burden. Although duplicate diet has some of its own limitations (in addition to cost and burden, there is potential for bias in foods provided for the duplicate diet), it is considered the “gold standard” for dietary exposure and therefore would be a useful method to include in future studies.

Our objective was to compare commonly used approaches for estimating PhIP intake in epidemiologic studies. Among the methods tested, there is no clear gold standard, making the poor associations observed across the three methods difficult to interpret. In general, this lack of association may be an indication of the uncertainty with which these measures are made and the need for additional research to improve assessment methods. Alternatively, the lack of association may be a reflection of the different time windows of exposure being captured by each method, rather than a flaw in any single method. Even the timing of the concurrently collected urinary PhIP concentrations and the diary-based PhIP intake may not be optimal. The very short half-life of PhIP (less than 12 h) suggests that foods consumed early in the day of

collection may not be captured by the PhIP measured in the last evening void.

This study provides insight into the interpretation of previous epidemiologic findings, suggesting that reported risk estimates, using a single FFQ to estimate exposure, could be substantially attenuated due to relatively large errors in exposure classification. The current study highlights concerns about the repeatability of current methods for assessing the episodically consumed HCA PhIP. Incorporation of repeated measures or a combination of methods in future studies could address this issue. In addition, development of a well-validated, widely applicable, longer-term biomarker for assessing dietary exposure would be useful.

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