Radiocesium Levels in Humans Over a Four-Year Period

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Following the Chernobyl accident, Austria was one of the most contaminated Western European countries. Predictions of internal dose in humans due to this contamination were based on the average activities in major dietary products and average consumption rates. We have measured the amount of radiocesium in human adult muscle samples obtained at forensic autopsies within a limited area in Southern Austria over a period of 4 yr. From the measurements, we have estimated a mean individual effective dose equivalent of 252.2 μSv (25.2 mrem) due to internal exposure to radiocesium during this 4-yr period. This estimate, based on actual measurements, is approximately 25% of the predicted dose and is less than 50% of the dose received in the body from naturally occurring potassium-40. Comparisons of radiocesium activities measured in muscle tissues with data obtained after nuclear weapons tests and whole-body countings are given.

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The reactor accident at Chernobyl caused widespread contamination in Europe. The largest source of long-term radiation exposure was from internal contamination with radiocesium as a consequence of food intake. After the fallout in April 1986, many efforts were made to measure activities in foodstuffs and to predict the radiation dose which could be expected (*1*). The predictions of the ingested dose were carried out using a multiplicative relation which combines average activity concentrations in major dietary products, average consumption rates, and dose conversion factors for ingested radiocesium (μSv/Bq intake).

We have measured the actual accumulation of the long-lived nuclides ^{134}Cs and ^{137}Cs (physical half-lives 2.05 and 30.0 yr, respectively) in human muscle samples and compared the effective dose equivalent calculated by means of measured activities with the predicted dose. Muscle tissues were collected because cesium accumulates mainly in the muscle mass of the human body (*2*). Since a whole-body counter was not available, sampling of muscle tissues was a suitable way to observe activity concentration in humans. The provincial government carried out a project and transferred groups of the local inhabitants to the research center Seibersdorf (near Wien) for whole-body counting. It was therefore possible to compare our measured activity concentrations in muscle with whole-body measurements.

MATERIALS AND METHODS

Ingested cesium is deposited mainly in muscles (*2*). Three hundred muscle samples were taken at forensic autopsies in the area of Graz between July 1986 and June 1990. Graz has about 300,000 inhabitants and is located in the southern part of Austria (Fig. 1, reprinted with permission from reference 1). Samples were collected from both sexes (114 females, 186 males), and the average age (±stand. dev.) of the deceased was 65.5 ± 14.4 yr (range 21–86 yr). Most of the persons were between 45 and 85 yr old at the time of their death. This survey covered only people who were living in Graz and were not patients in a hospital at the time of their death. Autopsies had to be performed to reveal the cause of death. The sudden unexpected deaths (90%) were mostly due to coronary heart disease and related clinical pictures. About 10% of the autopsies revealed a fatal trauma resulting from vehicle accidents. No information was available concerning the pattern of food intake or individual habits.

The ground deposition of ^{137}Cs in the area where the samples originated was found to be in a range between 25 and 35 kBq/m^2; the region of the nuclear accident was located approximately 1100 km away. We also discovered large local variations in the deposition rate in an area of 50 km radius around Graz (values from 5 to 45 kBq/m^2). In this regard, it is also important to point out that milk and other foods consumed by the people of the study may have been produced in other areas.

Samples did not undergo any special preparation before counting. Activities of all samples (weighing from 52.5 to 309 g) were determined using calibrated germanium detectors and a computerized spectrum analysis. It was therefore possible to measure simultaneously the activities of ^{134}Cs, ^{137}Cs, and those of the naturally-occurring ^{40}K in each sample.

RESULTS

Table 1 shows a comparison of selected results published by other investigators after the world-wide fallout from nuclear weapons testing together with data recorded in Austria after the Chernobyl fallout. It is to be noted that, in contrast to the weapons fallout, the contamination following the Chernobyl accident occurred within a shorter time. Mean values or medians of the specific activities of

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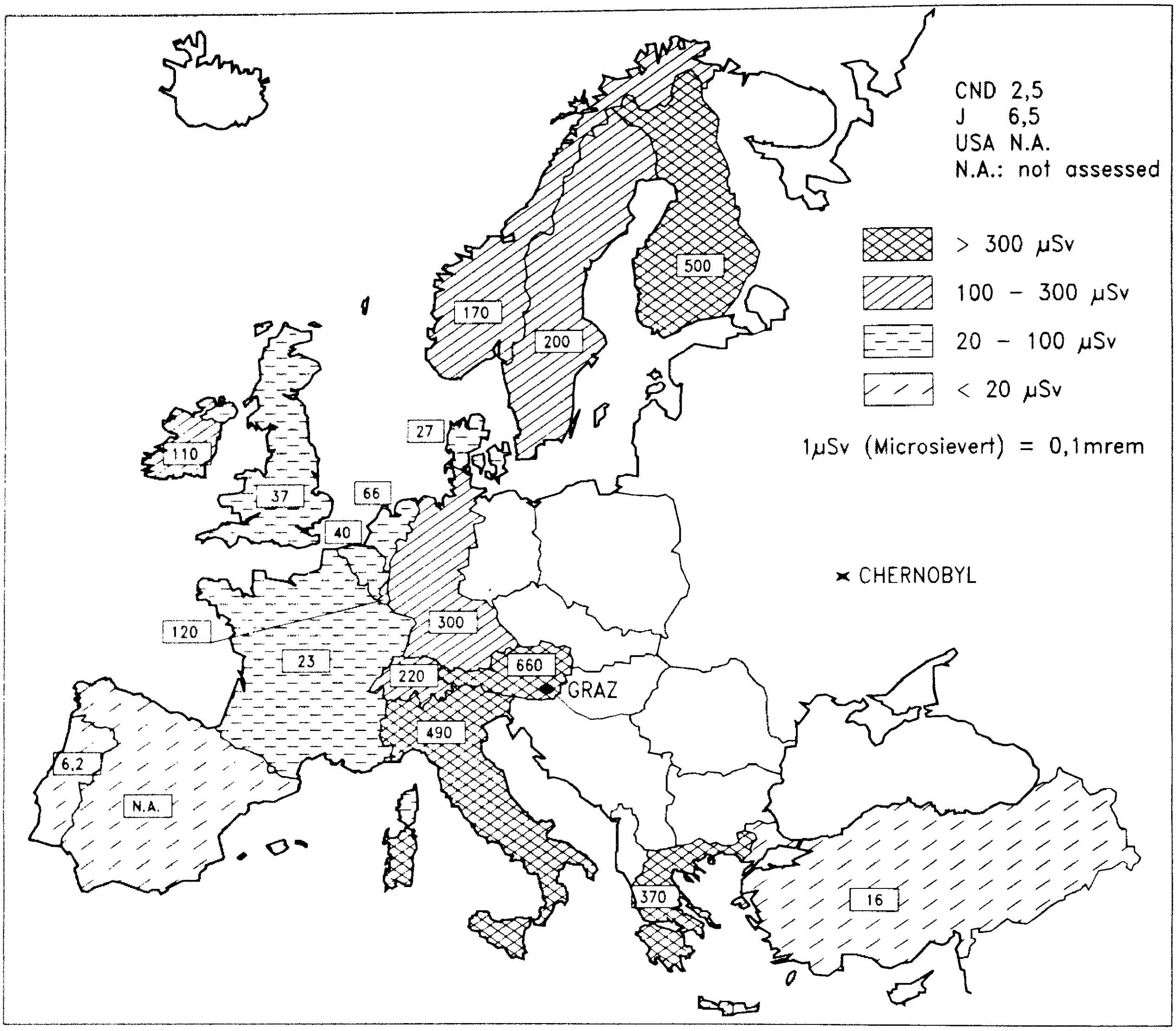

FIGURE 1. Average individual effective dose equivalents (*1*).

^{137}Cs are given in Bq/kg of wet tissue. As shown in Table 1, similar results were found in St. Pölten (130 km north of Graz). However, the St. Pölten study included people who had died in the hospital and were, for the most part, between 75 and 78 yr of age (*6*). Table 1 also gives the order of magnitude of ^{137}Cs activity concentrations in human muscle tissue that could thus be expected following a similar accident in a nuclear power plant where the contamination would be in the range described here.

Since about 70% of the whole-body content of cesium is distributed in muscle mass, the activity in muscle tissue can also be derived from results of the more commonly performed whole-body measurements and vice-versa (*7*). Using our measurements of muscle activities, the corresponding whole-body contents were calculated. These calculations are based on data from the ICRP concerning a standard man weighing 70 kg and with a muscle mass representing 40% of the total body (*8*).

As previously mentioned, several groups of people from Graz were transferred to the national research center for whole-body counting at various times following the Chernobyl accident. The results of our calculations of whole-body contents agreed with these whole-body measurements. For instance, the median of our muscle tissue measurements for ^{137}Cs in June and July 1987 (13 samples, aged 41–84 yr) was found to be 72.6 Bq/kg muscle weight. Whole-body measurements for a comparable group of individuals (13 people, aged 42–76 yr), at the beginning of July 1987 gave a median of 43.1 Bq/kg body weight. Taking the standard man as a basis, this corresponds to 75.4 Bq/kg muscle weight and agrees very well with the value obtained by muscle measurements. The variation of ^{137}Cs muscle activities with time is also in good agreement with the time course of the ^{137}Cs whole-body activities. Thus, it may be concluded that the data describing activities in the muscle tissue are a good representation of the

TABLE 1
Comparison of Specific Activities of ^{137}Cs in Humans

Tissue	Region	Period	Specific activity ^{137}Cs [Bq/kg]	Reference
Muscle*	Harwell, England	1959	8.3 (MA)	3
Muscle (thigh or lower abdomen)	Massachusetts, USA	Jan. 1961–June 1962	3.7 (ME)	4
Muscle (pectoral)	Japan	April 1963–Dec. 1963	4.4 (AM)	5
Muscle (gastrocnemius)	St. Pölten, Austria	July 1986–April 1987	59.2 (MD)	6
Muscle (iliopsoas)	Graz, Austria	July 1986–June 1987	56.2 (MD)	This work
		July 1987–June 1988	38.8 (MD)	
		July 1988–June 1989	12.6 (MD)	
		July 1989–June 1990	7.5 (MD)	

* Derived from whole-body measurements assuming that muscle mass contains 70% of the whole body activity.
MA = Max. value; ME = mean value; AM = average of mean month levels; and MD = median.

effects observed in a large part of the population. These findings also confirmed the distribution factor of 0.7 with regards to the amount of activity in muscle mass.

The multiple box-and-whisker plots in Figure 2 A–B show the time variation of the specific activities of ^{137}Cs and ^{134}Cs in human muscle tissues measured over the period of observation (July 1986–June 1990). In Figure 2C we present results for ^{40}K, a naturally-occuring radionuclide at a nearly constant level in the human body. Each box graph represents the distribution of the activities in the samples studied in a month. The central line in the box indicates the median of the single values. Outlying observations were not rejected in this analysis because they may be seen as a result of a natural variation in the specific activities caused by unusual food intakes. However, the maximum value of 354.6 Bq/kg muscle weight observed for ^{137}Cs in September 1986 is not presented in Figure 2A. A rapid initial increase in the specific activities of ^{137}Cs can be seen, which resulted in a broad peak of about 75 Bq/kg muscle weight and extended until October 1987. After that time, a decrease occurred, characterized by an environmental half-life of 9–10 mo. Figure 2A also indicates that more than 4 yr after the Chernobyl fallout, the ^{137}Cs activity concentrations returned to the values measured in the fifties and early sixties. The variation of the ^{134}Cs activities with time in Figure 2B follows a similar pattern to those of ^{137}Cs. The ratio of ^{137}Cs to ^{134}Cs in the muscle samples was found to be about 2 in July 1986. Because of its shorter physical half-life, ^{134}Cs has an activity decrease with a shorter environmental half-life of 6–7 mo.

To estimate the internal dose equivalents for radiocesium, medians were fitted to a mathematical function of time, and this function was integrated to obtain the specific cumulated activities. Since our observations did not start until July 1986, it was necessary to extrapolate the function back to April 1986. A value of 0.75 Bq ^{137}Cs per kg of muscle weight for April 1986 was used for best fitting (*9*).

In general, estimation of average dose is performed by applying the MIRD schema for specified source target configurations in the human body. Average absorbed dose is obtained by multiplying the cumulated activities in the source regions with tabulated values (S-factors), representing the average dose per unit cumulated activity (*10*). In our case, cumulated activities in the whole body were calculated from measured activity concentrations using data of the standard man from ICRP, and this activity content per year was then multiplied by the S-factor for the respective radionuclides.

Table 2 shows the average individual effective dose equivalent received by adults in the region of Graz. Uncertainties for estimated dose equivalents are within ± 25%. With regards to the variation of the ^{137}Cs levels with time, it is not surprising that the dose equivalent in the second year after the fallout was greater than in the first year. It is also interesting to note that the contribution of ^{134}Cs to the dose equivalent was substantial.

Predicted average individual effective dose equivalents due to radiocesium for Western Europe countries are given in Figure 1 (*1*). In Austria predictions have estimated an average individual total dose equivalent of 660 μSv for the first year after the fallout. This total dose includes the effects of countermeasures and takes into account all sources of exposure. Approximately 420 μSv can be attributed to internal dose in adults following exposure to radiocesium in the first year after the contamination (*11*). This predicted value of 420 μSv was later lowered to 386 μSv, and a value of 133 μSv was then predicted for the second year after the Chernobyl fallout (*12*). As a comparison with these values, our calculations from measured data gave 100.1 μSv and 107.1 μSv for the first and second year, respectively. We did not expect our values for the first and second year to be so comparable. It can, however, be seen that the calculated value for the first year is about a quarter of the predicted value. The calculated and predicted effective dose equivalents for the second year are comparable.

The mean individual effective dose equivalent following exposure to radiocesium during the 4 yr after the Chernobyl accident was calculated as 252.2 μSv (25.2 mrem).

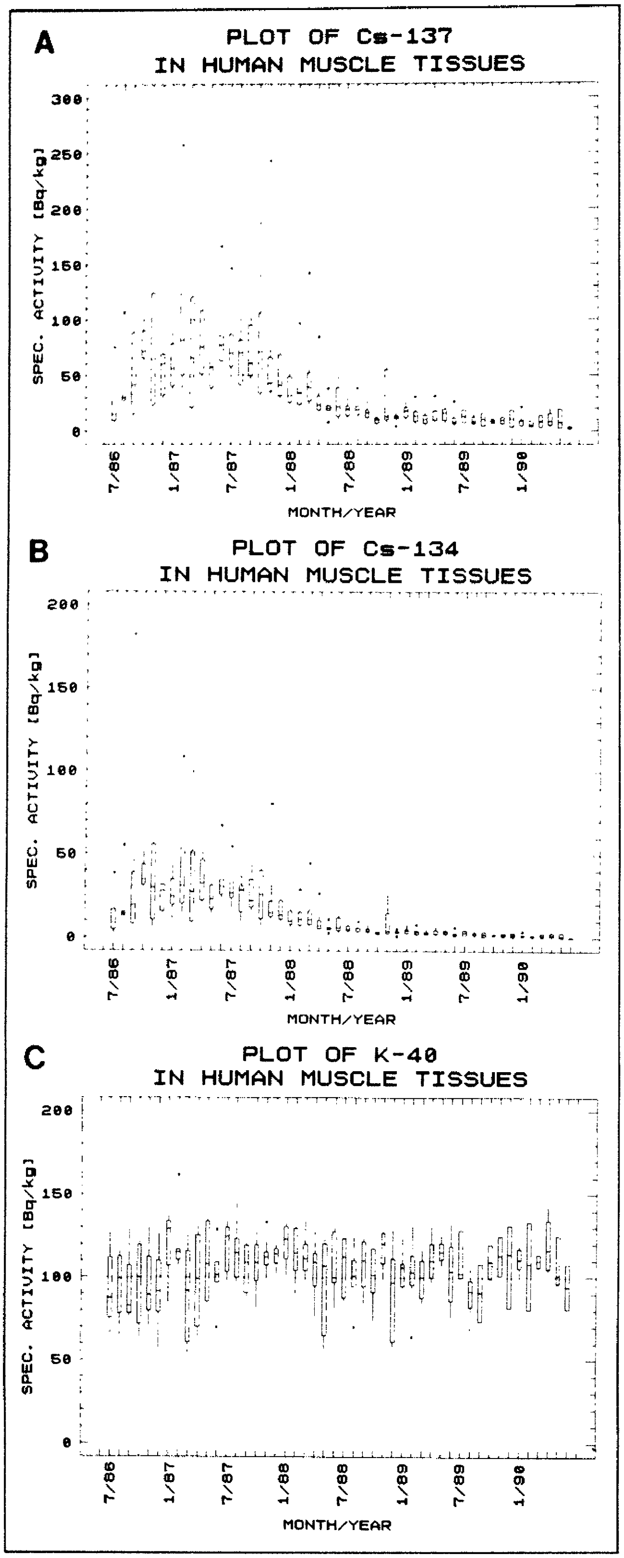

FIGURE 2. (A–C) The central box covers the middle 50% of data values between the lower and upper quartiles and the central line is at the median. The whiskers extend out to the minimum and maximum values that are within 1.5 times the interquartile range. Unusual values (outliers), removed from the bulk of the data, are plotted as separate points.

TABLE 2
Estimations of Internal Individual Effective Dose Equivalents

Period	Individual dose equivalent [μSv] ^{134}Cs	^{137}Cs
First year: May 1986–April 1987	40.4	59.7
Second year: May 1987–April 1988	38.1	69.0
Third year: May 1988–April 1989	8.9	22.2
Fourth year: May 1989–April 1990	3.2	10.7

1 μSv = 1 microsievert (= 0.1 mrem).

This value should also be compared to the 681 μSv (68.1 mrem) dose value found for ^{40}K during the same time period.

Our results also indicate that measurements of the radiocesium activities in human muscle tissues are an appropriate method to estimate effective dose equivalent and are a good complement to the usual whole-body counting procedure.

DISCUSSION

The results presented here show that predictions for internal doses have been in general overestimated. There are various reasons for this and many efforts are now being made to eliminate discrepancies between predicted doses and the doses calculated from activity measurements. We propose that the main reasons underlying the uncertainty of the predictions were the varying consumer rates and the unreliability of activity concentrations in major foods during the first year after the Chernobyl fallout.

Regarding the first point, the population of Graz was always very well informed about the most contaminated foods and, consequently, individuals took much care in their diet. Therefore, averaged consumer rates were changed in a significant manner. It is also possible that the effectiveness of the countermeasures was underestimated.

On the other hand, less attention was spent on obtaining reliable activity concentrations in major foods at the critical time after the fallout. Thus, we found great differences in the activity levels of radiocesium in milk which had been delivered by the producers to the dairy (raw milk) and the activity concentration in the milk which had been purchased and consumed by the population. To abide by the legal activity levels, highly contaminated milk was either mixed at the dairy with milk from low contaminated areas or processed into other milk products. In practice, however, the measurements did not take into account such measures and led to either suspect or high activity levels in the milk.

In summary, one may conclude that the value of the predictions is heavily dependent upon the quality of the data used to make them and that in any case measurements of human body activity are essential.

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