537

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USE OF A PORTABLE WHOLE-BODY COUNTER TO MEASURE INTERNAL CONTAMINATION IN A FALLOUT-EXPOSED POPULATION*

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Abstract—The evaluation of body burdens of radionuclides in large populations is a health physics problem of considerable importance. Measurement with the whole-body γ-spectrometer provides the best technique for this evaluation. A "portable" whole-body counter, such as the BNL model, makes it possible to carry out studies in remote areas.

The report presents the technique of carrying out, in the field, a survey of internal contamination in a population. The study used to illustrate the technique is the survey made in 1961 of the γ-ray spectra of a group of Marshallese people, some of whom had accidentally been exposed to fallout from nuclear detonation in 1954. The results of the latest study are presented in this report and compared to the findings from previous field studies among the Marshallese made in 1958 and 1959.

Possible directions in which the development of this technique might proceed, and other possible applications of whole-body counting in the field are also discussed.

INTRODUCTION

THE evaluation of body burdens of radionuclides in large populations is a health physics problem of considerable importance at present. Increasing production and use of fissionable materials, and renewed nuclear testing both contribute to contamination of the atmosphere, water supplies and soil, and thus to increasing body burdens of radionuclides among large populations. Concomitant with the application of nuclear materials is an ever-present possibility of accident. The importance of keeping the level of body burdens of various radionuclides in the general population, as well as in specific exposed groups under survey, is manifest.

For large scale surveys, measurement with whole-body gamma counters (both liquid scintillation detectors[1] and crystal detectors[2]) has proved to be the most satisfactory technique. An example of the successful application of this technique, using a portable whole-body counter, was the study of the Marshallese people of Rongelap Atoll who were accidentally exposed to fallout in 1954. Early evaluation of the body burdens in these people was carried out by radiochemical urinalysis, which is time-consuming and difficult. In 1957, several Rongelap people were brought to Argonne National Laboratory where it was demonstrated that their body burdens of gamma emitters could be measured in the whole-body counter.[3] Cs^{137} and Zn^{65} were shown to be the prominent isotopes in the Marshallese at that time.

The Rongelap people, originally evacuated to another island in 1954, were returned to their home island in July 1957. Since the island and the indigenous food sources still had a low level of persisting radionuclides, continued evaluation of the body burdens in these people was of considerable interest.

A portable whole-body counter was designed and constructed at Brookhaven Laboratory and transported to the Marshall Islands where it has since been employed during the annual medical surveys to ascertain the level of internally-deposited γ-emitting isotopes. In 1958, 100 Marshallese people were counted, and the procedure was repeated one year later to obtain

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γ-spectra on 227 people. Details of the exposure and findings of these medical studies have been reported.[4–7]

In February 1961, another survey was conducted. At that time the portable shield was used in conjunction with an improved detection and data-recording apparatus. The γ-ray spectra of 110 Marshallese people were obtained. Half of the people measured had been exposed to the fallout in 1954; the other half of the group were people (most of whom were related by blood) who had been living under the identical conditions of the exposed group for the past four years, but who had not been involved in the original accident.

This report describes our experience during the 1961 survey of the Marshall Islanders using the portable whole-body counter, with details on the measurements made, the methods used, and the automatic data-handling techniques developed for recording and analyzing the large amount of data associated with such a project.

METHOD

Shielding was provided by a 21 ton room with walls constructed of laminated ½ in. thick steel panels bolted together, which can be disassembled. The inside dimensions of the room are 5 ft × 5 ft × 6 ft high. In 1959 the room was mounted on a 25 ton trailer and positioned with a tractor on the tank deck of a U.S. Navy LST (Fig. 1). In 1961 the room was set up in the cargo hold of a civilian cargo ship (Fig. 2). Along with the steel room, an air-conditioned prefabricated wooden room 7 ft × 8 ft × 10 ft was set up to house the pulse-height analyzer and other electronic equipment (Fig. 1). The air-conditioning and dehumidification were of considerable value in maintaining the stability of the instrument in the tropical climate.

The subjects were ferried out to the ship for the counting. Prior to being counted, the subjects showered and donned paper coveralls and slippers. This procedure was necessary in order to minimize the possibility of counting external contamination from the island environment on their bodies and clothing. The subjects were seated on a folded hospital cot and placed in a standard, fixed position under the detector (see Fig. 3). A Marshallese subject is seen leaving the counting room through the pneumatically-driven sliding door (Fig. 4).

The counting geometry employed in the portable counter is identical to that used in the permanent whole-body counter at BNL, making possible the cross calibration of the two units.[8] The efficiency and precision of the portable counter for the various isotopes are presented in Table 1. The values obtained are very similar to those of the whole-body counter at BNL.

The background observed in the Marshal Islands counting room in the range 100 keV to 2 meV was 1796 cpm, a value somewhat higher than the average background level observed at BNL (1400 cpm). The increased background count in the Marshall Islands was chiefly in the very low energy range and probably can be explained in terms of the thinner shielding in the portable counter, and the omission of Pb lining for the ceiling of the counting room. To some extent the thinner shielding was compensated for by the shielding provided by the water under and around the ship.

Since, in previous years, difficulties were experienced in identifying small photopeaks of various isotopes deposited in the Marshallese in the presence of relatively large amounts of Cs^{137} and Zn^{65}, the counting time was increased for a number of subjects over that used in previous years. In addition, a larger crystal detector was substituted for the 5 in. detector formerly used. The majority of the subjects was counted for 10 min; a large number was counted for 30 min.

An 8 in. × 4 in. NaI (Tl) crystal (Harshaw) detector was used. The detector was placed above the patient at a distance of 19 in. (see Fig. 3). Pulses from three 3 in. photomultiplier tubes were fed into a Nuclear Data 256-channel transistorized pulse-height analyzer (Model 100). The analyzer fed the data directly to an IBM typewriter and simultaneously to a Tally paper punch unit, Model 420. Provision is made in this analyzer for transferring spectra recorded on paper tapes into the memory of the analyzer so that calibration spectra can be compared with the incoming data when it is so desired.

The data recorded on the punched paper tapes were transferred to IBM cards and thence to the magnetic tape of a 704 computer. The task of "spectral stripping" was carried out on

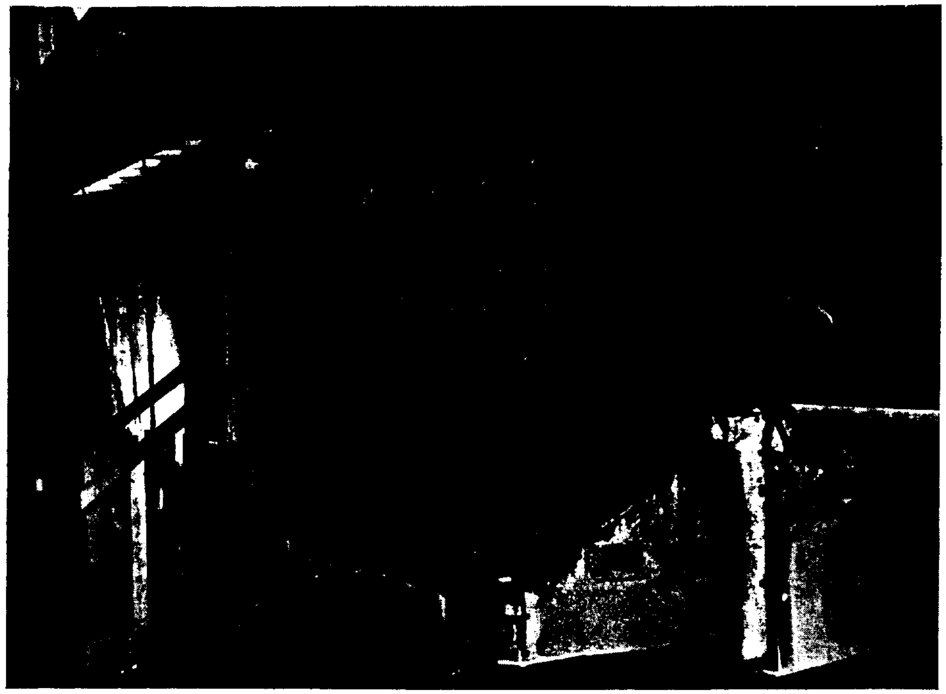

FIG. 1. Portable steel-shielded room and air-conditioned instrument room mounted on 25 ton trailer in the hold of a U.S. Navy LST ship as used in the 1959 survey.

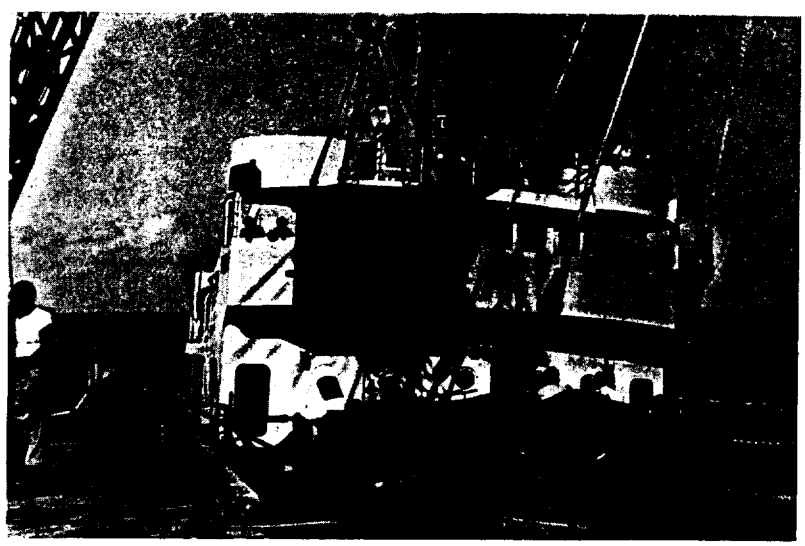

FIG. 2. Lowering the shielded room into the hold of the ship used in the 1961 survey.

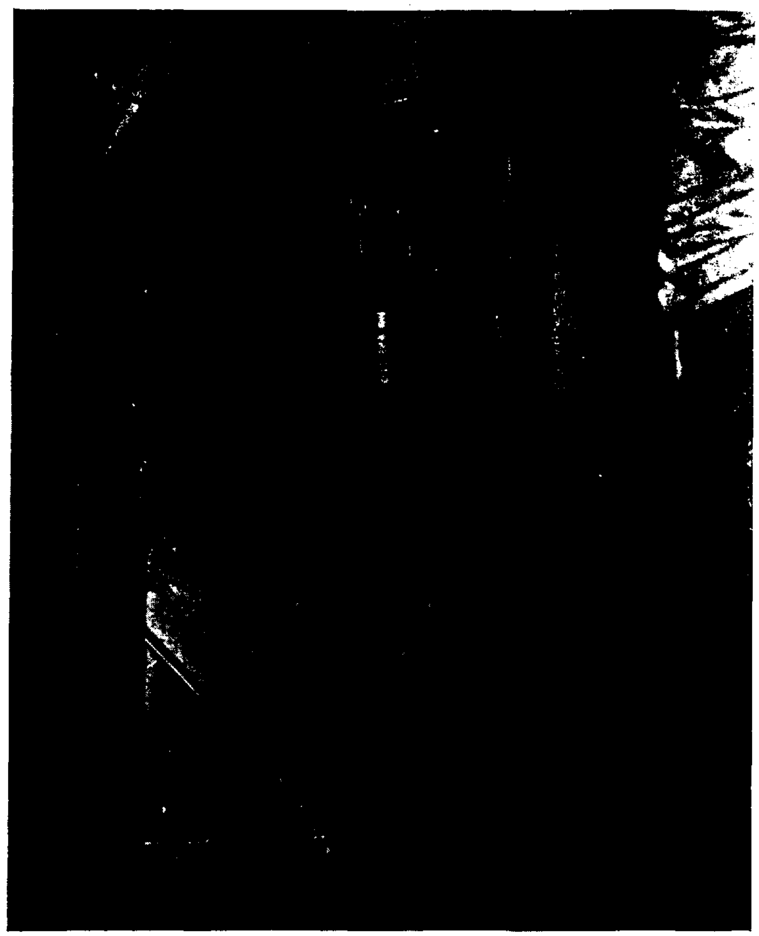

FIG. 3. Marshallese subject in the standard counting position in steel room under the NaI (Tl) crystal detector.

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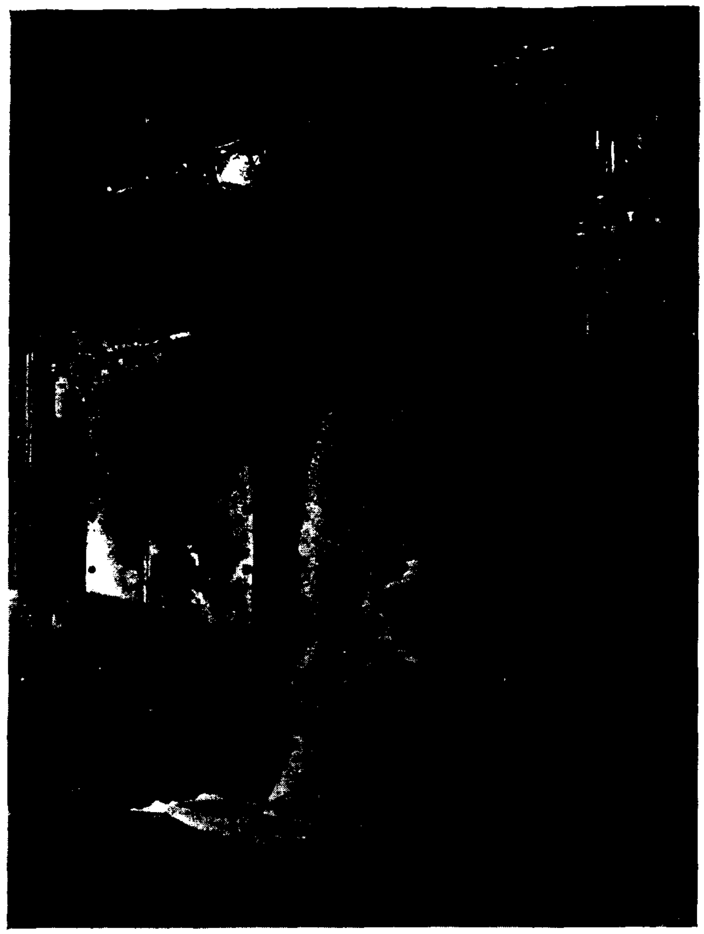

FIG. 4. Marshallese subject leaving the counting room on termination of whole-body count. The pneumatically-driven sliding door is illustrated.

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Table 1. Properties of portable whole-body counter for measuring specific radionuclides

	Cs^{137}	Co^{60}	Zn^{65}	K^{40}
Photopeak energy (meV)	0.66	1.17	1.12	1.46
Energy band measured (meV)	0.61–0.71	1.12–1.22	1.07–1.17	1.41–1.51
Background (cpm)	75.5	29.6	33.7	40.2
Calibration factor (C.F.) cpm/μc	6114	4320	1733	0.86 (cpm/kg)
Precision (P) of counter* (nc)	0.360	0.324	0.866	3.8 (g)
Standard deviation of count rate† (%)	$\pm$0.23	$\pm$10.0	$\pm$1.73	$\pm$3.58
Integrated background (cpm) 0.1–2 meV	1796			

* For 70 kg phantom in standard counting geometry, 30 min counting time.

$$\left[P = \frac{\sqrt{(R_c/t_c + (R_b/t_b)}}{C.F.}\right]$$

where P = precision $\left(\frac{\sigma_s}{C.F.}\right)$ in nc

R_c = combined counting rate (cpm)

R_b = background counting rate (cpm)

t_c = combined counting time (min)

t_b = background counting time (min)

$C.F.$ = calibration factor (cpm/nc)

† Average Marshallese adult male.

the computer with a Fortran program. In this operation the spectrum of each individual isotope is removed from the total spectrum obtained for the subject, which represents the combination of the contributions from all the isotopes deposited in that subject.

Spectra for each of the individual isotopes quantitated in this study were obtained with the use of an Alderson phantom (REMCAL). Solutions of known concentration of each radionuclide were placed in the phantom to approximate the effects of tissue absorption and scatter. The spectrum of the phantom for each of the isotopes was obtained under conditions of counting geometry identical with that used in counting the subjects. By this technique it was possible to simulate quite closely with the phantom the multi-component spectra of the Marshallese. A representative Marshallese spectrum obtained by adding K, Cs^{137} and Zn^{65} at average levels (as determined in the medical study of 1959) to the phantom to simulate the multi-component spectrum of the Marshallese is shown in Fig. 5. The K, Cs^{137} and Zn^{65} were distributed homogeneously throughout the phantom, while Co^{60} was placed in the liver only.

Analyses of the complex spectra were performed by subtracting the calibrated pulse-height spectrum for each γ-emitter to be quantified. Although these spectra are obtained ideally from a subject of identical build, an approximation is obtained with the use of the plastic phantom. Computation was carried out by an IBM-704 computer. Starting with the highest energy photopeak, that of K^{40}, (after correction for background and normalization of the K^{40} photopeak to that of the subject), the computer performs a channel-by-channel subtraction of the normalized K^{40} spectrum. In similar manner, the normalized spectra for Zn^{65}, Co^{60} and Cs^{137} were subtracted from the total spectrum (see Fig. 5).

RESULTS

A spectrum for an average Marshallese adult male, obtained in the 1961 study, is shown in Fig. 6. In the same figure, the spectrum of a member of the U.S. medical team of the same body weight and age is also illustrated for comparison. Almost identical amounts of the radionuclide K^{40} are noted along with large differences in the Cs^{137} and Zn^{65} levels between

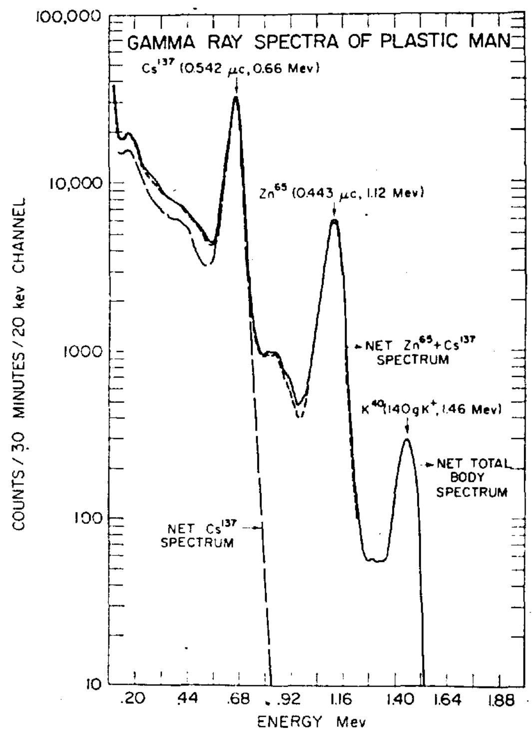

FIG. 5. γ-Spectrum of the calibration phantom containing Cs^{137}, Zn^{65} and K^{40} in the approximate range found in Marshallese subjects. The broken lines indicate the results of spectral stripping of the higher energy photopeaks.

the subjects. The summary of the average levels of Cs^{137}, Zn^{65}, K^{40} and Co^{60} determined in 1961 for both the exposed and the non-exposed Marshallese, according to age and sex, is presented in Table 2. The frequency distribution of values in various groups is illustrated in Fig. 7.

Cs^{137}. The mean value for all the groups for the body burden of Cs^{137} was 13.7 nc/kg body weight. Although the mean levels of the exposed are slightly higher than those of the unexposed groups, they do not differ significantly from each other. Variation in any group is large, as can be seen from Fig. 7 and in the value of standard error. As expressed here in terms of body weight, Cs^{137} body burdens in the groups over 16 years of age and in children under 16 years do not differ significantly. The mean levels of Cs^{137} in females tend to be somewhat lower than the levels in males, but the difference does not appear significant (Fig. 7).

Zn^{65}. Zn^{65} body burdens per kg body weight appear to be somewhat lower in the younger population group but, again, the differences are not statistically significant. Females also tend to have values lower than those found in the corresponding male group (Fig. 7). No significant difference between the Zn^{65} concentrations in the exposed and unexposed groups could be determined. The per cent variation within each group was approximately the same as that observed for the Cs^{137} levels.

K^{40}. The mean K concentrations for the younger groups were consistently higher than those for the corresponding adult group. The male adult group averaged 2.13 g/kg body weight, while the female adult group averaged 1.63 g/kg.

Co^{60}. Analyses of the residual spectra obtained after subtraction of the three above-mentioned photopeaks revealed the presence of the two photopeaks of Co^{60}. The levels of Co^{60} were quite low (mean = 0.148 nc/kg), but were nevertheless readily detectible. No significant differences between the Co^{60} levels in the exposed and unexposed groups, or on the basis of age or sex, were observed.

Total residual γ-activity. The total residual gamma activity level present after subtraction of the four above-mentioned spectra are also shown in Table 1. The activity in cpm/kg has no absolute significance, but is of value in indicating first that there is some activity left, and, secondly, the nature of its distribution by groups. Members of the adult group have considerably higher levels of residual activity per unit body weight than do members of the juvenile group. No significant differences were observed, however, on the basis of sex, or between the exposed and non-exposed groups.

DISCUSSION

It is interesting to note that no significant differences in the body burdens of the four γ-emitting radioisotopes measured in the 1961 whole-body spectrographic study were observed between the groups of Marshallese exposed to fallout in the 1954 accident and those living in the same environment as the exposed persons for the last four years. The original contamination of the exposed population of these γ-emitters has already been eliminated, and what

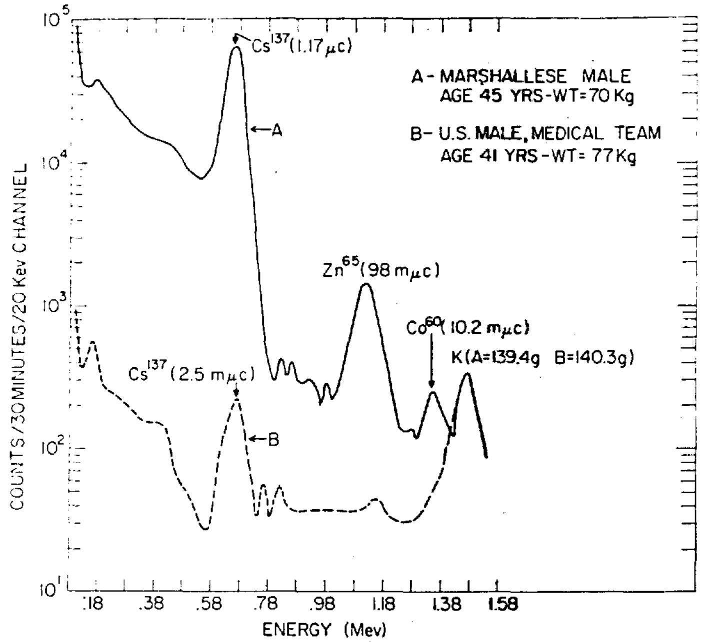

FIG. 6. Spectrum of typical Marshallese adult male compared with that of member of the U.S. Medical Team.

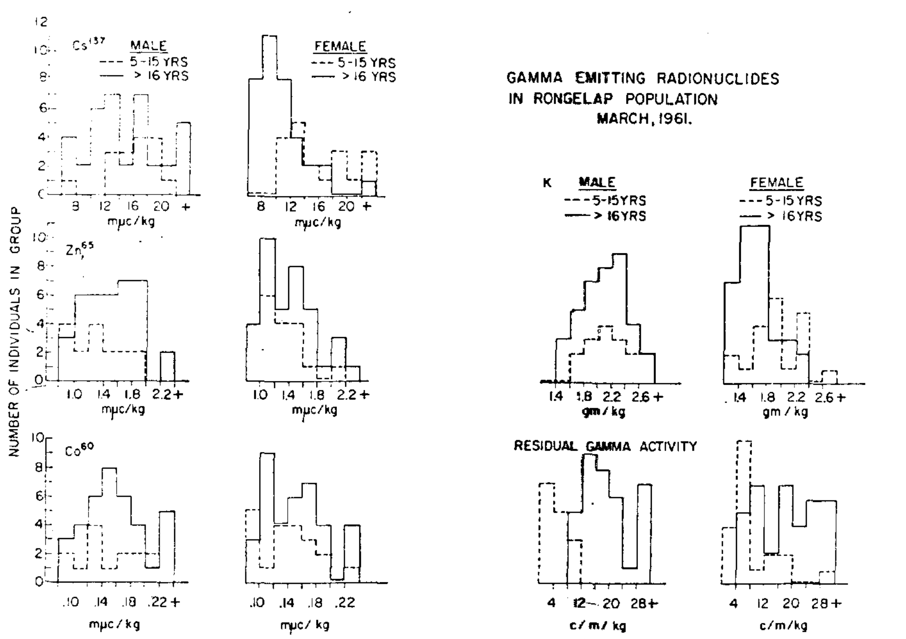

FIG. 7. Frequency distribution of levels of radionuclides in various Marshallese groups.

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Table 2. Summary of Marshall Islanders body burden—1961

	Rongelap				U.S. Medical Team
	Male		Female		
	Years		Years		
	5–15	>15	5–15	>15	
Cs^{137}—nc/kg:					
exposed	15.8 ± 1.28*	16.0 ± 2.12	16.3 ± 1.55	11.1 ± 0.95	
unexposed	15.7 ± 1.42	14.2 ± 1.27	15.9 ± 1.51	9.84 ± 0.90	0.048 ± 0.012
	15.8	14.7	16.2	10.4	
Zn^{65}—nc/kg:					
exposed	1.31 ± 0.13	1.70 ± 0.15	1.20 ± 0.08	1.58 ± 0.09	
unexposed	1.30 ± 0.02	1.43 ± 0.07	1.32 ± 0.15	1.28 ± 0.07	0.015 ± 0.003
	1.31	1.51	1.24	1.42	
Co^{60}—pc/kg:					
exposed	159 ± 14.5	161 ± 11.1	127 ± 14.4	170 ± 18.6	
unexposed	152 ± 22.6	159 ± 11.8	155 ± 27.3	137 ± 8.83	6.43 ± 1.39
	156	159	137	139	
K^{40}—g/kg:					
exposed	2.11 ± 0.10	2.07 ± 0.07	2.03 ± 0.05	1.53 ± 0.07	
unexposed	2.26 ± 0.09	2.13 ± 0.07	1.77 ± 0.11	1.71 ± 0.06	1.72 ± 0.05
	2.17	2.11	1.94	1.63	
Total residual activity cpm/kg:					
exposed	5.40 ± 0.89	20.5 ± 2.72	9.30 ± 2.53	19.8 ± 2.06	
unexposed	4.50 ± 1.42	20.3 ± 1.91	8.50 ± 2.00	18.0 ± 1.80	2.00 ± 0.59
No. of people					
exposed	10	11	13	17	
unexposed	6	26	7	20	
Total	16	37	20	37	7

*Standard error of mean.

we observe in this study is the radioactivity derived from the slightly contaminated environment.

The levels of radioactive contamination appeared to be about the same for juveniles as for adults, for men as for women. Factors of age and sex apparently do not influence significantly the deposition of these radionuclides. Wide variations in the level of contamination appear among individuals of all groups, as might be expected where the source of the contamination is via ingestion. Even with a fairly limited diet, individual tastes may dictate great differences in the food consumed.

As for the time course of the contamination in the population as a whole, it is necessary to consider each radioisotope individually, as source of supply and discrimination of the soil, plant and animal life, and the human body differ for each isotope.

The mean Cs^{137} body burden of the Rongelap adult males is 14.7 nc/kg as compared to 14.1 nc/kg in 1959. Thus, no significant change has occurred in the past two years. The high Cs^{137} body burdens of the Marshallese result from the high dietary intake through foodstuffs produced in the Marshallese environment. They reflect the level of residual fallout on the island, and also the higher uptake and retention of Cs^{137} by food plants grown in a K-deficient soil. It appears that the body burden of Cs^{137} has reached an approximate equilibrium with the levels of Cs^{137} in the diet (although this is a difficult point to ascertain). The uniformity of the Cs^{137}/g K in the entire Marshallese population suggests that the Cs^{137} level like K^{40} is proportional to the lean body weight.

The mean Cs^{137} body burden of the Rongelap adult (14.7 nc/kg) males was 300 times that of the mean of the medical team carrying out the study (0.048 nc/kg). The level of Cs^{137} in the world-wide population in July 1961 appears to have declined from the maximum level observed in 1959. The average value for Cs^{137} measured in BNL personnel, for example, declined from 59 pc/g K in June 1960 to 30 pc/g K in December 1961. The body burdens of the Marshallese will, of course, also be affected by this world-wide fallout as well as by the fallout released in the series of tests carried out by the U.S.S.R. in October 1961. As the accumulation is gradual both in the environment, as world-wide fallout settles out, and in the human body, via the ingestive route, it will be a number of months before a clear picture emerges. However, after the moratorium of three years, during which time the Cs^{137} levels had an opportunity to stabilize, it will be clear what the direct results are of that particular series of tests.

The mean Zn^{65} concentration/kg body weight of the Marshallese does not differ significantly between the exposed and unexposed groups, nor does it differ on the basis of sex or age. However, the mean was generally slightly higher among adults than in juveniles, and higher among adult males than adult females. In the period 1959–1961 the value of Zn^{65} body burden dropped by a factor of six. The value of Zn^{65} in male adult Marshallese dropped from 9.9 nc/kg body weight in 1959 to 1.51 nc/kg in 1961. No clear reason emerges as the basis for this difference, although it is possible that dietary variation may be responsible. It is known that the source of Zn^{65} in these people is from fish which selectively concentrate this element. Therefore, it is possible that the decrease in Zn^{65} levels noted may be due to the fact that the people are eating more canned meats in place of fresh fish. If the Zn^{65} intake in the diet were decreased radically during that period, the observed fall in the level of internally-deposited Zn^{65} would be consistent with the effective half-life of Zn^{65} which is approximately 120 days.[9] The evidence that could be obtained on this subject is insufficient to make any conclusive statement, however.

While levels of Zn^{65} body burdens equivalent to those found in the Marshallese (1.15 nc/kg body weight) were observed in certain BNL reactor workers,[10] the values in the Rongelap population were about 100 times those measured in the members of the medical team. The mean level of Zn^{65} in the medical team was 0.015 nc/kg body weight, less than or equal to the precision of the counter, and therefore not statistically significant (Table 2).

The K content of the adult Marshallese male averages 2.12 g/kg, compared to the mean for the medical team of 1.72. The average K in g/kg of a large group of male employees at BNL who have been studied is 1.84 g/kg body weight.[10] The higher value for the Marshallese males reflects their well-developed musculature and low fat content, as the value of K is proportional to the lean body mass. Thus, the K values for the Marshallese females are generally lower, in the range 1.52–1.71 g/kg body weight. As expected, the K concentrations measured in the children are somewhat higher than those of the adults, and particularly among females.

A new and very interesting finding of this study was the determination of the presence of Co^{60} in the Marshallese population. The mean level is fairly uniform, about $\frac{1}{9}$ of the Zn^{65} level, but the spread in values in any one group is large. There is a fairly consistent correlation between the Zn^{65} and the Co^{60} values, which could very well reflect their common origin in the fish, snails and clams of the Marshallese diet. The induced activity, Co^{60}, had not been detected previously in this population because its very low level was masked by the relatively large peaks of the other radionuclides in the relatively short counting periods hitherto used. It was to reveal just such secondary levels that the longer counting period and larger detector were adopted for the 1961 study.

The residual γ-activity in the spectra remaining after the subtraction of the major components indicates that there are some residual radionuclides not present in sufficient quantity to reveal themselves via their photopeaks. The adult groups all had approximately the same level of residual activity, while the juveniles had apparent values of 25–50 per cent of the levels of the adults. These lower values may be due, in part, to the use of the standard man phantom in calibration of the various radionuclides in the juveniles. The oversubtracting of the low energy end of the calibration spectra would give an apparent lower residual value for the juveniles. The residual activity values in the adult groups were at least 10 times the mean observed in the U.S. medical team. Unfortunately whole-body counting techniques have not been developed for external beta counting of the very important fission product Sr^{90}. Its levels can only be estimated from data obtained by radiochemical analysis of urine. Undoubtedly the bremsstrahlung resulting from the Sr^{90} body burdens in the Marshallese contributes to the residual activity noted above.

A study of the levels of body burdens of the several γ-emitting radionuclides in the Marshallese people indicates how the fission products move through the environment and accumulate in man. Further, the biological turnover rate of these radionuclides in human beings can be estimated. The survey made with the portable whole-body counter has veen invaluable in monitoring the levels of internal contamination of γ-emitters in this population. The experience gained in this study should be of value in future surveys among other populations.

No difficulty was encountered in setting up the shielding for the BNL portable counter as equipment for moving it intact was readily available. Although it was not necessary to dismantle the shielding between surveys, it would not have been difficult to do so. However, because of the weight and bulk of the shielding, thought has been given to developing other types of shielding for use in the field, particularly for use in places where weight might give rise to transportation difficulties. Materials other than steel and in smaller units of weight might possibly be used. The shipment and operation of the electronic facilities present no particular problem. Once a satisfactory counting geometry has been worked out at the "home" installation, its duplication provides the best solution to the problem of setting up a satisfactory counting geometry for field use, as it enables calibration measurements to be checked at later times in the "home" laboratory.

The whole-body γ-spectrometer can be valuable in the field, not only to survey situations in which populations are contaminated with radionuclides, but as a clinical research tool.[8] It is possible, and may be desirable, to carry out in the field demographic studies with the use of radioactive tracers, and it is also possible to carry out such clinical studies as the investigation of metabolic and nutritional diseases, which may have their origin in the particular local environment.

Thus the portable whole-body spectrometer is an instrument with considerable application in health physics and clinical research problems.

CONCLUSION

The usefulness of a portable whole-body γ-spectrometer in the assay of the body burdens of mixed fission products and induced activities is illustrated by the 1961 field study of the internal contamination in a population of Marshallese people at Rongelap Atoll. The apparatus and the techniques of measurement, automatic data-handling and computer analysis of complex spectra are described. The results of the spectral analyses are presented and compared with a control group, and with the previous values obtained.

In addition to its application in the determination of body burdens of radioactive isotopes in populations exposed to fission products, numerous clinical applications of the whole-body γ-spectrometer may be made. Studies of large scale health problems, such as epidemics by means of radioactive tracers and whole-body counting, offer a new approach to a number of old problems. By means of the portable whole-body counter, these studies may be carried out anywhere in the world.

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