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APPLICATION OF *in-vitro* BIOASSAY FOR ^{137}Cs DURING THE EMERGENCY PHASE OF THE GOIÂNIA ACCIDENT

Joyce L. Lipsztein, Luiz Bertelli, Dunstana R. Melo, Adelaide M. G. F. Azeredo, Ligia Julião and Maristela S. Santos
Instituto de Radioproteção e Dosimetria/CNEN, Av. das Américas, Km 11,5, Rio de Janeiro, CEP 22602, Brazil

***Abstract*—In the Goiânia accident, many individuals suffered external and internal contamination. The screening of internal contamination was done through ^{137}Cs urinary excretion. During the first month after the accident, only *in-vitro* bioassay procedures were done. Incorporation into the body and committed doses were estimated using age-specific mathematical models correlating these quantities to the ^{137}Cs excreted in urine. The ratio of feces to urine of ^{137}Cs excretion was used to evaluate the effectiveness of the administration of Prussian Blue on removal of ^{137}Cs from the body.**

INTRODUCTION

IN THE ^{137}Cs radiological accident that occurred in Brazil in September 1987, several individuals of different ages were involved. The main pathways for internal contamination were ingestion and penetration through wounds. The first step taken was to collect and analyze urinary excreta from all individuals with suspected exposures and use these data as a screening procedure. The next step was to collect and analyze daily fecal and urinary excreta from contaminated individuals to estimate, through suitable mathematical modelling, what had been the intake and to project the 70-y committed doses. Fecal and excretion data were also used to evaluate the efficiency of decontamination treatment with "Prussian Blue." Because of the need to rapidly provide information on internal contamination to the physicians, we used standard information on ^{137}Cs metabolism, which we found needed to be adjusted for body weight. Detailed statistical analysis of the data was conducted later after the emergency phase was over, and those results are reported in another paper (Lipsztein et al., this issue).

THE *in-vitro* BIOASSAY FACILITY

All excreta samples from the individuals involved in the Goiânia accident were shipped by air to Rio de Janeiro to be processed at the Radiation Protection and Dosimetry Institute's *in-vitro* laboratory. By chance, this laboratory had a layout that proved efficient for dealing with very highly radioactive samples. It had two separate entrances: one from the exterior of the building accessing the chemistry laboratory and one from the interior of the building, immediately accessing the counting room and through a corridor the chemistry laboratory. Adjacent to the exterior entrance was a storage room.

This configuration proved very efficient. Each highly radioactive sample was brought through the exterior entrance and placed in the storage room until it was processed. Waste samples were also kept in this storage room until they were disposed of by appropriate means. At the other entrance of the chemistry laboratory, standard radiation protection procedures were established.

SAMPLE COLLECTION AND PREPARATION

In our laboratory, excreta samples from contaminated individuals in Goiânia and from patients hospitalized at the Marcílio Dias Navy Hospital in Rio de Janeiro were processed. Complete, 24-h urinary collections were requested, but this instruction was rarely followed, especially in Goiânia. The samples were collected in plastic bottles and containers and were handled very carefully to avoid cross-contamination. A portable dose-rate meter was used to select samples that needed dilution (dose rate above 0.5 Gy h^{-1}, at contact).

The volume of the urine samples was measured. A 0.25-L aliquot was transferred to a plastic bottle labelled with the name of patient, day of sample collection, and total volume for analysis.

The bottles were packed in sealed plastic bags. The fecal samples were transferred to suitable containers for spectrometry. Their weights were determined, and the containers were labelled with the name of the patient, day of sample collection, and total daily weight. Nitric acid, 1 M, was added to each sample, transforming it into a homogeneous mass. The containers were packed in sealed plastic bags before counting. A planar 0.076 × 0.076 m NaI(Tl) detector enclosed in a Pb shielding was used.

A point source of ^{137}Cs and urine, feces, and diaper phantoms were used to calibrate the detector. Because the

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contamination levels were very high, a 1-min counting time was sufficient for most of the samples. The minimum detection level was 5.3×10^3 Bq L^{-1} for a 1-min counting time, $p < 0.05$. For the low activity samples, a longer counting time was required. As all samples were packed in sealed plastic bags, we had no problems with contamination of the detector or shield. More than 4300 samples from a total of 90 people were analyzed during the October to December 1987 period. Sixty-five percent of the samples had activities in the range 10^4 to 10^5 Bq.

DOSE MODELS

As internally contaminated individuals were screened, it was necessary to provide information on ^{137}Cs incorporation and to estimate committed dose, as required by the medical team. It was necessary to use age-specific mathematical models to calculate these data from urine sample analysis because the biological half-life of Cs in the body is age-dependent. A model based on the Oak Ridge National Laboratory (ORNL) report (Leggett et al. 1984) was adapted for use in the Goiânia case. The ORNL models were designed for newborn, 1, 5, 10, and 15 y old and adult groups. The models were adapted to fit Goiânian childrens' biotypes into the ORNL age groups. This was necessary since for each age group, most of the children involved in this accident had weights and heights much smaller than the standard American ones. One of the most contaminated teenagers for example, a 13-y-old, weighed 38 kg and was 1.45 m tall. Fortunately, we had recently developed a computerized sophisticated mathematical modelling capability at our institute (Bertelli and Lipsztein 1987), which made it possible to carry out the required calculations rapidly.

In our modelling, we assumed that ^{137}Cs compounds are rapidly and completely absorbed by blood from the gastrointestinal tract and after that, distributed uniformly in the body for all age groups. The nuclide retention is represented adequately by a two-component exponential expression, one representing a rapidly clearing compartment and the other a slower clearing one (ICRP 1979). In the adult, this is expressed by a 10% transfer of Cs to a compartment that has a biological half-life of 2 d and by a 90% transfer to a compartment with a half-life of 110 d (ICRP 1979).

Leggett et al. (1984) have shown that transfer coefficients and half-lives are age-specific. For a 5-y-old, for example, for a two compartment model, there is a transfer of 44% of the Cs to a compartment that has a biological half-life of 8.8 d and a transfer of 56% to one with a half-life of 32 d. For a 10-y-old, the transfer fractions and biological half-lives are, respectively: 36%—7 d and 64%—52 d (Leggett et al. 1984).

Using the model described above with coefficients and half-lives given in Leggett et al. (1984) and assuming a single intake of ^{137}Cs through ingestion, we have produced tables that predict the concentration in urine, feces, and the body per Bq of intake. These tables were produced for various times after exposure and for various age groups, as given in Table 1, for 5-y-old and adult subjects. For the adult case, our tables are similar to the ones presented for Cs in the U.S. Nuclear Regulatory Commission document, *Interpretation of Bioassay Measurements* (U.S. NRC 1987).

In most cases, exposure had occurred 10 to 15 d before anyone became aware of it, and it was very difficult to reproduce the exact time when exposure occurred. Most of the contamination came from eating with dirty hands and from contaminated kitchen utensils. We have assumed a single intake occurred on the first day each individual recalled he had been in contact with the opened source. Using this approach, we estimated the intake using urinary excretion samples taken before Prussian Blue treatment was initiated.

In ICRP Publication No. 30 (ICRP 1979), values for the 50-y committed dose equivalents per Bq intake are given. As these values are only applicable to occu-

Table 1. Predicted amounts of ^{137}Cs in urine, feces, and the body (in Bq per unit intake) calculated from age-specific metabolic models as described in the text.

	5-y-old child			Adult		
Time after intake (d)	Urine (24 h)	Feces (24 h)	Whole body	Urine (24 h)	Feces (24 h)	Whole body
	($\times 10^{-4}$)	($\times 10^{-4}$)	($\times 10^{-2}$)	($\times 10^{-4}$)	($\times 10^{-4}$)	($\times 10^{-2}$)
1	227.70	56.93	97.15	180.30	45.07	97.74
15	162.70	40.69	54.71	43.59	10.90	82.08
30	79.56	19.89	33.71	37.71	9.43	74.55
60	29.51	7.38	15.74	31.15	7.78	61.59
90	14.26	3.56	8.03	25.73	6.43	50.88
120	7.32	1.83	4.17	21.26	5.31	42.04
150	3.81	0.95	2.17	17.57	4.39	34.73
180	1.98	0.50	1.13	14.51	3.63	28.70
240	0.54	0.13	0.31	9.91	2.48	19.59
300	0.15	0.04	0.08	6.76	1.69	13.37
360	0.04	0.01	0.02	4.62	1.15	9.13

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pational exposure (e.g., quality factors determined for occupational exposure ranges), it was necessary to derive conversion factors that would correlate 70-y committed absorbed dose with intake for each age-range group considered in the accident. The following equation was used:

$$D_T = 1.6 \times 10^{-10} \times U_T \times \text{SAE Gy Bq}^{-1}, \quad (1)$$

where

D_T = committed absorbed dose at T days after 1 Bq intake;
1.6×10^{-10} = conversion factor J g MeV^{-1} kg^{-1};
U_T = total number of transformations per Bq intake over a period of T days; and
SAE = specific absorbed energy (MeV g^{-1}).

The number of transformations per Bq intake, during a period T, in a compartment is the time integral of activity within the compartment over the period T. Using the age-specific metabolic parameters cited above, we have calculated U_T for different time periods.

The specific absorbed energy (SAE) is the energy absorbed for each decay. Cesium-137 decays by β radiation, with mean energies of 0.1734 MeV (94.6%) and 0.4246 MeV (5.4%) (ICRP 1983) all being absorbed in the body. As Cs distributes itself uniformly in the body, and as the contamination was high, we assumed the human body to be a single compartment. SAE was calculated for ^{137}Cs as $(0.946 \times 0.1734) + (0.054 \times 0.4246)$ divided by the mean body mass appropriate for each age group; 94.6% of ^{137}Cs decays result in the formation of ^{137m}Ba, which in its turn decays to stable ^{137}Ba through a 0.662-MeV γ at 89% yield. The fraction of this γ energy that is absorbed in the body (AF) for a source uniformly distributed in the body was taken from a report on specific absorbed energy fractions at various ages from internal photon sources (Cristy and Eckerman 1987) and applied in:

$$\text{SAE}(^{137m}\text{Ba}) = 0.946 \times 0.89 \times 0.662 \times \text{AF}. \quad (2)$$

Finally, the committed absorbed dose for a period T is calculated by:

$$D_T = 1.6 \times 10^{-10}[U_T(^{137}\text{Cs})\text{SAE}(^{137}\text{Cs}) + U_T(^{137m}\text{Ba})\text{SAE}(^{137m}\text{Ba})] \quad (3)$$

or

$$D_T = 1.6 \times 10^{-10}[\text{SAE}(^{137}\text{Cs}) + \text{SAE}(^{137m}\text{Ba})] \times U_T(^{137}\text{Cs}), \quad (4)$$

since

$$U_T(^{137}\text{Cs}) = U_T(^{137m}\text{Ba}).$$

Figure 1 shows the time required to reach the maximum committed absorbed dose for different age groups. From this figure, it is clear that the dose is delivered to the patients during a limited time period, during which all decontamination treatment should be attempted. After that, no treatment is worthwhile.

RESULTS AND DISCUSSION

Using the mathematical models described above, it was possible to generate data on ^{137}Cs intakes and committed dose profiles (daily, monthly, and lifetime committed dose) from urinary sample analyses, as required by the medical staff.

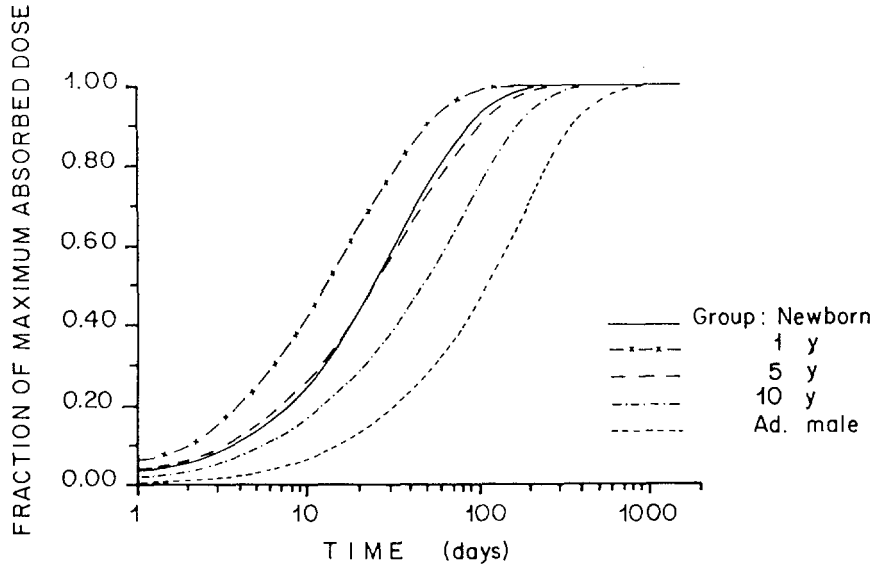

Fig. 1. Time after ^{137}Cs contamination vs. percentage of maximum absorbed dose for different age groups.

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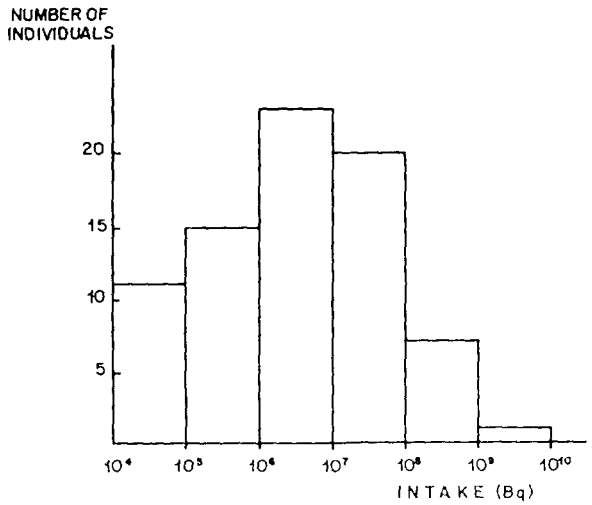

Fig. 2. Histogram of calculated ^{137}Cs intakes in the Goiânia accident group. (Reproduced from *The Radiological Accident in Goiânia*, 1988, with permission by the International Atomic Energy Agency.)

In Fig. 2, a histogram of the calculated ^{137}Cs intakes is presented. Figure 3 is a histogram of the internal 70-y dose commitment that would have been delivered if decontamination procedures were not utilized.

The subject with the highest internal burden, a 6-y-old girl, died on 23 October with an estimated internal dose of 4 Gy and an estimated intake of 1×10^9 Bq. The other three people that died had estimated intakes of 1×10^8 Bq, 5.5×10^7 Bq, and 2.0×10^7 Bq. As seen in the histogram presented in Fig. 2, intakes on the range 1.0×10^7 to 1.0×10^8 Bq were very common in Goiânia, and the internal contamination probably contributed very little to the death of these three adults.

It was also necessary to advise physicians on the effectiveness of the therapies applied to remove ^{137}Cs from the body. This was done through daily analyses of Cs excretion in urine and feces.

Prussian Blue is expected to remove Cs through fecal excretion. From the Cs metabolic model, it is expected that Cs elimination from the body is done mainly by urinary excretion, at a 4:1 ratio of urine to feces elimination (U.S. NRC 1987). This prevalent pathway for Cs elimination was indeed observed on the patients before Prussian Blue administration.

After administration of the drug in doses higher than 3 g d^{-1}, feces became the prevalent pathway for Cs excretion. As an easy way to visualize these relationships, graphs were generated showing Cs elimination in feces and urine (see Fig. 4).

Urinary excretion is directly correlated to the amount of Cs in the body fluids and consequently in the body, and we wanted to know if the decrease of Cs excretion in urine reflected a higher-than-expected decrease of Cs from the body through the action of Prussian Blue. Through our mathematical model, we transformed daily urinary excretion into simulated intake. As the intake was considered unique in our model, all urine data collected without Prussian Blue treatment would reproduce the same simulated intake, and one would end up with a straight horizontal line. A real decrease in the body burden would be reflected by a decreasing slope. Figures 5, 6, and 7 show the graphs for (a) an individual who had not taken Prussian Blue, (b) one that was given that same dose of Prussian Blue during the whole treatment, and (c) one that was given two different dosages of the medication, respectively.

Subsequently, the estimates of body burden from *in-vivo* measurements were compared to those derived from excretion data. A statistical test showed no significant difference between the two ($p < 0.5$).

CONCLUSIONS

We conclude that *in-vitro* excretion data are valuable and reliable for assessing internal contamination of exposed individuals. For ^{137}Cs, *in-vitro* bioassay is a fast and easy way to rapidly screen contaminated individuals. In our Goiânia accident case, people had very high external contamination of the skin that took several weeks to remove. Therefore, excreta measurements were the only reliable indicators of real internal contamination levels. It was also proven that when applying metabolic models to experimental data from individuals, it is very important to use a biological half-time appropriate to their age, weight, and height.

Prussian Blue, when given at the right dosage, proved to be a very good decontaminant, eliminating ^{137}Cs through the fecal pathway.

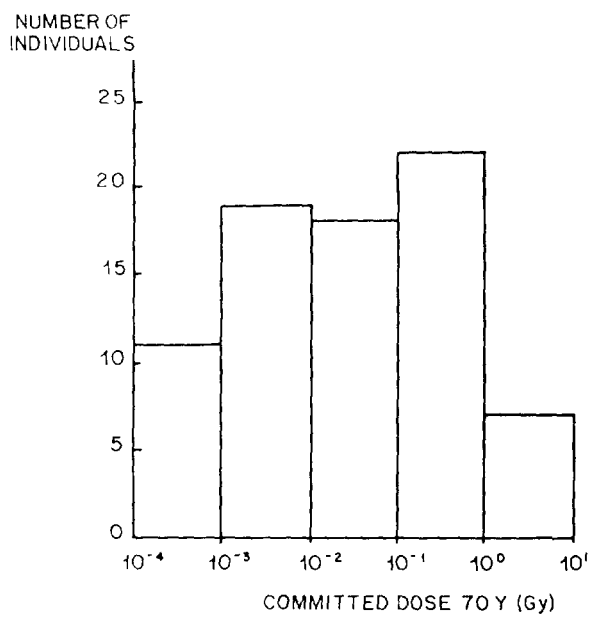

Fig. 3. Histogram of predicted 70-y internal committed doses without treatment. (Reproduced from *The Radiological Accident in Goiânia*, 1988, with permission by the International Atomic Energy Agency.)

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EXCRETION (X 10⁴ Bq)

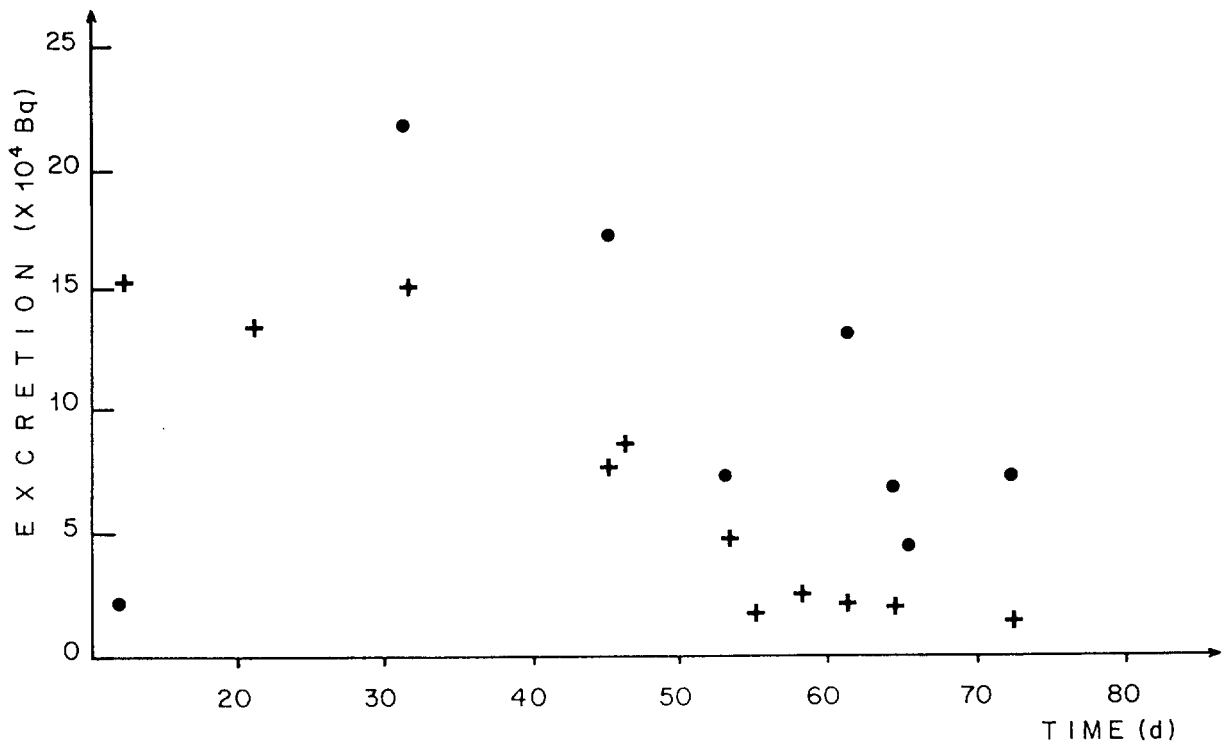

Fig. 4. Cesium-137 elimination in feces and urine for one patient in the Goiânia accident group. + = urine; ● = feces.

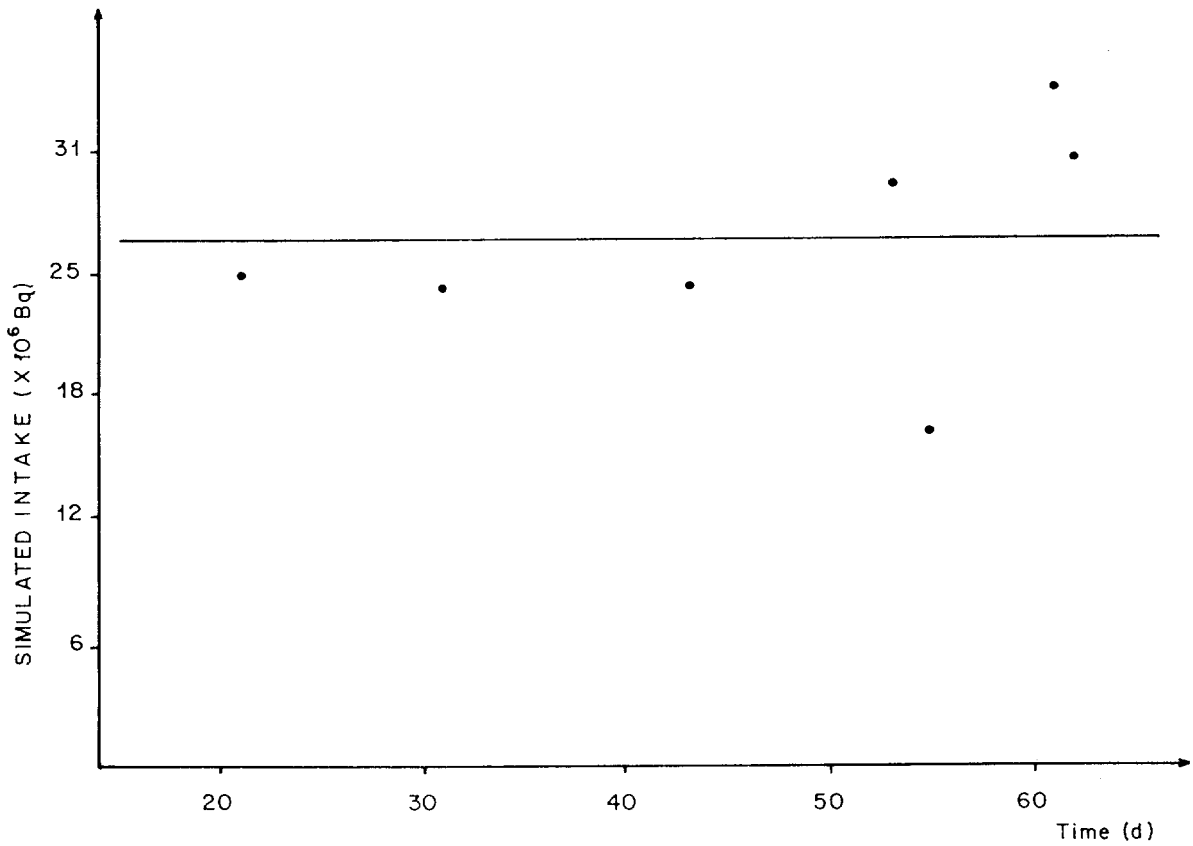

Fig. 5. Simulated intakes for an individual not treated with Prussian Blue.

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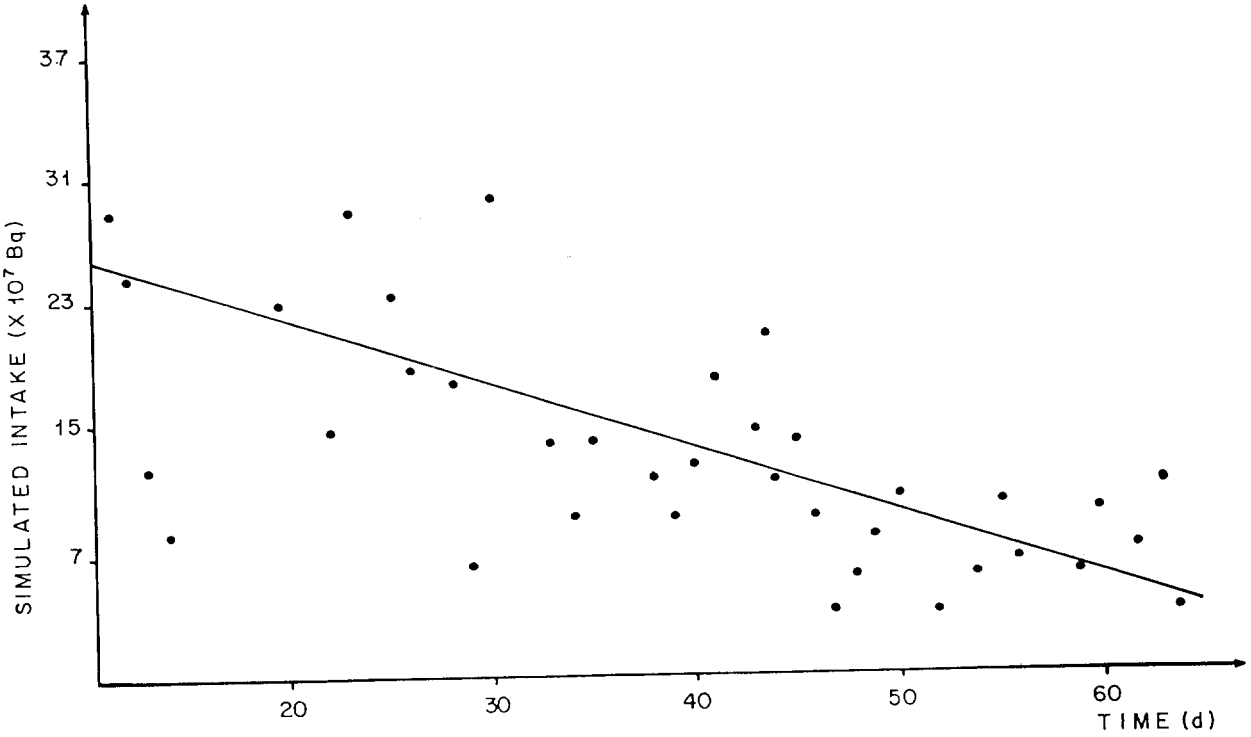

Fig. 6. Simulated intakes for an individual treated all the time with the same dosage of Prussian Blue.

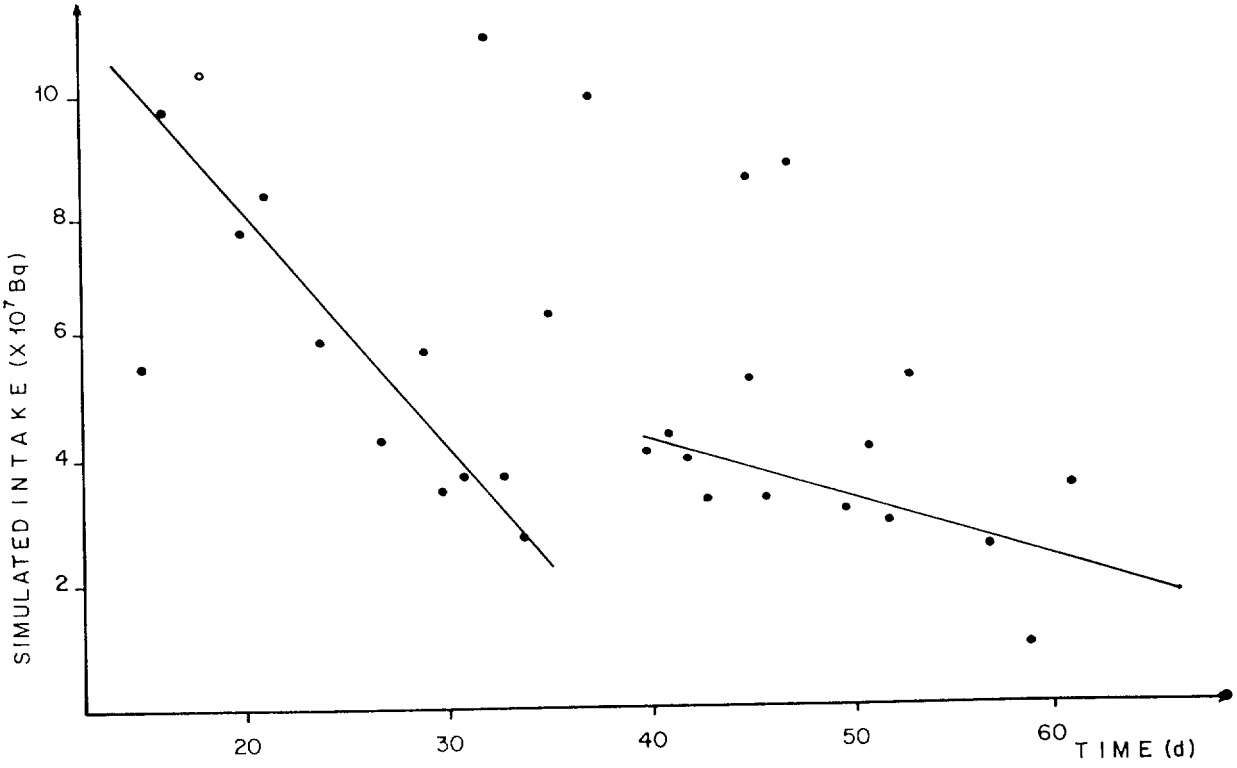

Fig. 7. Simulated intakes for an individual treated with two different dosages of Prussian Blue.

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