Measurement of background gamma radiation in the northern Marshall Islands

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We report measurements of background gamma radiation levels on six islands in the northern Marshall Islands (Enewetak, Medren, and Runit onEnewetak Atoll; Bikini and Nam on Bikini Atoll; and Rongelap on Rongelap Atoll). Measurable excess radiation could be expected from the decay of ^{137}Cs produced by the US nuclear testing program there from 1946 to 1958. These recordings are of relevance to safety of human habitation and resettlement. We find low levels of gamma radiation for the settled island of Enewetak [mean = 7.6 millirem/year (mrem/y) = 0.076 millisievert/year (mSv/y)], larger levels of gamma radiation for the island of Rongelap (mean = 19.8 mrem/y = 0.198 mSv/y), and relatively high gamma radiation on the island of Bikini (mean = 184 mrem/y = 1.84 mSv/y). Distributions of gamma radiation levels are provided, and hot spots are discussed. We provide interpolated maps for four islands (Enewetak, Medren, Bikini, and Rongelap), and make comparisons to control measurements performed on the island of Majuro in the southern Marshall Islands, measurements made in Central Park in New York City, and the standard agreed upon by the United States and the Republic of the Marshall Islands (RMI) governments (100 mrem/y = 1 mSv/y). External gamma radiation levels on Bikini Island significantly exceed this standard ($P = << 0.01$), and external gamma radiation levels on the other islands are below the standard. To determine conclusively whether these islands are safe for habitation, radiation exposure through additional pathways such as food ingestion must be considered.

gamma radiation | nuclear testing | Marshall Islands | nuclear weapons | Bikini

Nuclear weapons testing by the US government in the northern Marshall Islands during the 1940s and 1950s resulted in severe radioactive contamination of numerous islands. Enewetak and Bikini Atolls, which were used as ground zero for 67 nuclear tests, as well as neighboring atolls Rongelap and Utirik, were all exposed to high levels of radioactive fallout (1). Inhabitants of Bikini and Enewetak Islands were evacuated to distant islands before the tests. However, alleged underpredictions of the yield of the largest thermonuclear weapon tested by the United States, Castle Bravo (1), coupled with an unexpected easterly wind, resulted in substantial radioactive fallout on Rongelap and Utirik Atolls, where no evacuation had been implemented. The inhabitants of these islands suffered greatly from health complications, resulting in death and illness for adults and children, both born and unborn. Many of these effects are still being felt by the descendants of the exposed populations (2–4).

The subsequent history of resettlement decisions has been riddled with mistakes, including the premature resettlement of Rongelap in 1957 and Bikini in 1968. In both cases, large populations were moved back to their home islands when radiation levels on those islands remained well above standards for safe exposure limits. By contrast, the resettlement history of Enewetak Atoll includes a major cleanup of the islands of Enewetak and Medren. This cleanup entailed the removal of radioactive topsoil on these islands, performed from 1977 to 1980. Following the cleanup, Enewetak and Medren islands were resettled. A population of Marshallese people lives on Enewetak today and Medren has since been abandoned. In addition, a concrete dome was constructed on Runit Island in the Enewetak Atoll to serve as a chemical and nuclear waste site. Enewetak Island is inhabited today by a population of less than 1,000 people. Cleanup efforts were also undertaken on the islands of Bikini and Rongelap. Several agreements (Memorandums of Understanding) related to nuclear testing legacy and acceptable levels of radiation have been signed by the Marshallese and US governments beginning in 1982. However, resettlement of populations to the islands of Bikini and Rongelap has not been realized. Today, just a handful of inhabitants live on Bikini Island and approximately a dozen people live on Rongelap Island, both groups primarily serving as contractors working for the US and Marshallese governments.

The relocation of Bikinian and Rongelapese Marshallese citizens back to the northern Marshall Islands is still an issue of relevance today, more than half a century after the testing program was halted (5–8). The vast majority of Marshallese people now live on just two islands: Majuro (Majuro Atoll) and Ebeye (Kwajelein Atoll). The country has experienced rapid population growth, primarily from the 1960s to the 1990s, and as a result, these two islands suffer from severe overcrowding. The possibility of relocation to the otherwise pristine islands could potentially have an enormous impact on the Marshallese people and culture. Thus, evaluation of the radiological conditions on these islands is of the utmost importance.

Significance

Sixty-seven nuclear tests were conducted on two atolls in the northern Marshall Islands between 1946 and 1958. These tests produced radioactive fallout, which even today gives rise to radiation measurable above naturally occurring background levels. Rather than obtain new data, recent estimates of contamination levels in the northern Marshall Islands use measurements made decades ago to calculate present radiation levels. In contrast, we report on timely measurements on three different atolls, and also provide detailed fits and simulated maps across several islands, including the islands of Bikini and Rongelap. Bikini and Rongelap Islands are of particular interest as they are relevant to the discussion of human resettlement; indeed, our radiation values for Bikini Island are higher than those previously reported.

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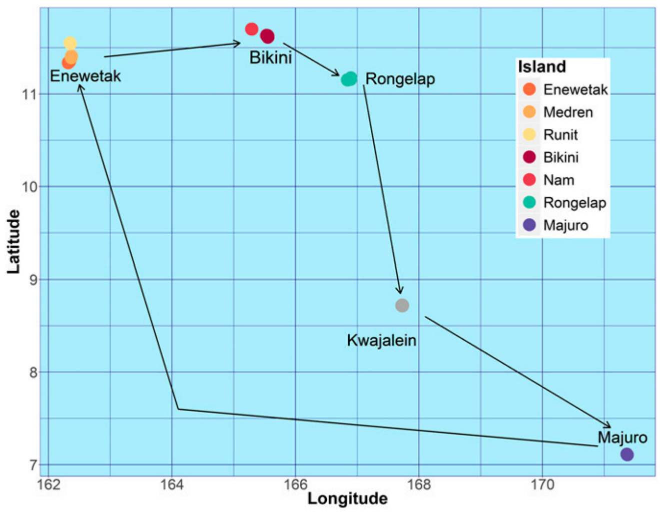

Fig. 1. Simplified map of the Marshall Islands indicating the research team's trajectory and visited atolls. Only the visited atolls and islands are shown on the map.

Previous studies (9–13) have characterized the background radiation levels of the land, water, and food [including local fruits and fish (14, 15), both of which are staples of the Marshallese diet], for several of the contaminated islands. However, these studies calculate radiation levels based on old measurements and assumptions about the half-life of ^{137}Cs in the environment, the major source of gamma radiation, as described below. In contrast, we report on timely measurements of external gamma radiation levels, made in August 2015, on six northern Marshall Islands: Enewetak, Medren, and Runit on Enewetak Atoll; Bikini and Nam on Bikini Atoll; and Rongelap on Rongelap Atoll. To make these measurements, we chartered a scuba diving boat and traveled more than 1,000 miles over a 2-wk period in August 2015 (Fig. 1). All northern island data were collected over a 1-wk period (23–30 August 2015). As part of our study, we compare measurements on these six islands to the measurements we made on the island of Majuro (Majuro Atoll in the southern Marshall Islands) and in Central Park in New York City.

The major source of remaining background radiation attributed to the nuclear weapons testing is the radioactive decay of ^{137}Cs (9, 16, 17), which accounts for well over 90% of all gamma radiation attributable to fallout from the nuclear testing (9). This isotope has settled into the soil and is taken up by the local food sources. The ^{137}Cs nucleus undergoes beta decay to ^{137}Ba, which itself rapidly decays, giving off a 0.662-MeV gamma ray. It is this gamma ray that our detectors recorded.

Results and Discussion

Raw Observations.

Control island. We designated Majuro Island to serve as the control island against which the contaminated islands can be compared. Majuro, the capitol of the Marshall Islands, is located in the southern Marshall Islands, and received a very low level of fallout due to the US nuclear testing program (2). We took 19 measurements on Majuro Island. The mean of our sample is 9.5 millirem/year (mrem/y), which we take as a standard measurement for external gamma radiation in the northern Marshall Islands. Note that 1 mrem is equivalent to 0.01 mSv.

Enewetak Island. We made a total of 137 measurements on Enewetak, covering the majority of the island. Overall, we observed values on Enewetak ranging from 4.8 to 16.6 mrem/y (Fig. 2). We made a single measurement that was substantially higher than the rest of our data at 84.1 mrem/y. We consider this measurement, which was made on the southern tip of the island (Fig. 3*A*), to be an accurate recording of elevated radiation there. Removing this outlier from analysis results in a slight shift in the computed mean (7.6 mrem/y vs. 6.9 mrem/y). This slight shift is within the error limit of our detectors.

We fit several semivariogram models to describe the structure of covariance within our observed data, and ultimately selected a Gaussian model as most appropriate. We used the Gaussian model to perform kriging interpolation of external gamma

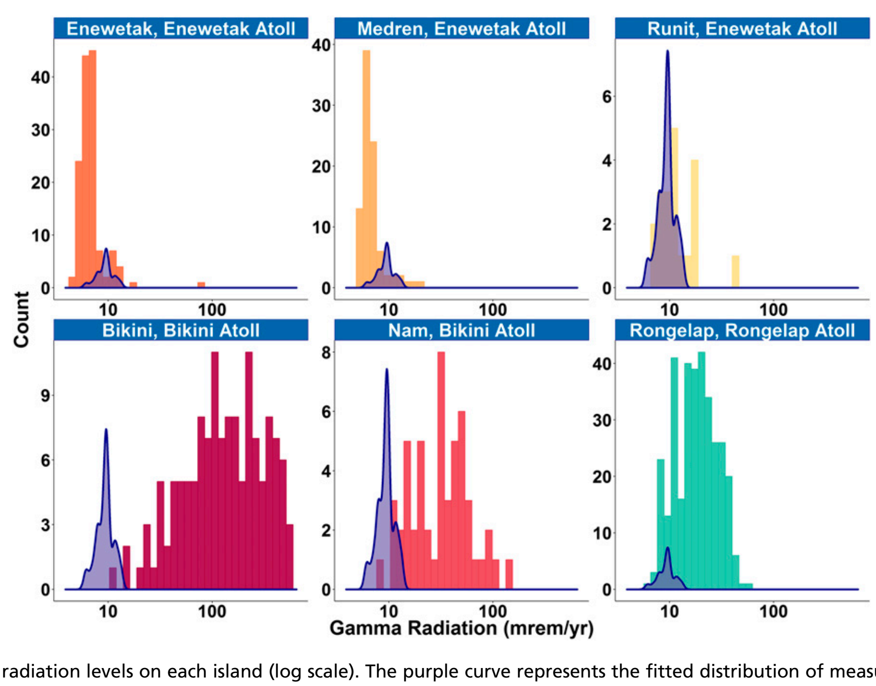

Fig. 2. Measured gamma radiation levels on each island (log scale). The purple curve represents the fitted distribution of measured radiation levels on the control island, Majuro. The vertical axis is scaled differently for different islands to account for varying radiation levels. Enewetak Island, *n* = 137; Medren Island, *n* = 91; Runit Island, *n* = 20; Bikini Island, *n* = 137; Nam Island, *n* = 52; Rongelap Island, *n* = 332.

radiation values across the expanse of Enewetak (Fig. 3A) (18). Our interpolation produced a fairly narrow range of predicted values, with a slight skew toward higher values in the vicinity of the observed hot spot. However, even with consideration of the hot spot, the distribution of predicted values is fundamentally flat, ranging from 5.5 to 6.8 mrem/y (see Table S1 for summary statistics of each island and Table S2 for measures of central tendency of each island).

Medren Island. A total of 91 measurements were taken on Medren Island, with observation points spanning the entirety of the island. However, substantial patches of land between points were unobserved (Fig. 3B). This was primarily due to the arduous terrain of Medren, which consisted of densely overgrown vegetation. As in the case of Enewetak, we found the distribution of our observations to be rather flat, ranging from 5.3 to 21.9 mrem/y (Fig. 2). Unlike the measurements on Enewetak, this flat distribution was not distorted by any measured hot spots. We measured a mean external gamma exposure of 7.1 mrem/y.

We fit an exponential semivariogram model to characterize the covariance of our measurements on Medren, and used this model to perform kriging over the extent of the island (Fig. 3B). As in the case of Enewetak, our interpolation produced a very narrow range of predicted values (6.2–7.9 mrem/y).

Runit Island. We made a total of 20 measurements on Runit, 18 of which were taken on the western beach (Fig. 3C). We also took one measurement at the base, and one on top of the Runit Containment Dome: a waste storage facility for over 85,000 m^3 of radioactive material produced during the US nuclear weapons testing program in the Marshall Islands. The mean value for external gamma radiation on Runit is 13.1 mrem/y, ranging from 7.01 to 42.9 mrem/y. However, given that our measurements only cover the perimeter of one side of the island, our values are unlikely to be representative of the true gamma radiation levels on the island as a whole. Our values at the base and top of the dome (42.9 and 17.5 mrem/y, respectively) are not adequate measurements of the total radiation levels at the dome. This is because the majority of the material contained in the dome is contaminated with ^{239}Pu, which is an alpha emitter. Our detectors measure gamma radiation and are thus insensitive to ^{239}Pu. Due to the low number of measurements and lack of coverage, we did not perform interpolation for Runit Island.

Bikini Island. We made 137 measurements on Bikini Island, coincidentally the same number as made on Enewetak Island. Unlike those on the islands in Enewetak Atoll, however, we saw significant spatial variation in external gamma radiation values (Fig. 3D). Specifically, we measured substantially higher values toward the center of the island (as high as 648 mrem/y) and quite low values toward the edge of the island (as low as 10.0 mrem/y). The distribution of measured values is roughly log-normal (Fig. 2), with a mean of 184 mrem/y. The mean is shifted considerably to the right of the median (137 mrem/y) as a result of the right skew of the data. Our coverage of the island was not complete; although we did make points across the extent of the island, there are large areas that remain uncovered (Fig. 3D). However, our coverage was sufficient to allow a robust interpolation of the external gamma levels across the island, particularly given the strong spatial trend observed in the data. A Gaussian model was fit to the semivariogram for our Bikini measurements, and used to perform kriging across the island. Our interpolation shows a trend moving from high values in the interior of the island, trailing off to rather low values on the beaches. The range of predicted values mimics the range of our observed values (0–500 mrem/y), in contrast to Medren and Enewetak where the interpolated values across the entire island were roughly consistent with the mean. Because large sections of island were not covered, many prediction points were a considerable distance from any observed values. This resulted in substantial uncertainty on prediction for these points.

Nam Island. We made 51 measurements on Nam, all of which were limited to the outermost edge of the island (Fig. 3E). As in the case of Medren, our ability to conduct measurements was somewhat limited by the dense, intensely overgrown vegetation

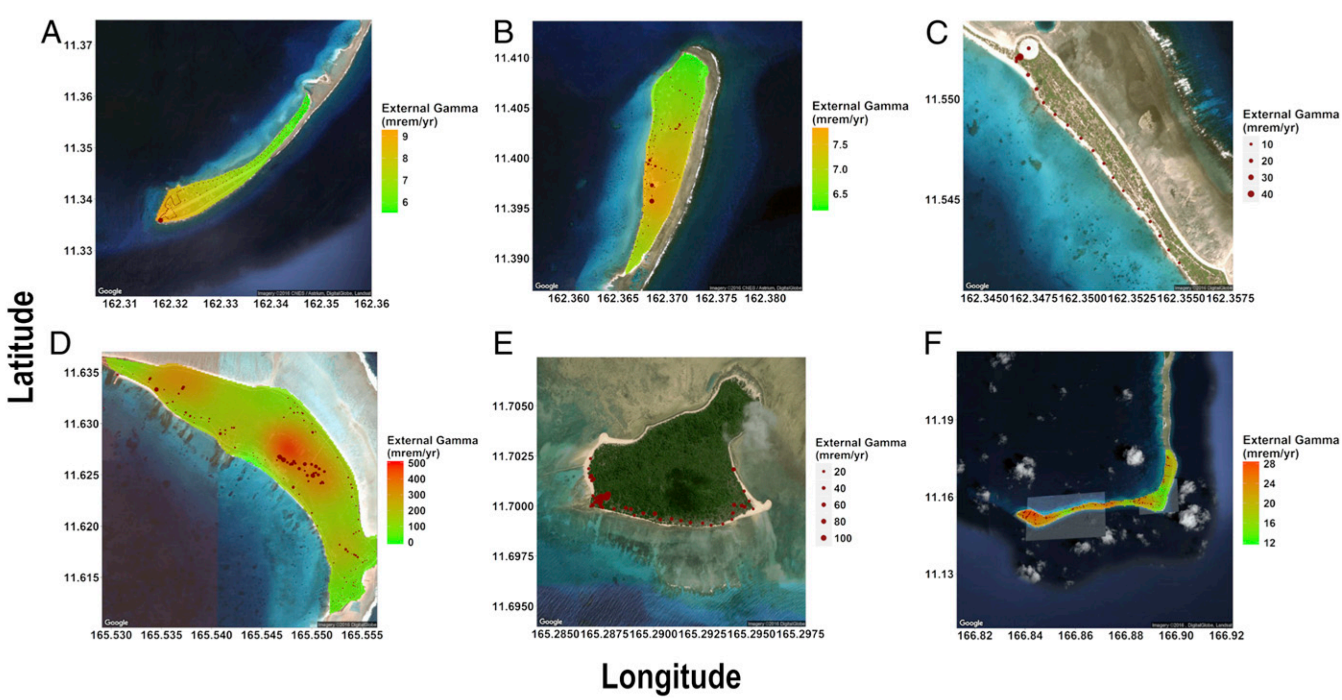

Fig. 3. Measured and interpolated external gamma radiation on different islands (mrem/y). The scale for magnitude of radiation is different for each island. (*A*) Enewetak Island, Enewetak Atoll (n = 137). (*B*) Medren Island, Enewetak Atoll (n = 91). (*C*) Runit Island, Enewetak Atoll (n = 20). (*D*) Bikini Island, Bikini Atoll (n = 137). (*E*) Nam Island, Bikini Atoll (n = 52). (*F*) Rongelap Island, Rongelap Atoll (n = 332).

on the island. We measured a considerable range of values, from 7.9 to 143.0 mrem/y, with a mean of 38.4 mrem/y. However, given that our measurements were exclusively taken on the beaches of Nam, it is extremely unlikely that our values are representative of the true exposure levels on the island. Given our lack of sufficient coverage of Nam, we did not perform interpolation of this island.

Rongelap Island. We took 332 measurements on Rongelap Island, resulting in thorough coverage of the island (Fig. 3*F*). The distribution of our measurements on Rongelap, although nonnormal, comes closest to a normal distribution of any of the islands we measured (Fig. 2). Most measurements were in the range of 15–20 mrem/y, with a somewhat strong upper tail, encapsulating measurements as high as 55.2 mrem/y. The lowest measured value was 6.1 mrem/y. The mean external exposure for Rongelap was found to be 19.8 mrem/y. An exponential model was fit to the semivariogram constructed for our Rongelap measurements and used to perform kriging interpolation. Our interpolation results ranged from 10 to 32 mrem/y, and corresponded closely to our observed values. No strong spatial trend was observed, although values were predicted and observed as lower on the beaches vs. off the beaches.

Central Park, New York City. As a point of comparison, we took 163 measurements in Central Park in New York City, following our trip to the Marshall Islands. Our measurements in Central Park ranged from 13.1 to 213 mrem/y, with a mean of 100 mrem/y. Coincidentally, our mean measurement of 100 mrem/y for Central Park has the same numerical value as the Republic of the Marshall Islands (RMI)/US government agreement for Marshall Islands habitation. Although nonnormal, primarily as a result of a heavy upper tail (Shapiro–Wilk test, $P = 2.03 \times 10^{-9}$), the distribution of measurements did assume a rough bell curve. We also performed a fluctuation test, taking 100 measurements of the same location (Fig. S1). We did not produce an interpolated map of the gamma radiation across the park.

Comparison Across Islands. We used the Kruskal–Wallis test to compare measured gamma radiation across the three atolls: Bikini, Enewetak, and Rongelap (19). We conclude that gamma radiation levels differ between atolls at a high significance level ($P << 0.001$). Radiation in Rongelap Atoll is significantly elevated relative to that in Enewetak Atoll, and radiation in Bikini Atoll is significantly elevated relative to radiation observed in Rongelap.

We used the Shapiro–Wilk normality test to our data sets for each island, and found none to be normally distributed (20). We therefore used the nonparametric Wilcoxon Rank-Sum test to measure whether there are significant differences in observed external gamma radiation between pairs of islands (Fig. S2) (21). We found no significant difference in external gamma radiation levels between Enewetak and Medren ($P = 0.87$). In all other cases we found the differences in external gamma radiation levels between islands to be significant ($P << 0.05$) (Table S3).

Our findings that radiation levels on islands in Enewetak Atoll are significantly lower than radiation levels on Rongelap Atoll, and that, in turn, radiation levels on Rongelap Atoll are significantly lower than radiation levels on Bikini Atoll, are consistent with the history of these islands. As stated above, Enewetak was extensively cleaned by the US government from 1977 to 1980, and thus is expected to have relatively low levels of radiation. Although Rongelap and Bikini also underwent some radiation cleanup, those efforts do not appear to be as extensive as the ones on Enewetak. Our data corroborate this. Additionally, Rongelap received fallout from the nuclear tests, whereas Bikini was a direct test site. Thus, it is reasonable that radiation levels on Bikini Atoll are elevated relative to those on Rongelap Atoll.

Our control island, Majuro, was found to have a mean external gamma radiation of 9.5 mrem/y. Our coverage of Majuro was less than comprehensive, with a sample size of 20 measurements. However, our measurements were remarkably consistent, ranging from 6.1 to 13.1 mrem/y, with an approximately normal distribution (Shapiro–Wilk test, $P = 0.27$), and relatively low variance (SD: 1.7 mrem/y). Thus, despite our low sample size, we have a reasonable degree of confidence in our control gamma radiation levels.

In addition, we used upper-tailed Wilcoxon Rank-Sum tests to determine whether external gamma exposure on our test islands is significantly elevated relative to our control island, Majuro. We find external gamma radiation exposure on Medren and Enewetak not to be significantly elevated relative to radiation observed on Majuro ($P = 0.99$ in both cases). We find the third measured island in Enewetak Atoll, Runit, to be significantly elevated relative to Majuro ($P = 0.03$). In all other cases, we find the northern islands to have significantly elevated external gamma radiation relative to the southern island control ($P << 0.05$ for all, Table S4).

Four of our contaminated islands (Bikini, Nam, Runit, and Rongelap) were found to have mean external gamma radiation values above this "control background;" we assume that this signal above background indicates radiation attributable to contamination from the nuclear tests.

Paradoxically, two of the islands we monitored were found to have lower average external gamma radiation exposure values than this assumed background. Specifically, our mean for Medren is 7.1 mrem/y and our mean for Enewetak is 7.5 mrem/y. This contradictory finding may be attributed to Majuro having a very low level of radiation attributable to fallout, above the natural background now only observed on the cleaned-up islands of Enewetak and Medren. In addition, given that the systematic error on our detectors is about 10%, it may be that the observed values on Enewetak, Medren, and Majuro are within the detector's error range. This conclusion is in accord with our finding of no significant difference between Enewetak, Medren, and Majuro (Tables S3 and S4).

To make comparisons to fallout radiation doses reported in the literature, we subtracted our control background (9.5 mrem/y) from our measured values and computed summary statistics for each island (Tables S5 and S6). We set negative values obtained for Enewetak and Medren at 0 mrem/y.

Comparison with Previous Studies. The 1994 National Research Council Report on the Radiological Assessments for the Resettlement of Rongelap in the RMI noted that mean external gamma radiation attributable to fallout at Rongelap for 1995 would be 11 mrem/y, whereas our measurements indicate a mean value of 10.3 mrem/y above the Majuro control for 2015 (7). Although these values are very close, they are actually in disagreement, as a significant percentage of ^{137}Cs should have decayed over the 20-y period (half-life of ^{137}Cs is 30.2 y, although somewhat reduced as the result of erosion). One reason for the apparent disagreement is that the report made assumptions about how much time residents would spend on different parts of the island, including inside houses, whereas we have reported actual measured values. The 1994 Rongelap Report concluded that Rongelap was, at that time, safe for resettlement. To draw a definitive conclusion, our study needs to be supplemented by analysis of additional exposure pathways. In particular, a significant portion of gamma radiation exposure above background is attributable to ingestion of contaminated local foods such as pandanus, breadfruit, and coconut. To make an adequate determination of the safety of inhabitation it is critical that this additional exposure pathway be investigated.

Our values for Bikini Island are also in disagreement with the 2010 projections by Robison and Hamilton (9). These authors suggest that the total annual effective dose for a person living on Bikini Island would have been 160 mrem/y for 2010. Their annual effective dose includes all pathways, including external exposure, which is thought to account for 10–15% of the total radiation dose (roughly 16–24 mrem/y), assuming a fully native diet (7, 9). Robison and Hamilton's projected values are presented for the scenario before treatment by removal of the top 15 cm of soil and subsequent filling with crushed coral. Our external gamma radiation measurements are well above the external gamma dose projected by Robison and Hamilton, and even above the annual effective dose projected by these authors. Given the relatively high values of external gamma radiation that we have measured above control (mean 175 mrem/y, high 639 mrem/y), our findings represent a disagreement with their projections based on past measurements.

Comparison with Standards. We compared our measurements to the radiological provisions of the Memorandum of Understanding between the US and the RMI regarding the resettlement of Rongelap Atoll, herein referred to as the RMI/US Agreement. This standard states that in order for Rongelap to be safe for habitation, the maximally exposed person shall not receive a cumulative effective dose greater than 100 mrem/y above background. To make these comparisons, we used values adjusted for the Majuro control background of 9.5 mrem/y (Tables S5 and S6). We set negative values obtained for Enewetak and Medren at 0 mrem/y.

We once more used the Wilcoxon Rank-Sum test to investigate whether observed levels of radiation on the different islands exceed this standard. We found Bikini Island to have radiation levels significantly elevated relative to this standard ($P << 0.01$). For all other islands we found external gamma radiation levels to be below this standard with high significance ($P << 0.01$, Fig. S3).

The RMI/US standard was agreed upon for cumulative effective dose, which involves a variety of exposure pathways (dermal absorption, food ingestion, water ingestion, incidental soil ingestion, etc.). However, our measurements only assess exposure from one pathway: external exposure. Thus, our findings that radiation levels on Rongelap, Enewetak, and Medren are below the RMI/US standard are not sufficient to conclude that these islands are fit for habitation. Our findings do, however, suggest that these islands could be safe for habitation. To draw such a conclusion, it is vital to carry out the analysis of additional exposure pathways. By contrast, we find that radiation levels on Bikini Island exceed the RMI/US standard for safe habitation (Fig. 4). Indeed, by considering additional exposure pathways, the estimation of effective cumulative dose could only increase, presumably by at least several fold (9).

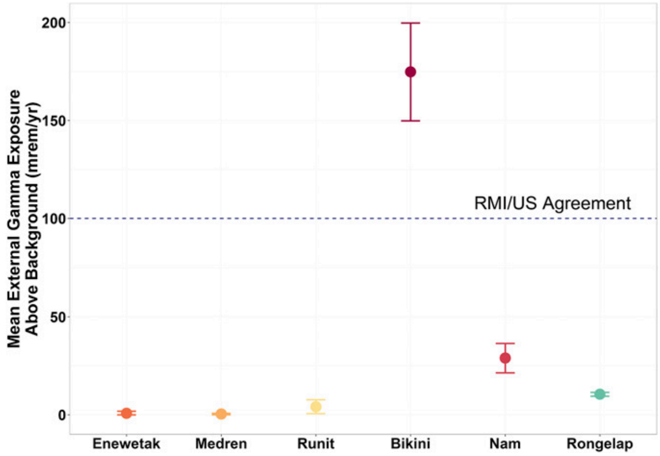

Fig. 4. Adjusted external gamma radiation on each island, compared with the RMI/US Agreement standard for safe habitation of Rongelap (100 mrem/y for maximally exposed individual). Values adjusted by subtracting the Majuro background control. Dots represent the mean value and error bars represent ±1 SD. Enewetak Island, n = 137; Medren Island, n = 91; Runit Island, n = 20; Bikini Island, n = 137; Nam Island, n = 52; Rongelap Island, n = 332.

In the case of islands of Nam and Runit, our findings also suggest that external gamma radiation exposure is below the 100-mrem/y limit. However, on both of these islands, our data collection was limited to beach areas, as we did not assess the interiors of these two islands. Previous work suggests that gamma radiation measurements on beaches are likely to be much lower than measurements taken on the interior of an island (12). Our data from Bikini and Rongelap Islands corroborate this finding. The effect is hypothesized to be due to dispersal of contamination near the sea by waves crashing onto the beach. Thus, it is quite likely that the external gamma radiation levels on both Nam and Runit are substantially elevated relative to our measurements. However, given that Runit is home to a radioactive waste disposal site, and that Nam is in ruins as the result of the Bravo test being detonated there, it is unlikely either will ever be fit for habitation.

In the case of Runit Island, and particularly the Runit dome, forms of radiation other than gamma may play a nontrivial role in determining the cumulative effective dose. For example, the dominant isotope buried in the Runit dome is ^{239}Pu, which is an alpha emitter. Similarly, although ^{137}Cs accounts for well over 90% of radiation exposure, several other isotopes such as ^{90}Sr and ^{240}Pu are likely to be present in small quantities. To thoroughly assess radiation levels on these islands, another step would be to assess levels of these additional isotopes.

Comparison with Central Park. The assessment of external gamma radiation levels in Central Park served primarily as a means to establish a comparison point for radiation levels in a populated area and those on the contaminated islands in the Marshall Islands. Radiation levels were found to be significantly elevated in Central Park relative to the islands of Enewetak Atoll (Enewetak, Medren, and Runit), Rongelap, and Nam ($P << 0.01$), but were not found to be significantly elevated relative to Bikini. This is because background gamma radiation in Central Park is much higher than in the Marshall Islands, on the order of 100 mrem/y, compared with our assumed background of roughly 10 mrem/y in the Marshall Islands. The background gamma radiation in Central Park is, presumably, substantially elevated due to the abundance of granite in the park (the Manhattan Schist runs through a considerable area of the park). Typically, safe levels of radiation exposure are set in terms of above background exposure (19). Regardless of the source, it is interesting to note that individuals in Central Park in New York City (NYC) may be receiving a higher dose of external gamma radiation than an individual living on one of the islands affected by the US nuclear testing in the Marshall Islands. It is critical to stress that our measurements do not capture the total effective dose of an exposed individual. Moreover, to adequately compare the true radiation health risk of living in NYC versus in the northern Marshall Islands, additional exposure pathways must be analyzed.

An average American citizen gets exposed to 620 mrem/y, according to the Nuclear Regulatory Commission. Half of this dose is from natural sources, such as radon, cosmic rays, and the Earth itself, and half of the dose is from man-made sources, such as medical, commercial, and industrial sources. In addition to fallout-related radiation, Marshallese people get ∼220 mrem/y from a high fish content diet and cosmic rays.

Conclusion

Our findings suggest that there is significant variation in the levels of external gamma radiation on the islands affected by the US nuclear testing program in the Marshall Islands. Notably, Bikini Island is found to have radiation levels exceeding the agreement promulgated by the US and RMI governments for safe habitation of Rongelap. This finding suggests that Bikini Island exceeds this standard and may not be safe for habitation. Islands on Rongelap and Enewetak Atolls are found to have external gamma radiation levels well below the RMI/US standard for safe habitation. However, without measuring other exposure pathways, we are not able to make a determination as to whether these islands are indeed safe for habitation. There is a population currently living on Enewetak, in some trepidation as to whether or not their environment is safe. In addition, there is currently a large population of displaced Marshallese people who desire to return to Rongelap and Bikini. Given these circumstances, it seems imperative that further steps be taken to analyze additional exposure pathways to make a definitive statement as to whether these islands are safe for habitation.

Materials and Methods

Gamma Radiation Detectors. We conducted gamma radiation measurements using Ludlam model 44–20 Gamma scintillators, which are connected to and operated by Ludlum model 2241–2 survey meters. The scintillators are 3 inches in diameter and are composed of thick sodium iodide crystals optically coupled to photomultiplier tubes. The detectors are sensitive to gamma radiation over an energy range of 60 keV to 2 MeV. The survey meters were read out visually by a liquid-crystal digital display. Two independent sets of survey meters with scintillators were used to perform the measurements in the Marshall Islands and in Central Park in NYC.

Detector Calibration. The Ludlum scintillators and survey meters were each calibrated by Ludlum Measurements, Inc. before their delivery in July and August 2015. The overall detector linearity is rated to be accurate to 10% of the true value. Relative calibrations of the detectors using uranium glass were performed daily on the boat before measurements taken on the islands. The radioactivity of the uranium glass was known; thus, the calibration served to create a point of reference for the on-site detector readings relative to the readings of the known radioactivity of the uranium glass (i.e., to see if the detectors were systematically reading high or low, and if so by how much). Calibration was achieved by directing the instruments' scintillators at a sample of uranium glass of known radioactivity for several seconds and taking a measurement of the gamma radiation detected. Gamma radiation backgrounds on the boat were typically 5.3 mrem/y and rose to ∼26.3 mrem/y when exposed to the uranium glass. No time variations in the calibrations for either detector system were observed during the 1 wk of data collection in the northern Marshall Islands (23–30 August 2015). Measurements performed in Central Park were made in November 2015. Measurements of the distribution for single-point measurements were also taken in Central Park. These values depend on the detector resolution as well as the natural background fluctuations of the signal. We found the distribution to be normal (Shapiro–Wilk test, $P = 0.83$) and to have an SD of ∼10% (Fig. S1). These values are also consistent with fluctuation measurements performed with the fully analyzed data sets.

Data Collection. Data were collected by two teams, each consisting of a pair of researchers. Per pair, one member read out the Ludlum detector results while the second member recorded the value and the location of the measurement using a Garmin eTrax GPS, saving it as a waypoint record. On each island, the two teams traveled in diverging directions to efficiently map the island expanse. The Ludlum scintillator was pointed from waist height at an ∼45° angle toward the ground. Measurements were taken at ∼100–200-m separations, although the consistency in distance traveled between data points was not strictly enforced. On the islands of Enewetak, Medren, Runit, and Nam, the teams walked throughout the islands. For the islands of Bikini and Rongelap, the data were collected by a combination of walking and transport in a truck, allowing for more coverage in the allotted time.

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