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Technical Basis Document

A Statistical Basis for Interpreting Urinary Excretion of Plutonium Based on Accelerator Mass Spectrometry (AMS) Data from the Marshall Islands

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A Statistical Basis for Interpreting Urinary Excretion of Plutonium Based on Accelerator Mass Spectrometry (AMS) for Selected Atoll Populations in the Marshall Islands

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SUMMARY

We have developed refined statistical and modeling techniques to assess low-level uptake and urinary excretion of plutonium from different population group in the northern Marshall Islands. Urinary excretion rates of plutonium from the resident population on Enewetak Atoll and from resettlement workers living on Rongelap Atoll range from <1 to 8 μBq per day and are well below action levels established under the latest Department regulation 10 CFR 835 in the United States for *in vitro* bioassay monitoring of ^{239}Pu (Hamilton et al., 2005). However, our statistical analyses show that urinary excretion of plutonium-239 (^{239}Pu) from both cohort groups is significantly positively associated with volunteer age, especially for the resident population living on Enewetak Atoll. Urinary excretion of ^{239}Pu from the Enewetak cohort was also found to be positively associated with estimates of cumulative exposure to worldwide fallout. Consequently, the age-related trends in urinary excretion of plutonium from Marshallese populations can be described by either a long-term component from residual systemic burdens acquired from previous exposures to worldwide fallout or a prompt (and eventual long-term) component acquired from low-level systemic intakes of plutonium associated with resettlement of the northern Marshall Islands, or some combination of both.

INTRODUCTION

Researchers from the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory (LLNL) have recently developed a new technology for low-level detection and measurement of heavy elements based on accelerator mass spectrometry (AMS) (Brown et al., 2004). The accelerator mass spectrometry (AMS) system has a detection sensitivity of < 1 μBq for plutonium-239 (^{239}Pu) (Brown *et al.*, 2004; Hamilton *et al.*, 2004) and is currently being used for routine analysis of plutonium bioassay samples collected from potentially exposed populations in the northern Marshall Islands (Hamilton *et al.*, in preparation). Under an approved protocol, over 400 individual bioassay samples have been collected under the Marshall Islands Urinalysis Program over the last five years and analyzed for plutonium isotopes using AMS. All sample analyses were performed on 24-h void urine samples collected under carefully controlled conditions and analyzed for plutonium-239 (^{239}Pu) and plutonium-240 (^{240}Pu) with accompanying field blanks.

This technical basis document describes statistical and modeling methods developed to aid interpretation of plutonium urinary excretion data based on high-quality AMS measurements, and the corresponding results obtained by applying these methods to data obtained under the Marshall Islands Urinalysis Program at LLNL. The study was undertaken specifically to determine whether elevated levels of plutonium excretion could be observed in different cohort population groups, if such elevations exhibit any age- or gender-related patterns, and identify how such patterns may relate to (1) cumulative exposure to

historical worldwide fallout; (2) occupational exposure of workers engaged in cleanup activities or agricultural practices; or (3) long-term chronic exposure of resident atoll populations in the Marshall Islands.

METHODS AND PROCEDURES

Bioassay samples were collected from two separate cohorts: (1) a relative homogenous group of Marshallese living on Enewetak Island (Enewetak Atoll), and (2) a heterogeneous group of adult male contract workers, of mostly Marshallese decent, engaged in cleanup and rehabilitation programs on Rongelap Island (Rongelap Atoll). Associated fields blanks were prepared using identical methods except for the substitution of 18 Megohm deionized H_2O for urine. An outline of the samples analyzed by data group is shown in Table 1. A full description of the sample collection and measurement techniques used for low-level bioassay measurements of plutonium isotopes by accelerator mass spectrometry will be given elsewhere (Hamilton *et al.*, in preparation).

Table 1. Summary of ^{239}Pu bioassay samples from Enewetak and Rongelap participants.

Atoll group	Source	Number of samples	Number of volunteers	Volunteer Age (y)[a]		
				Median	Minimum	Maximum
Enewetak	Field Blank[a]	29	N/A	N/A	N/A	N/A
	Female	83	73	31.8	13	67
	Male	157	124	38.2	13	88
Rongelap	Field Blank[a]	21	N/A	N/A	N/A	N/A
	Male	167	115	36.1	18	66

[a] Field Blanks were prepared using deionized water rather than urine, but otherwise prepared and treated identically to urine bioassay samples. Volunteer ages were rounded to nearest year.

METHODS FOR STATISTICAL ANALYSIS OF AMS PLUTONIUM BIOASSAY DATA

A total of 457 sample measurements (including field blanks) with associated uncertainties were used in the statistical analyses. The uncertainties of each measurement were propagated from the combined uncertainty of the individual bioassay measurement and those of the associated reagent blanks and AMS target background counts. For each set of plutonium measurement data described, traditional parametric and nonparametric tests for comparisons were not directly applicable because of the heterogeneous nature of individual measurement errors and relative errors. Moreover, multiple bioassay samples were collected from single participants from each population group. For each such individual, a corresponding weighted average value; $x_j = W_j^{-1} \sum_{i=1}^{n_j} w_i x_{i,j}$ was calculated with $W_j = \sum_{i=1}^{n_j} w_i$, where $w_i = s_{i,j}^{-2}$ for reported measurement errors $s_{i,j}$.

Volunteer participants on Enewetak and Rongelap Atolls were grouped by age into three age ranges corresponding to three divergent (low, medium and high) levels of estimated relative exposure to historical levels of fallout due to atmospheric nuclear testing. To this end, annual Northern hemisphere deposition of ^{137}Cs produced in atmospheric nuclear testing (Figure 1; UNSCEAR, 2000) were used to estimate cumulative ^{239}Pu exposure that might account in some part for any observed accumulation of elevated ^{239}Pu levels in urine as a function of age, by integrating the area under the function plotted in Figure 1 from birth to the date of urine sampling for each volunteer. Activity ratios of $^{239+240}$Pu to ^{137}Cs measured at various locations in the Northern hemisphere during and subsequent to atmospheric testing are known to have remained fairly constant at about 1% (Perkins and Thomas, 1980). Although ^{137}Cs fallout levels varied substantially by latitude during and beyond this period, the patterns over time at different latitudes were approximately proportional (UNSCEAR, 2000) and serve as a meaningful estimate of potential ^{239}Pu exposure due to worldwide fallout. Inhalation would have accounted for ~95% of urinary ^{239}Pu partitioning from blood concentrations that arise primarily from concentrations of ^{239}Pu in stored bone, kidney and liver (Martin and Bloom, 1980).

Intra-individual variation among corresponding deviations $d_{i,j} = x_{i,j} - x_j$ was compared to inter-individual variation among combined age-group-specific deviations $d_{h\neq i} = x_{h\neq i} - \bar{x}$ between remaining non-replicate measures $x_{h\neq i}$ and each corresponding, age-group-specific weighted mean value $\bar{x}$, using a compound, semi-parametric version of the usual nonparametric Wilcoxon test for variance homogeneity. Whereas the standard Wilcoxon mean-homogeneity test assigns ranks to the ordered set of combined, ordered sample values from each of two sources (Lehman and D'Abrera, 1975), the test for unequal dispersion assigns a rank of 1 to the lowest of these sample values, but then assigns each adjacent pair of ranks in alternating fashion to corresponding pairs of values that are first lowest, then

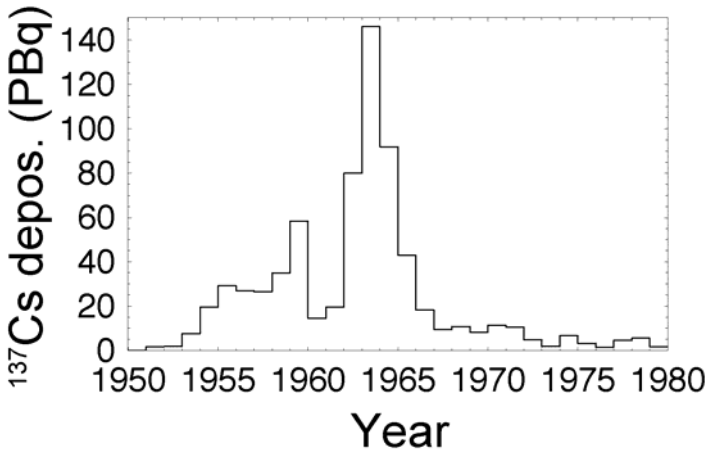

Figure 1. Annual Northern hemisphere deposition of ^{137}Cs produced in atmospheric nuclear testing (UNSCEAR, 2000). Cumulative ^{239}Pu exposure that may partially explain observed accumulation of elevated ^{239}Pu in urine as a function of age was estimated by (exact) integration of the area under the plotted function, from birth to the date of urine sampling for each participant.

highest, then next lowest, etc. The compound, semi-parametric version of the standard variance test was implemented by nested Monte-Carlo sampling of 100 sets each of $d_{i,j}$ and $d_{h\neq l}$ from linearly smoothed versions of their respective empirical distribution functions, and each deviation d in each of the sample sets was itself sampled 10 times assuming $d \sim N(d, s^2)$ in which s is the reported measurement error corresponding to d. The total of 1000 p-values assessing the likelihood of equal inter- verses intra-individual dispersion thus generated were sorted to evaluate the null hypothesis that $X=Y$.

Because less intra- than inter-individual variance was observed (see under Results), each set of n_j multiple measures $x_{i,j}$ obtained for a jth individual were replaced by its corresponding single weighted average value x_j defined above, and each corresponding set of reported measurement errors $s_{i,j}$ was likewise replaced by a single estimate s_{wj} of the standard error of the weighted mean x_j, where: $s_{wj}^2 = \text{Max}(s_x[n_j/(1+\gamma_w^2)]^{-1/2}, s_{\text{min}})$, s_x is the sample variance of $x_{i,j}$, γ_w is the sample coefficient of variation (i.e., standard deviation divided by the mean) of weights w_i, and (to avoid spuriously low s_{wj}^2 values) $s_{\text{min}} = \text{Min}(s_{i,j})$ over all i and j.

The Mann-Whitney version of the Wilcoxon test referred to above was modified to compare one set of measures x_i (i = 1,...,n_x) of X to another set y_j (j = 1,...,n_y) of Y, conditional on each k^{th} measure z_k (for $z = x$ or $z = y$) being normally distributed as $\sim N(z_k, s_{z,k}^2)$, where $s_{z,k}$ is the k^{th} corresponding reported measurement error. To implement this compound Mann-Whitney test by nested Monte Carlo sampling, a linearly smoothed version of the sample distribution function (F_x) for x_i, and a similar function (F_y) for y_j, were used to draw 100 sets of

{x_i*, y_j*} sample vectors each of dimension {n_x, n_y}. Each sample vector set {x_i*, y_j*} was in turn used to draw 10 new sets {$x_{i,h}$**, $y_{j,h}$**}, h = 1, ..., 10, by sampling N(x_i*, $s^2_{x,i}$) and N(y_j*, $s^2_{y,j}$) ten times for each i and j. The unbiased estimate of P = Prob(X>Y) is the area under the corresponding receiver operating characteristic (ROC) curve (Zweig and Campbell, 1993). The distribution F_P of P was estimated from 1000 P values each calculated by the usual exact ROC method (Lehman and D'Abrera, 1975) applied to a simulated set {$x_{i,h}$**, $y_{j,h}$**}. The estimate $\hat{F}_P$ was in turn used to estimate (a) the expected P-value $\hat{P}$, (b) 2-tail lower and upper 95% confidence limits on P, and (c) a 2-tail significance value Prob(X=Y) of the null hypothesis that X=Y, with the latter quantity evaluated as p = Min[2 Min[Prob(X≤0.50), Prob(Y≤0.50)], 1] as is the case for the usual Mann-Whitney or equivalent Wilcoxon rank sum test (Lehman and D'Abrera, 1975).

Sample age distributions were compared using the Kolmogorov 2-sample test (Wilcox, 1997). Sample distributions of measured ^{239}Pu levels, weighted by corresponding $1/s^2_{z,k}$ values, were compared graphically to supplement the more rigorous Monte Carlo compound Mann-Whitney test described above. Association of ^{239}Pu levels with age, and with relative fallout-Pu exposure) was assessed by weighted least-squares linear regression, using $1/s^2_{z,k}$ as weights, reporting the corresponding squared correlation coefficient (R^2) and 2-tailed significance level for non-zero slope. Regression slopes were compared using similarly weighted analysis of covariance (ANOCOVA). Additional tests for 2x2 association at each age range relative to field blank data, for overall homogeneity, and for overall trend in the fraction of elevated levels of ^{239}Pu, were done heuristically (ignoring measurement errors) using Fisher exact tests, extended Fisher exact tests (Baglivo *et al.*, 1988), and Bartholemew's trend tests (Fleiss, 1981), respectively. All calculations were done using *Mathematica* 5.0® (Wolfram, 1999) and *RiskQ* (Bogen, 2002) software. All p-values $<10^{-10}$ are reported as being ~0.

RESULTS

Comparisons of AMS ^{239}Pu measures by data group (urine sample, field blank or positive control), by island, by gender and by age are summarized in Table 1, and corresponding comparisons done using the compound Mann-Whitney test are summarized in Table 2. Figure 2 shows estimated relative levels of cumulative historical exposure to ^{239}Pu fallout due to atmospheric nuclear tests, due primarily from inhalation of suspended 239Pu, plotted as a function of participant age. This plot reveals three age ranges that correspond to the following estimates of (unitless) relative fallout on each island (listed here ±1 SDM): <35 y old (0.020 ± 0.003 for Enewetak, 0.050 ± 0.005 for Rongelap), 35-44 y old (0.403 ± 0.043 for Enewetak, 0.478 ± 0.045 for Rongelap), and ≥45 y old (0.963 ± 0.009 for Enewetak, 0.967 ± 0.011 for

Table 2. Comparison of ^{239}Pu levels in 24-h urine assessed by Monte Carlo compound Mann-Whitney test.

Group 1 (X)[a]	Wt. Mean of X (μBq)[b]	Standard Error of Wt. Mean (μBq)[b]	n_1	Group 2 (Y)[a]	P = Prob(X>Y)[c] $\hat{P}$	95% LCL	95% UCL	p = Prob(X=Y)[c]
Enewetak FB	-0.027	0.067	29					
Rongelap FB	0.001	0.030	21	Enewetak FB	0.53	0.33	0.74	0.78
All FB	-0.016	0.040	50					
Enewetak <35 y	0.046	0.17	105	All FB	0.58	0.46	0.69	0.15
Enewetak 35-44 y	0.19	0.085	41	All FB	0.67	0.51	0.81	**0.037**
Enewetak ≥45 y	0.30	0.32	51	All FB	0.70	0.57	0.82	**~0**
Enewetak M <35 y	0.062	0.21	73	All FB	0.59	0.47	0.72	0.15
Enewetak M 35-44 y	0.24	0.11	20	All FB	0.64	0.44	0.83	0.16
Enewetak M ≥45 y	0.24	0.49	31	All FB	0.70	0.52	0.85	**0.030**
Enewetak F <35 y	0.025	0.28	32	All FB	0.56	0.41	0.72	0.42
Enewetak F 35-44 y	0.17	0.13	21	All FB	0.67	0.49	0.84	0.074
Enewetak F ≥45 y	0.41	0.28	20	All FB	0.72	0.53	0.88	**0.048**
Rongelap <35 y	0.044	0.12	51	All FB	0.60	0.46	0.75	0.14
Rongelap 35-44 y	0.18	0.15	42	All FB	0.68	0.54	0.82	**0.012**
Rongelap ≥45 y	0.10	0.52	22	All FB	0.70	0.50	0.88	0.054
All Control	0.16	0.19	22	All FB	0.71	0.53	0.87	**0.028**

[a] A name and (as applicable) age range (in y) are listed for each data group. M = male; F = Female; FB = field blanks (samples of double-distilled H_20 rather than urine, but otherwise prepared and treated identically to urine samples); Control = urine samples obtained from >5 Marshallese individuals (primarily from Rongelap and Enewetak).

[b] Wt. mean = weighted sample mean of n_i total measures (for i = 1 or 2) using n_i corresponding values of SE^{-2} as sample weights, where SE = corresponding combined standard error of AMS sample preparation and measurement.

[c] Evaluated by Monte Carlo compound Mann-Whitney test.

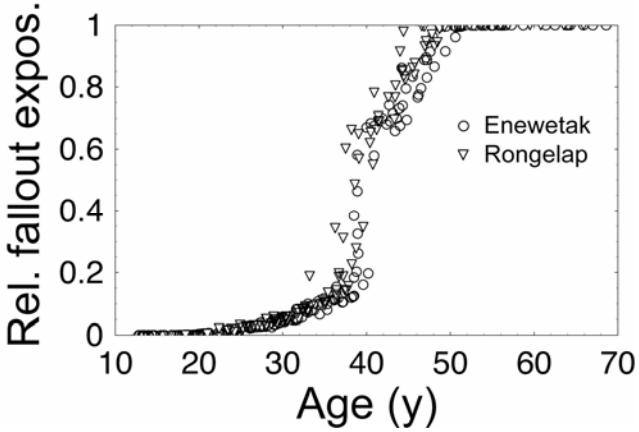

Figure 2. Cumulative respiratory exposure of program participants in the Marshall Islands to worldwide fallout contamination from atmospheric nuclear testing plotted as a function of volunteer age at the time of sample collection.

Rongelap), where 35-44 y denotes the 10-y interval at which age is ≥35 y and <45 y.

Figure 3 compares two cumulative probability mass functions (cmfs) involving differences between measured and corresponding mean ^{239}Pu levels for study participants (both islands): one "inter-individual variability" cmf of differences for 243 participants who were sampled only once (subtracting age-group-specific mean values), and one "intra-individual variability" cmf of differences between 164 measures collected on ≥2 occasions from 69 other participants (subtracting corresponding participant-specific mean values). The 243 singly sampled and 69 multiply sampled participants had mean (±1 SEM) ages of 34.6 ± 0.9 y and 38.3 ± 1.6 y, respectively; the corresponding age distributions do not differ significantly (p = 0.14, by Kolmogorov 2-sample test). The two sets of deviations (that by definition. the same weighted-mean value of 0) do not differ significantly by 2-tail compound Mann-Whitney test (p = 1). The variance of intra-individual deviations is ~57% of that of the inter-individual deviations, but this could be due to chance as assessed by compound Wilcoxon-variance test (p = 0.96).

^{239}Pu levels measured in field blanks prepared on Enewetak and Rongelap are summarized in Figure 4. As sets of field-blank measures made on each island on do not differ significantly (p = 0.78, Table 2), all field blanks were pooled in subsequent statistical comparisons. Estimated likelihoods $\hat{P}$ that ^{239}Pu measures from participants' urine samples are greater than those from combined field blanks are listed in column 6 of Table 2. The sets of age-specific likelihood estimates obtained for each island, and those obtained for each sex on Enewetak, in each case increase by age across the three age groups considered.

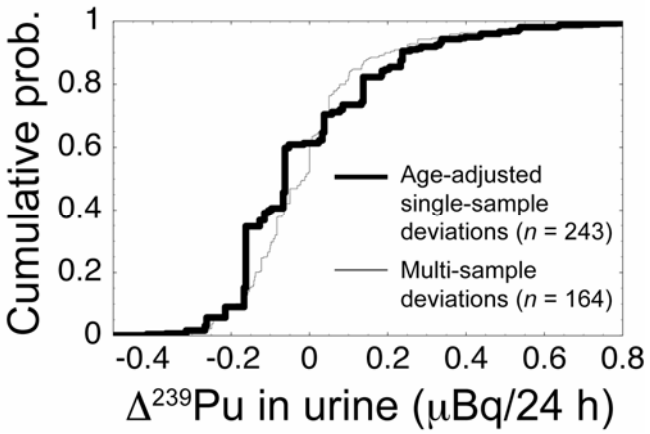

Figure 3. Empirical cumulative probability mass functions (cmfs) for deviations between measures of ^{239}Pu in urine collected only once from study participants (both islands) and their corresponding age-group-specific mean values (bold curve), and for such deviations between measures collected on ≥2 occasions from the remaining participants and their corresponding participant-specific mean values (light curve). Each cmf shown is weighted by the inverse squares of corresponding measurement errors associated with each contributing measure. The two sets of deviations have the same weighted-mean value of 0 and do not differ significantly by 2-tail compound Mann-Whitney test (p = 1). The variance of intra-individual deviations is 57% of that of the inter-individual deviations**.**

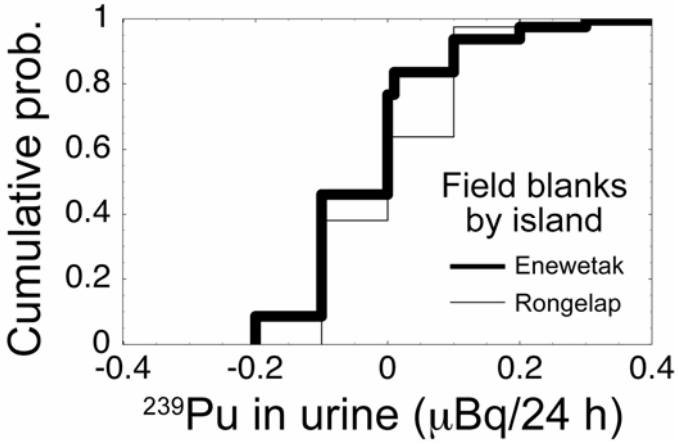

Figure 4. Empirical cumulative probability mass functions (cmfs) for ^{239}Pu measured by AMS in field blanks prepared on Enewetak (*n* = 29) and on Rongelap (*n* = 21). Each cmf is weighted by the inverse squares of corresponding measurement errors associated with each contributing measure. The two sets of measures do not differ significantly by 2-tail compound Mann-Whitney test (0.78).

The most significantly elevated ^{239}Pu measures were observed in samples from older participants (of age ≥45 y) on Enewetak compared to combined field blanks ($p = \sim 0$). However, significantly elevated levels were detected in samples from at least one age group within each of the four sets of island- and sex-specific data sets studied (see bold p-values listed in rightmost column of Table 2).

Figure 5 compares cmfs for ^{239}Pu measured in all field blanks combined with those of urine samples collected within three age groups on each island. An age-related trend is more evident for Enewetak than for Rongelap, although based on the compound Wilcoxon test, the trend for increasing ^{239}Pu is monotonically related to age on each island (Table 2). Using combined field blank data as a baseline reference group, pan-group non-homogeneity of ^{239}Pu levels and a corresponding age-related trend on both islands is also supported heuristically by Fisher exact, extended Fisher exact and Bartholomew's trend tests performed, without regard to measurement error, on the fractions of ^{239}Pu values >0.35 μBq per 24-h in each age range (Table 3).

Even when ^{239}Pu data for the youngest age group are used as the reference group (i.e., excluding field blank data from the trend analysis), a significantly positive linear trend with age is evident in the Enewetak data set (Table 3). Nearly all (>98%) of 312 individual-specific urinary ^{239}Pu levels derived from both islands were outside a range of -1 to 5 μBq. Figure 6 plots urinary ^{239}Pu levels in this range vs. age (left plot), and vs. relative exposure to fallout-^{239}Pu (right plot), for all (male and female) Enewetak donors, together with corresponding weighted linear fits. Both plots show a highly significant positive trend ($p \approx 0$). A significantly positive age-related trend in urinary ^{239}Pu was also found in corresponding data for all (male) Rongelap donors ($p = 0.00017$), but with a slope significantly less than that for Enewetak ($p = 0.0036$), and no significant association between urinary ^{239}Pu and relative fallout exposure was evident using Rongelap data ($p = 0.092$).

DISCUSSION

Under the auspices of the Office of International Health Studies, Office of Health Safety, U.S. Department of Energy, researchers from the Center for Mass Spectrometry at the Lawrence Livermore National Laboratory are providing radiological surveillance monitoring of island population groups in the northern Marshall Islands. The AMS detection system used to assess plutonium uptake and dose far exceeds the standard requirements established under the latest Department regulation 10 CFR 835 used in the United States for *in vitro* bioassay monitoring of ^{239}Pu (Hamilton *et al.*, 2007). This newly established bioassay program based on accelerator mass spectrometry clearly provides a more accurate and reliable basis to assess incremental intakes of

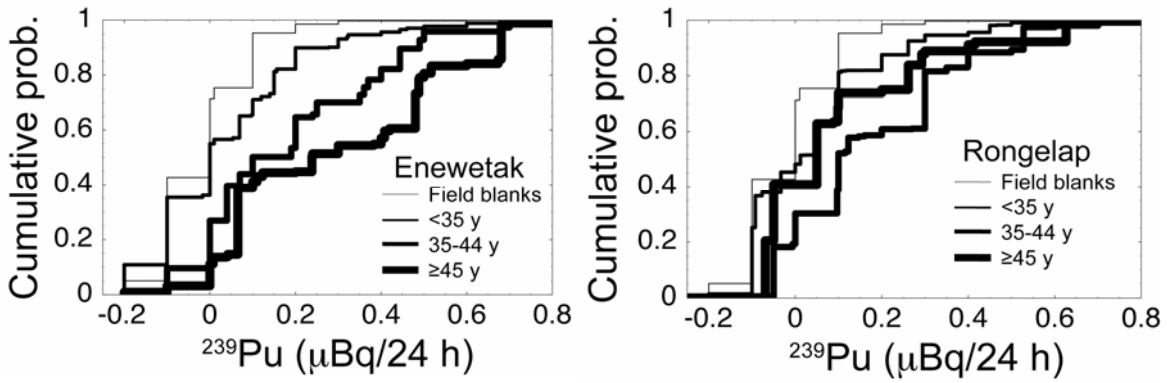

Figure 5. Empirical cumulative probability mass functions (cmfs) for ^{239}Pu measured by AMS in combined field blanks vs. that measured in urine samples collected from 194 total females and males on Enewetak (left plot), and from 115 males on Rongelap (right plot). Each cmf is weighted by the inverse squares of corresponding measurement errors associated with each contributing measure. Urinary ^{239}Pu levels are significantly elevated among all participants 35 to 44 y old on each island ($p < 0.05$), and among participants ≥45 y old on Enewetak ($p \approx 0$), by 2-tail compound Mann-Whitney test.

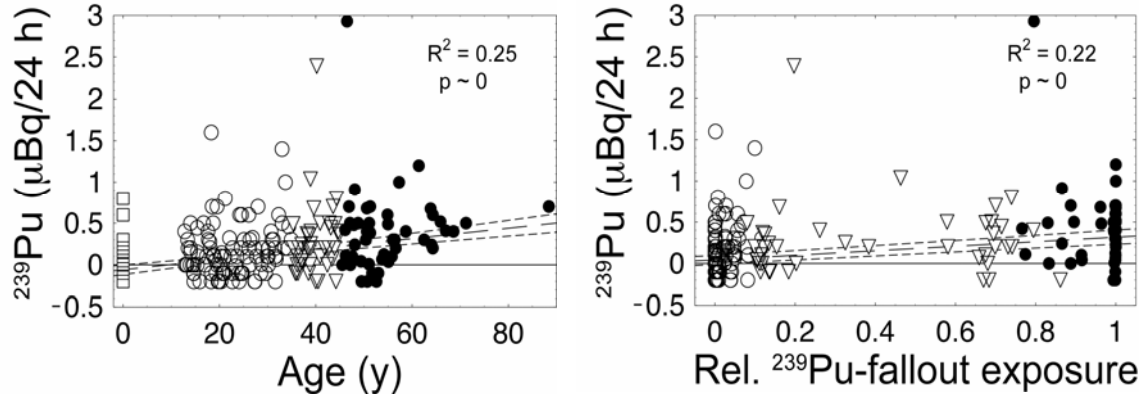

Figure 6. Urinary ^{239}Pu is significantly positively associated both with age (left plot), and with estimated relative exposure to ^{239}Pu from worldwide fallout, for all (male and female) Enewetak participants (*n* = 194), as assessed by weighted linear regression using inverse-square measurement errors as weights (solid horizontal lines = 0 μBq/24-h). In each plot, ○ = <35 y, ▽ = 35-44 y, ● = ≥45 y; the left plot (and corresponding regression) includes pooled field blank (□) data (*n* = 50). Both regressions exclude (3) measures < -1 or > 5 μBq. Each plot shows an estimated linear fit (long-dashed line), and 95% confidence limits on that fit (short-dashed lines).

Table 3. Fraction of samples containing >0.35 μBq ^{239}Pu versus volunteer age.[a]

Atoll	Sample group[a]	N	Number of measures >0.35 μBq	p-values[b]		
				Association	Homogeneity	Trend
Enewetak	FB	50	2			
	<35 y	103	20	0.014	6.9×10^{-8}	1.9×10^{-8}
	35-44 y	41	14	0.00036	[0.00022]	[4.8×10^{-5}]
	≥45 y	50	26	6.2×10^{-8}		
Rongelap	FB	50	2			
	<35 y	50	11	0.016	0.00050	0.00029
	35-44 y	51	15	0.00018	[0.29]	[0.14]
	≥45 y	42	6	0.011		

[a] FB = All field blanks, *N* = total number of Field Blank measures (pooled from both islands) or number of volunteer measures obtained from each island for each age group listed. Measurement errors were ignored in these analyses, and only measured values between -1 and 5 μBq were included (measures for 3 Enewetak and 2 measures from the Rongelap group, respectively). Multiple samples from any single individual were pooled as explained above.

[b] Association with age (relative to Field Blank data) was assessed by 2-tail Fisher exact test; homogeneity and linear trend were assessed using extended Fisher exact tests for independence, and by Bartholemew's test for trend, respectively, in the implied 2×*k*-fold contingency table with *k*=4 ordered as listed by age group; p-values in brackets correspond to *k*=3 with Field Blank data excluded.

plutonium in association with future resettlement programs in the northern Marshall Islands or from changes in existing dietary and/or land-use patterns (Hamilton *et al.*, in preparation).

Under present living conditions, the plutonium bioassay program established for the resident population on Enewetak Island and for resettlement workers living on Rongelap Island clearly show that the systemic uptake of plutonium from potential exposures to elevated levels of fallout contamination in the local environment is extremely low. Moreover, the amount of plutonium measured in bioassay samples collected from these groups is comparable to or less than that measured in a small number of non-Marshallese U.S. workers with no known previous exposure to plutonium besides that in worldwide fallout (Bogen *et al.*, 2004a,b). Interpretation of the bioassay data is complicated by the large uncertainties in individual measurements – most of which fall into a sub μBq range or below the critical level of detection (Hamilton *et al.*, 2007). Withstanding this, our detailed statistical analysis of the combined bioassay data using the methods outlined in this report and our high-quality AMS measurement data do show some interesting trends in that urinary excretion of plutonium is consistently low yet significantly positively associated with age. The significant age-related trend observed for Enewetak residents compares with a less pronounced (albeit still statistically significant) age-related trend observed for the Rongelap resettlement workers. Rongelap resettlement workers involved in soil remediation were expected to have a higher probability of receiving a significant increment of intake detectable above any baseline excretion from systemic burdens acquired from previous exposures (Hamilton et al., 2005). If this were true then we would not expect to see a significant age related trend in urinary excretion of plutonium in this cohort. The difference in the strength of the age-related trends between the two population groups is more likely due to the inter-cohort variability in volunteer age and island-specific residence time. For example, one of the selection criteria for the Enewetak cohort group was that all volunteers should have lived on Enewetak Island since the atoll was resettled in 1980 (Hamilton *et al.*, 2007). By comparison, resettlement workers on Rongelap lived on island for more limited and variable amounts of time (i.e., from weeks to several years) interspersed with residence in other parts of the Marshall Islands.

CONCLUSION

Advances in the quality and reliability of *in vitro* bioassay monitoring of ^{239}Pu based on AMS detection and measurement appear to be provide new insights into the uptake and urinary excretion of plutonium in cohort populations from the Marshall Islands. Select island population groups monitored through 2005 show low-level age-related patterns consistent with either (1) a long-term urinary excretion component associated with systemic burdens acquired from cumulative exposure to worldwide fallout

contamination or (2) a prompt (and eventual long-term) component acquired from low-level systemic intakes of plutonium associated with resettlement of the northern Marshall Islands. If hypothesis (1) is true, this study would be the first ever to document a human ^{239}Pu-specific biomarker signature of worldwide ^{239}Pu fallout. We would further predict that individuals born after about 1970 who now or may someday reside on the islands will continue to have and excrete background levels of plutonium that do not increase with age (i.e., with duration of island residence). The alternative hypothesis (2) predicts that the age-related pattern of urinary plutonium excretion may be derived from chronic or small incremental intakes associated with resettlement of the northern Marshall Islands where residual levels of plutonium contamination in the environment are elevated over that expected in integrated worldwide fallout deposition. The strength of age-related trends in plutonium excretion across the two study cohort populations appears to be more consistent with hypothesis (2) because it would be reasonable to assume that both population groups have been similarly exposed to cumulative worldwide fallout but experience different intakes from local sources. In future work, we will assess baseline urinary excretion of plutonium from other population groups in the northern Marshall Islands and conduct a re-evaluation of exposure pathways, especially in relation to dietary intakes from consumption of fish and other marine products.

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