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● *Internal Contamination—Assessment*

DESIGN AND OPERATION OF A WHOLE-BODY MONITORING SYSTEM FOR THE GOIÂNIA RADIATION ACCIDENT

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Abstract—**With as many individuals involved in the Goiânia ^{137}Cs accident who had high levels of internal contamination, it was necessary to improvise a whole-body counter installation *in loco*. The *in-vivo* counting system was located in a 4.0 × 3.5 × 3.5-m room, where seven layers of 2-mm lead sheets with dimensions of 2.0 m × 1.0 m were overlaid on the floor at loci that were equidistant from the walls. A 20-cm diameter NaI(Tl) detector was installed at a height of 2.05 m above the floor at the center of the room. The detector was shielded and collimated with 5 cm of lead. The enormous amounts of activity in the subjects required the detector to be positioned at a height of 2.05 m. Subjects were required to wear disposable clothing and lie on a reclining, fiberglass chair. Counting time for the subjects was 2 min (live-time). The minimum detectable ^{137}Cs activity for this counting time was 7.3 kBq* (0.05 significance level). Besides the accident victims, all individuals who had direct or indirect contact with contaminated people or areas were also monitored. More than 300 people of both sexes, with ages varying from a few months to 72 y, were measured for whole-body radioactivity. The observed activities ranged from less than the minimum detectable activity (MDA) to 59 MBq.**

INTRODUCTION

THE RADIOLOGICAL accident that occurred in Goiânia, Brazil in September 1987, by the violation and rupture of a CsCl source containing 50.9 TBq (1375 Ci) of ^{137}Cs, resulted in external and internal exposures of members of the public who were directly or indirectly involved with the source. To evaluate the radiological hazards from these exposures, several individual monitoring methods were used.

Because of the distance between the accident site and any radiation protection center with the capability of performing internal monitoring by *in-vivo* measurements, the dosimetric assessment of the internal contamination was done initially by urinary and fecal bioassay. As the intakes were calculated through the use of age-specific metabolic models (Leggett et al. 1984), it became evident that we were dealing with subjects who had very high internal contamination and that evaluation by whole-body counting would present some unfamiliar problems.

Whole-body counting was attempted for the 14 subjects that were brought from Goiânia to the Navy Hospital in Rio de Janeiro where an *in-vivo* shadow-shield monitoring system was available. However, as was foreseen, the activities were far too high for that instrumentation, as well as those in all other existing facilities in the country, which were designed to measure internal contamination levels just slightly higher than the ICRP reference limits (ICRP 1979). To solve this problem, an *in-vivo* measurement system had to be designed and built *in situ*.

Due to the number of people internally exposed to ^{137}Cs and the seriousness of the accident, it was necessary to set up the counting system in the city of Goiânia so that many subjects could be measured as quickly as possible. These measurements were of fundamental importance in establishing the committed effective dose equivalent and the effectiveness of the internal decontamination therapies applied (mainly oral Prussian Blue administration).

METHODS

To perform dosimetric assessment by *in-vivo* bioassay methods, on 29 October 1987 we began the design, construction, and testing of three different systems at the Institute of Radiation Protection and Dosimetry/National Nuclear Energy Commission (IRD/CNEN), which were taken to the Goiânia General Hospital (GGH) a week later. The reason for installing and testing all three systems *in loco* was to determine the one that had the best performance for any measurement situation in terms of (a) counting efficiency, (b) counting time, (c) counting geometry, (d) minimum detectable activity, and (e) system dead time.

These systems were set up sequentially in a 4.0 × 3.5 × 3.5-m room, where seven layers of 2-mm lead sheets,

* The MDA of 7.3 kBq refers to the site on 57th Street. Another MDA of 9.1 kBq was the limit at the hospital location, discussed in the text.

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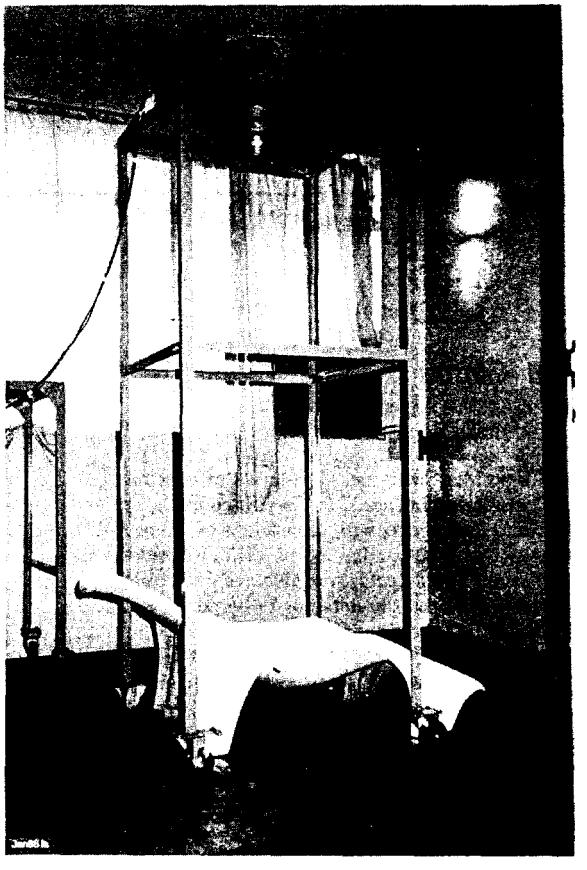

Fig. 1. *In-vivo* monitoring system #3. Note the unusually large separation between patient and detector and the use of a fiber chair. (Reproduced from *The Radiological Accident in Goiânia*, 1988, with permission by the International Atomic Energy Agency.)

2.0 m × 1.0 m, were overlayed on the floor equidistant from the walls. The walls and ceiling were not shielded.

The first system tested consisted of a 20-cm diameter × 10-cm thick (8″ × 4″) NaI(Tl) detector, shielded and collimated by 5 cm of lead wrapped around the crystal. The detector was mounted in the center of the room at a height of 1.31 m above the floor in an iron framework (1.36 m height × 0.9 m width × 0.85 m length). The subject was positioned below the detector, lying on a 3-cm thick foam mattress on the floor. An Ortec 7100† portable analyzer was used for the hospital measurements.

After 3 d of measurements, it was observed that this system did not accommodate all measurement situations, especially when counting people with high levels of internal contamination, i.e., up to 59 MBq (1.6 mCi). For these subjects, the net counting rate ranged from 2.5×10^5 to 1.8×10^6 cpm, and the dead time ranged from 20% to 45%, resulting in a sum peak (i.e., the sum of two 662 keV ^{137m}Ba photons interacting in the crystal volume close enough together in time to be observed as a 1324-keV peak). This provoked counting rate losses in the 662-keV peak and thus a calibration error.

The second system tested consisted of a 7.6-cm × 7.6-cm (3″ × 3″) NaI(Tl) detector, without lead collimation, positioned over an iron framework similar to the one described above but at a distance of 2.19 m between the center of the detector and the floor. This arrangement did not accommodate our purpose either. Although it did not exhibit the dead time and sum peak problems, it had very low detection efficiency. To solve this problem, we would have had to increase the counting time. This was attempted, but because of subjects' refusal to be measured for longer periods (10 to 20 min), this array was also rejected.

After analyzing all the factors that made both of these configurations inapplicable, we tried to use the second framework described, with the collimated detector used in the first system. Because of the refusal of some subjects to lie down on the thin foam mattress, we replaced it with a fiber chair (the type used at swimming-pool facilities). In this configuration, close to an arc geometry, the distance from the center of the chair to the geometric center of the detector was 2.05 m, as shown in Fig 1. This system was demonstrated to be efficient for all subjects in this series of measurements, so it was adopted as the final configuration. The dead time was lower than 8% for the subject with the highest contamination, and the minimum detectable activity (MDA) was equal to 9.1 kBq (247 nCi) for a 2-min measurement (0.05 significance level).

An adult-sized phantom consisting of a commercially available, hollow, thin-walled (3 mm), fiberglass mannequin (Maiello et al. 1986) was used for calibrating this system. The modification of the mannequin shell for use as a phantom was minimal; i.e., "windows" were cut to allow access to the hollow interior and flexible hip and knee joints were added so the filled phantom conformed to the same counting position as the subjects.

The ^{137}Cs standard [118 ± 2 kBq (3.2 μCi)] used within the phantom was calibrated by the Metrology Department of IRD/CNEN. The source was diluted in a 0.1 N nitric acid solution and distributed uniformly within the phantom in 60 polyethylene bags. Each bag contained approximately 250 mL. The validity of the arc geometry was tested and verified by placing the bags in a smaller, shorter-length phantom. The counting efficiency remained the same, within statistical limits, regardless of the size of the phantom. Thus, using the arc geometry, the same calibration factor could be used for a contaminated infant

Table 1. Corrections made to data of three highly contaminated subjects.

Subject	Net CPM ($\times 10^5$)	R	Fitted net CPM ($\times 10^5$)
DAF	11	7.19	14
RSA	8.7	14.60	9.9
ODJ	5.6	38.10	5.9

† EG&G Ortec, 100 Midland Road, Oak Ridge, TN 37831-0895.

1005146

or a 2-m adult, since the average distance from the center of the crystal of all points along either the adult or child body is the same.

The system was set up at the hospital initially because some of the contaminated subjects were clinically debilitated due to their acute radiation exposure and had to be kept isolated. The same procedures applied to routine *in-vivo* measurements were also applied to the accident subjects, i.e., changing of clothes, disposable overshoes, measurement of height and weight, and completion of personal data sheets. Subjects were not required to shower immediately before measurement since daily showering was performed as a rule. However, they were routinely monitored for external contamination using a β counter before measurement. In addition, those subjects who had transferrable external contamination had been decontaminated previously.

The whole-body counter at GGH was in operation until 15 January 1988 when it was transferred to a single-story house at 121 57th Street, Central Sector, Goiânia, GO. This location was chosen for a follow-up program since the subjects were no longer interned at the GGH and most lived in the adjacent neighborhood.

As the background counting rate at the 57th Street location was found to be about four times higher than at GGH, it was necessary to identify the origin of the increase and to adopt a corrective action before further *in-vivo* measurements could be made. Some shielding designs were tested, such as covering the walls and the sides of the iron framework with a few millimeters of lead. The problem of excess background was finally solved by shielding the top part of the detector. The increased room background was due mainly to ^{137}Cs roof contamination, which was confirmed subsequently by a team investigating environmental radiation.

With this new shielding design, the MDA for the same 2 min of counting was lower than at the hospital, i.e., 7.3 kBq (197 nCi) for ^{137}Cs, which corresponds to approximately 0.2% or 1.2%, respectively, of the annual limit on intake (ALI) for radiation workers for ingestion

Table 2. Number of contaminated subjects per range of body burden as determined by first whole-body monitoring.

Body burden (kBq)	No. of subjects
7.4–37	57
37–370	43
370–3,700	22
3,700–29,600	19
29,600–59,200	2

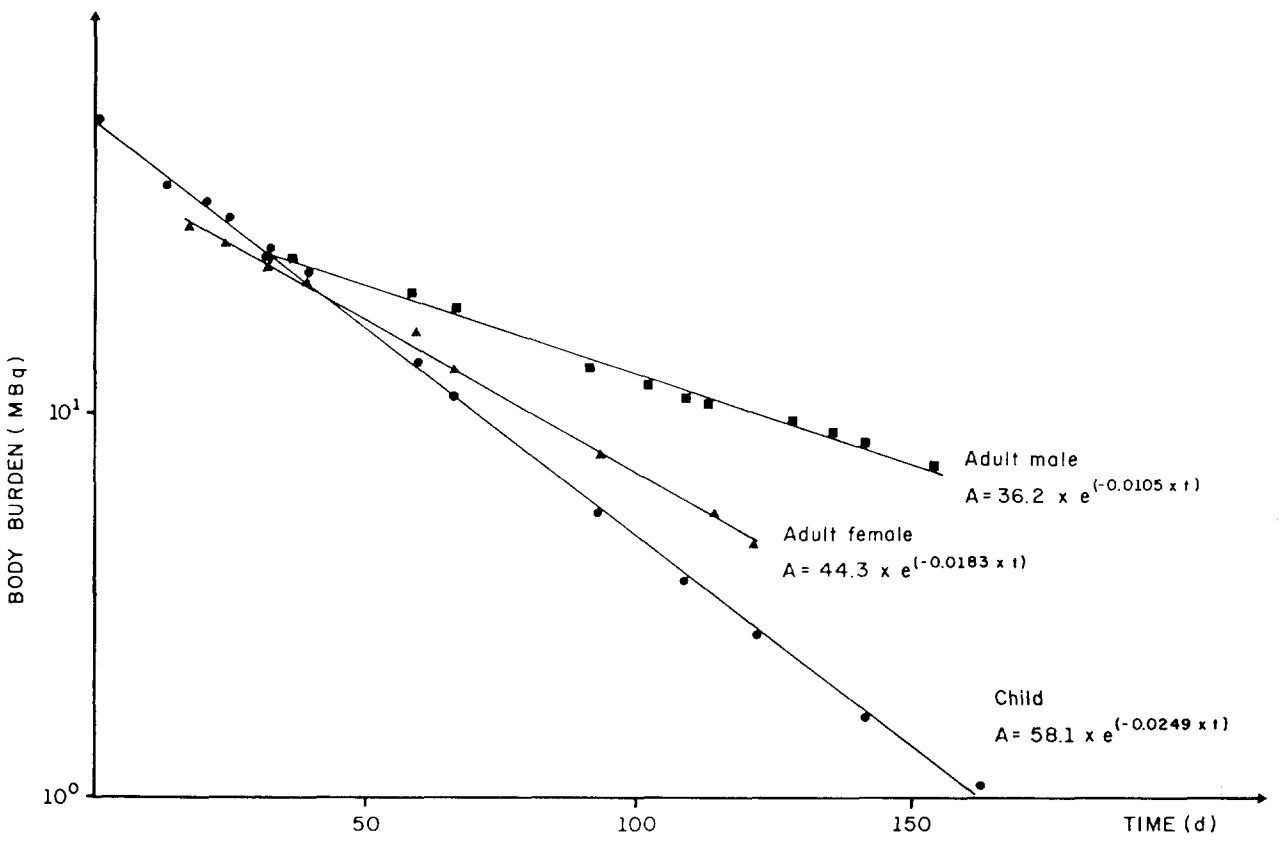

Fig. 2. Body burden of ^{137}Cs vs. time after first measurement for an adult male (■), an adult female (▲), and a 13-y-old child (●) during Prussian Blue administration.

1005147

or inhalation (ICRP 1979). After establishing the best shielding design, remeasurement of subjects began on 5 February 1988.

RESULTS AND DISCUSSION

From 8 November 1987 to 13 April 1988, we performed whole-body counting on 356 subjects nonoccupationally involved in the accident. Among these, 143 showed internal contamination levels above MDA, which was determined by the method described by Altshuller and Pasternack (1963). The emergency workers were monitored in this system and at the IRD/CNEN whole-body counter unit as well (Oliveira et al. 1989). The internal contamination of all the workers was far below the ALI for ^{137}Cs. Although the first set of measurements with system #1 presented very high counting rates, dead time, and losses due to summing, these measurements were not discarded but were corrected (Knoll 1979).

We verified the existence of an exponential relationship between the net counting rate in the ^{137}Cs region of interest (P) and the ratio (R) between P and the net counting rate in the sum peak region (S). To determine the coefficients of this relationship, measurements were done using a 333-kBq (9.0-μCi) ^{137}Cs standard point source placed at different distances from the center of the detector. With this arrangement, we reproduced the counting rates in the ^{137}Cs region that were observed with the subjects measured with system #1. The relationship between the counting rates in the ^{137}Cs photopeak and the sum peak was found to be:

$$R = 213e^{(-3.08\times10^{-6}\times P)}$$

$$r^2 = 0.9986, \qquad (1)$$

where

r^2 = the linear correlation coefficient.

Assuming that each count that appears in the sum peak region corresponds to two counts lost from the region of ^{137}Cs photopeak when there is no dead time, the fitted net counting rate could be expressed as the following:

$$\text{Fitted net cpm} = \text{net cpm} + (2 \times \text{net cpm } R^{-1}). \qquad (2)$$

As an example of the method described above, Table 1 shows the corrections made on three subjects whose counting rates resulted in substantial dead times. The corrected activity values fitted closely to the subsequent measurements made with system #3 at a much lower dead time, indicating that the method described is acceptable.

According to the ^{137}Cs body burden of each individual, a whole-body counting frequency was estimated. Among the 143 subjects that showed detectable internal contamination, the highest measured level was 59.2 ± 2.0 MBq (1.6 ± 0.1 mCi) on 11 November 1987. Table 2 presents the number of contaminated subjects per range of body burden, considering only the first *in-vivo* measurement result.

Figure 2 shows examples of ^{137}Cs body burden as a function of time after the first measurement for an adult male, an adult female, and a 13-y-old child during the period of Prussian Blue treatment. All curves presented were fitted to a single exponential of the form:

$$Y = ae^{-bX}, \qquad (3)$$

where

Y = fitted body burden on day X (Bq);
X = day of measurement (d);
b = diminution constant (d^{-1}); and
a = fitted body burden on day 1 (Bq).

All changes in body burdens obtained from the measurements of the subjects were found to follow an exponential pattern. A detailed estimate of the biological half-lives for most of the measured subjects is presented in this issue (Lipsztein et al., this issue).

The body-burden curve of one adult male subject showed a different pattern compared to the other subjects. A two-exponential function was observed, as shown in Fig. 3, which could be explained by two different dosages of Prussian Blue. Although he was directed to take 10 g d^{-1} of medication continuously, it was suspected that these instructions were not followed all the time. The five initial measurements were performed while he was kept under rigorous medical control. During this period, he was really taking Prussian Blue. During the subsequent measure-

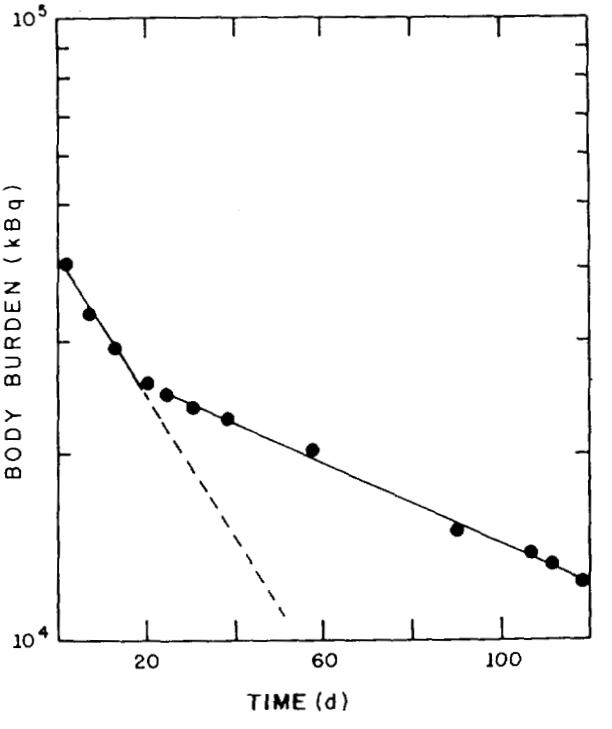

Fig. 3. Body burden of ^{137}Cs in an adult male subject vs. time after first measurement.

1005148

ment period, he had been discharged from the hospital and probably decreased the dosage or stopped taking the medication.

A follow-up *in-vivo* monitoring program is underway. As part of this program, special measurements relating to the uniformity of ^{137}Cs distribution in the body and hot spots are being carried out. "Hot spots" are areas of the bodies of certain subjects who rubbed the ^{137}Cs on themselves. These areas are scarified, and the Cs is apparently being retained at these sites as evidenced by increased counts seen during preliminary measurements. These studies are still underway, and the conclusions will be published as soon as possible.

CONCLUSIONS

The system attended the necessities for whole-body measurements, considering that the work was carried out under suboptimal conditions and necessary time constraints. We believe that our design and use of the whole-body monitoring system might be useful in the future to another investigator confronted with a similar situation.

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