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UPTAKE AND EXCRETION OF ^{134}Cs FROM FALLOUT SIMULANT AND VEGETATION BY COTTON RATS

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Abstract—Cesium-134 tagged simulants with varying *in vitro* nuclide solubilities were analyzed with respect to absorbabilities of the ^{134}Cs by the gastrointestinal tract of cotton rats (*Sigmodon hispidus*). Analysis of fecal material showed a rapid increase in radioactivity until the 42nd hr postadministration. Complete passage of the particulate matter was assumed to have occurred by the 66th hr. The elimination coefficients (λ_b) and biological half-lives (T_b) of the ^{134}Cs absorbed from the various simulants were: (1) 0.76 %/hr, 3.79 days; (2) 1.16%/hr, 2.50 days; (3) 1.46%/hr, 1.98 days.

The second experimental phase was to establish uptake rates and equilibrium levels for ^{134}Cs in laboratory-born and wild-trapped cotton rats under chronic ingestion conditions, using ^{134}Cs tagged lettuce as simulated contaminated vegetation, and to determine retention curves for ^{134}Cs following termination of the chronic ingestion regimen. The ^{134}Cs uptake for both groups appeared to be a multicomponent curve. Equations for uptake in the first component, from hour 16 to hour 208, were as follows:

$$\text{wild trapped:} \quad Y = 0.7727 \cdot 10^{-2} X^{0.5614}$$
$$\text{laboratory born:} \quad Y = 0.7746 \cdot 10^{-2} X^{0.5354}$$

The second component began at hour 208 and continued until hour 544:

$$\text{wild trapped:} \quad Y = 0.4039 \cdot 10^{-2} X^{0.3448}$$
$$\text{laboratory born:} \quad Y = 0.4327 \cdot 10^{-2} X^{0.3278}$$

After the 544th hr the rate increase was so slight that it was considered to be zero. While the rate increase of both groups was not different, the amount of ^{134}Cs absorbed by the wild-trapped and laboratory-born groups showed a significant difference by the 64th hr. Retention curves, using the equilibrium levels as 100% incorporated ^{134}Cs, broke down into two components. The first component (day 1 through 7), considered to be representative of systems such as the liver and intestinal tract, gave retention equations and biological half lives of

$$\text{laboratory born:} \quad Y = 92.8e^{-0.1332X} \qquad T_b = 5.20 \text{ days}$$
$$\text{wild trapped:} \quad Y = 100.8e^{-0.1116X} \qquad T_b = 6.21 \text{ days}$$

The second component (days 8 through 35) is believed to be indicative of the longer compartments, such as muscle, and is represented by:

$$\text{laboratory born:} \quad Y = 61.7e^{-0.0853X} \qquad T_b = 8.12 \text{ days}$$
$$\text{wild trapped:} \quad Y = 79.0e^{-0.0827X} \qquad T_b = 8.38 \text{ days}$$

Serial sacrifices were made during both the uptake and excretion phases of the experiment, and eight tissues were analyzed for ^{134}Cs. Accumulation and loss of ^{134}Cs was slowest in muscle.

It appears that the type of material ingested and the method of ingestion, acute (simulant particles) vs. chronic (vegetation), influenced the metabolic kinetics of ^{134}Cs in cotton rats under laboratory conditions. Presumably, the cesium T_b was shorter in animals receiving a single dose of simulant because less cesium was incorporated in systemic compartments with slow uptake and long retention times.

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Human Subjects Project

INTRODUCTION

THE PROBLEM of predicting consequences to free-ranging mammal populations exposed to environmental contamination by fallout involves a variety of factors. Initial consideration must be given to the external level of radiation, both gamma and beta, caused by the fallout. However, the ingestion and metabolism of fission products carried by fallout particles and incorporated in food should also be investigated in order to evaluate the total dose to which the animals are exposed.

Radionuclides in fallout debris enter vertebrates primarily by ingestion and inhalation of the particles and by ingestion of foods contaminated with nuclides leached or weathered from the particles. Incorporation and accumulation of these radionuclides by mammals will depend on ingestion rate of the nuclides, solubility of the nuclides within the GI tract, and physiological importance of the nuclides. Internal radiation doses to vertebrates from fallout thus result from two pathways of exposure. First, ingested radioactive particles essentially are point sources of irradiation while in the gastrointestinal tract. Second, radionuclides leached from fallout particles or from contaminated vegetation may be incorporated into tissues.

Knowledge of the metabolic patterns of fission products under laboratory conditions will enhance ability to interpret and predict consequences of fallout contamination in natural ecological systems. Therefore, the objective of this research was concerned with establishing baseline values of ^{134}Cs metabolism in a wild species, the cotton rat (*Sigmodon hispidus*). We measured (1) absorbability of ^{134}Cs from a single dose of simulated local fallout and transit time of the simulant particles through the GI tract, and (2) accumulation and retention of ^{134}Cs during chronic ingestion of the isotope. Values obtained from these studies will be useful in the design of future field studies with cotton rats in ^{137}Cs-contaminated field enclosures and in the interpretation of results from these studies.

ABSORPTION OF ^{134}Cs FROM FALLOUT SIMULANTS AND TRANSIT TIME OF THE SIMULANT PARTICLES THROUGH THE GASTROINTESTINAL TRACT OF *SIGMODON HISPIDUS*

The availability of radionuclides from ingested fallout particles to vertebrates is determined mainly by (1) solubility rates of the nuclides from the particulate matter in the GI tract, (2) transit time of the fallout particles through the GI tract, and (3) absorbabilities of the nuclides by the GI tract.

Cesium-134 tagged simulants with varying in vitro nuclide solubilities were analyzed with respect to ^{134}Cs solubilities in GI tracts and absorbabilities by GI tracts of cotton rats (*Sigmodon hispidus*). Determinations of whole body retention and excretory patterns were used to discern variations in ^{134}Cs metabolism caused by solubility differences. Transit times of the particles through GI tracts were determined because the particles constitute internal point sources as long as they are present.

Methods

Three batches of ^{134}Cs-tagged sand were prepared by the Stanford Research Institute in cooperation with the United States Naval Radiological Defense Laboratory, San Francisco, California, to be used as simulants for localized or regional fallout debris. A wide variation in solubilities among the batches was requested to permit us to evaluate the absorption of the radionuclide from the simulant and the transit time of the particles. The solubility of the isotope was determined, by the manufacturer, by measuring the amount of isotope leached overnight from 1 g of simulant in 10 ml of a solution of pH 1. Properties of the simulants were as follows:

Batch 1: No reheating after absorption of the isotope
Specific activity: 1.31 μCi/g
Solubility: 60.6%

Batch 2: Reheated to 900°C after absorption of the isotope
Specific activity: 1.34 μCi/g
Solubility: 17.6%

Batch 3: Reheated to 1200°C after absorption of the isotope
Specific activity: 2.09 μCi/g
Solubility: 4.34%

All animals used in the study were laboratory-born cotton rats (*Sigmodon hispidus*) whose ages ranged from three to four months.

Placement of the simulant into the stomachs presented a unique problem since conventional

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gavaging methods would not allow administration of the large quantity of sand necessary to achieve the desired dosage without entering the stomach several times. A method utilizing polyethylene catheter tubing was devised. A 16 cm length of tubing (ID 0.086 cm, OD 0.127 cm) was filled with the desired amount of sand and plugged with a thin layer of chemical-grade gelatin at the bottom. Following loading of the tube, the sand was saturated with tap water. A hypodermic syringe and 16 gauge needle were filled with 2 ml of tap water and the tube containing the sand was attached. Immediately before insertion of the tube into the animal's mouth the gelatin plug was broken to allow the sand to flow freely when pressure was applied. The tube was then worked into the animal's stomach, and the water contained in the syringe was used to force the sand into the stomach. Prior to gavage, all animals were anesthetized with an injection of pentobarbitol sodium (4.5 mg per 100 g body weight) to facilitate handling.

Eleven cotton rats were divided into three groups, each group corresponding to the three batches of prepared simulant. The three animals (2♂♂, 1♀) in group I each received 0.197 μCi; the four animals (2♂♂, 2♀♀) in group II each received 0.201 μCi; and the four animals (3♂♂, 1♀) in group III each received 0.209 μCi.

Colony room conditions have been previously described.[1] Experimental animals were housed in suspension cages, with houses and nesting material removed in order to prevent self-contamination by the animals and to allow collection of fecal material and urine. Water and Purina lab chow were available *ad libitum* throughout the duration of the experiment. Collection of excreta was made possible by the construction of a double layer of screen mesh with a piece of blotter paper between the layers. The mesh size of the screen closest to the floor of the cage was small enough to retain fecal material dropped between counting times, and the blotter paper was used to collect most of the urine.

A Packard Armac liquid scintillation detector was used for whole-body counting and for feces and urine assays. The phantom for the chronic ingestion experiment consisted of a polyethylene bottle containing distilled water to approximate the average geometry of the experimental animals. A single 0.060-μCi dose was placed in the phantom and used to calculate the counter efficiency on each counting day. Whole body, fecal, and urine samples were counted every 18 and 24 hr for 66 hr to approximate periods of postabsorption and preabsorption and then every 24 hr for 138 hr.

Results

There were no apparent differences between males and females in each group so they were lumped together and treated as a single unit. Whole body retention and cumulative feces and urine excretion of ^{134}Cs absorbed from the simulant material are shown in Table 1. Analysis of fecal material showed a rapid increase in radioactivity until 42 hr postadministration. After 66 hr the radioactivity levels reached a plateau, after which no increase in ^{134}Cs was detectable. It was at this point (66 hr) that complete passage of the particulate matter was assumed to have occurred. Regression analysis, using the percent activity after 66 hr, gave Y intercepts of 68.7, 16.8, and 8.2% for groups I, II, and III, respectively. These figures closely approximate the in vitro solubility values supplied by the manufacturer for each batch of simulant.

The λ_b's and T_b's for the absorbed ^{134}Cs are shown in Table 2. Retention and excretion patterns for the varying solubilities are shown in Fig. 1.

Discussion

Our findings indicate that serial sacrifices of animals to evaluate distribution patterns of absorbed ^{134}Cs in tissues could begin three days after introduction of the simulant. Our data suggest that the in vivo leaching was greater than the in vitro leaching except in group II where it was about the same. LeRoy *et al.*[2] also reported that more leaching occurred in the intestinal tract of man than in vitro. Hayes *et al.*[3] used ^{140}La citrate as an insoluble tracer in humans and measured the activity in the feces. It is interesting to note that his curves for cumulative excretion are quite similar to the ones obtained in this study.

There is an indication of an increasing elimination of the absorbed ^{134}Cs with a decrease in

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Table 1. Whole body retention and loss by feces and urine expressed as percentages of the initial activity

	Hours post-injection	% Retention whole body	% Activity lost by urine (cumulative total)	% Activity lost by feces (cumulative total)
Group I	0	100	0	0
(60.6% in vitro leach,	18	85.4	7.2	6.9
injected dose 0.15 g,	24	82.8	8.3	7.3
0.197 μCi)	42	54.8	16.0	26·3
	48	51.9	17.5	26.4
	66	41.8	25.1	30.7
	72	39.7	26.0	30.7
	90	34.7	31.1	31.7
	114	28.4	35.9	32.1
	138	24.3	39.2	32.3
Group II	0	100	0	0
(17.6% in vitro leach,	18	43.7	6.1	46.9
injected dose 0.15 g,	24	38.6	7.3	50.0
0.201 μCi)	42	12.5	10.3	70.5
	48	10.9	10.9	70.9
	66	7.6	12.7	72.7
	72	7.2	12.9	72.7
	90	6.1	14.2	72.7
	114	4.9	15.2	—
	138	3.2	15.9	72.7
Group III	0	100	0	0
(4.34% in vitro leach,	18	65.6	1.8	36.4
injected dose 0.10 g,	24	55.4	2.1	40.5
0.209 μCi)	42	14.3	2.8	78.9
	48	11.8	3.0	80.7
	66	3.3	3.5	89.0
	72	3.0	3.6	89.0
	90	2.0	3.8	89.8
	114	1.4	—	—
	138	1.2	3.9	89.8

Table 2. Biological elimination rates and half-lives of ^{134}Cs and transit time of the particles

	λ_b* (%/hr)	T_b (hr)	T_b (days)	Transit time of simulant (hr)
Group I	0.76	91.1	3.79	66
Group II	1.16	60.0	2.50	66
Group III	1.46	47.4	1.98	66

* λ_b calculated by regression analysis with y-values transformed to natural logarithmic equivalents.

solubility, but the evidence is inconclusive and a wider range in solubility gradient is needed to resolve this question.

The amount of radioactivity (Fig. 1) measured during the time intervals from hr 18 (8 a.m.) to hr 24 (2 p.m.) and hr 42 to hr 48 seem to indicate that the animals might be in a postabsorptive state. Very small amounts of fecal material were passed during this time and the amount of ^{134}Cs contributed to the cumulative fecal excretion was less than 5% for all groups.

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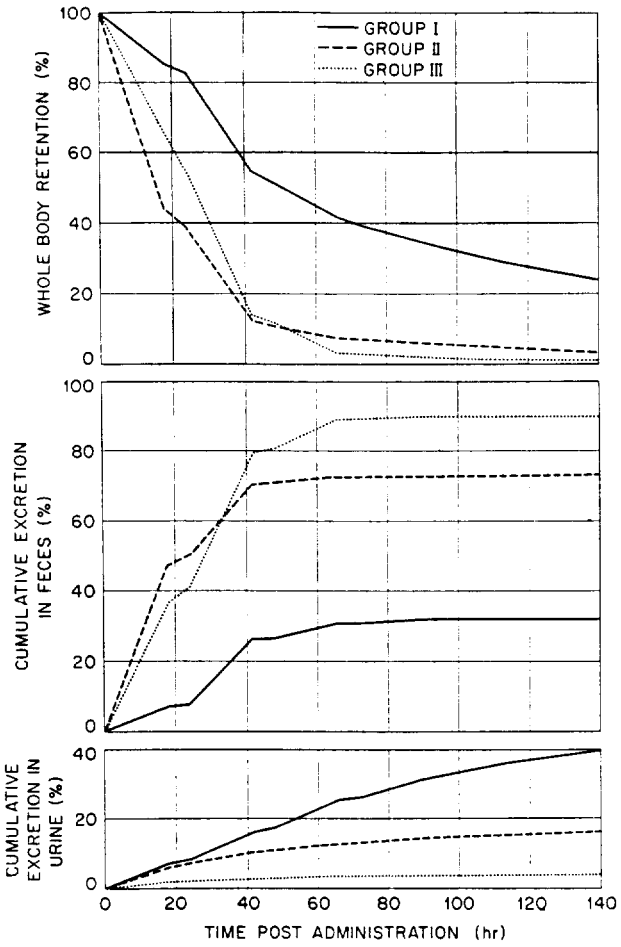

FIG. 1. Whole body and excretion patterns following acute administration of simulated fallout particles. % represent percentage of initial dose administered. Groups I, II, and III denote experimental animals receiving fallout simulant with manufacturer's *in vitro* ^{134}Cs solubilities of 60.6%, 17.6%, and 4.34%, respectively.

ABSORPTION AND RETENTION OF CHRONICALLY INGESTED ^{134}Cs IN *SIGMODON HISPIDUS*

Evaluation of accumulation and retention of ^{134}Cs in cotton rats under field conditions requires establishment of some basic parameters which can be used in subsequent analysis of the effects of environmental variables (temperature, moisture, population stress, etc.) on normal metabolic patterns of this isotope.

After fallout particles reach the soil or litter layer, the quantity of radioactive materials in small mammals normally is the culmination of long-term uptake of the nuclide from contaminated foods. Thus, chronic administration of an isotope is more likely to simulate uptake under field conditions a few weeks or longer after fallout cessation. The following experiment was designed to (1) establish uptake rates and equilibrium levels of ^{134}Cs in the cotton rat under chronic ingestion conditions, and (2) determine retention curves for ^{134}Cs following termination of chronic ingestion. Cesium-134-tagged lettuce was used to simulate vegetative material contaminated with a radionuclide leached from fallout.

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Groups of laboratory-born and wild-trapped cotton rats were used in the experiment to determine if significant variations in absorption or retention between the groups were discernible. If no large variations occur, it should be possible to use laboratory-born animals to control such variables as age, parasitism, disease, and intraspecific stresses in field studies.

Methods

Six male and six female cotton rats, wild-trapped on the Oak Ridge National Laboratory reservation, were whole-body counted during uptake and excretion phases, while the same number of male and female laboratory-born cotton rats comprised another study group.

Colony room conditions and radioactivity detection procedures were the same as described for the simulant study.

Cesium-134, in doses of 0.06 μCi, was given daily to each experimental animal for 30 days. The ^{134}Cs solution was pipetted onto a 4 g piece of lettuce and was then evaporated using a heat lamp. After evaporation of the solution, the lettuce was fed to animals at 4:00 p.m. each day. This method of administration of the isotope provided a highly satisfactory means of inducing chronic ingestion because the animals readily accepted the contaminated lettuce. Analysis of possible contamination areas of the animals (mouth-nasal region, urogenital region, and front paws) revealed no significant amounts of external radioactivity.

Whole body and excreta counts were made initially 16 hr after the first feeding, then every 24 hr for the first 256 hr and, subsequently, 1 or 2 times a week until an equilibrium level was attained. After 712 hr, feeding of the tagged lettuce was ceased, and measurements of the excretion of the absorbed cesium were begun. Periodic counts were made until the level of radioactivity reached low proportions. All counts were made between 8 a.m. and 11 a.m. to insure as much physiological uniformity as possible.

A group of 24 animals was used for tissue analysis. These animals were treated in the same manner as the other experimental groups except that all animals were not counted every day, but whole body and excreta counts of the animals at the time of sacrifice were included in the respective experimental groups. Serial sacrifices were made during both the accumulation phase and the excretion phase of the experiment and eight tissues were analyzed for ^{134}Cs. All tissues were stripped of excess connective tissue, washed, blotted to remove excess water, and weighed. All intestinal contents were cleaned out and discarded.

Results

The whole-body accumulation of ^{134}Cs in the wild-trapped and laboratory-born groups is shown in Fig. 2. No significant difference was noted between the males and females of each group so they were treated as a single group. The initial absorption was very similar in both groups, but as equilibrium levels were

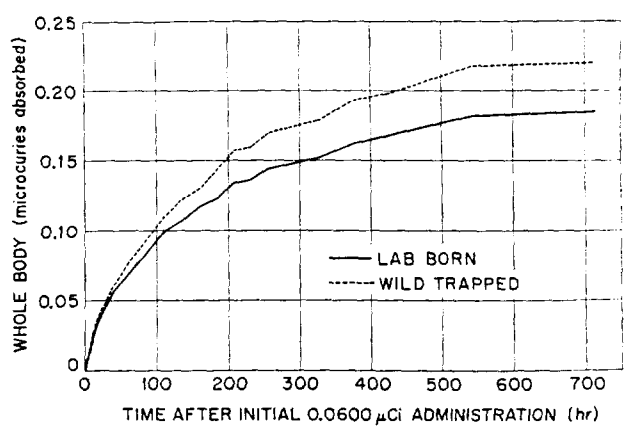

FIG. 2. Whole body uptake of ^{134}Cs during chronic ingestion of tagged lettuce.

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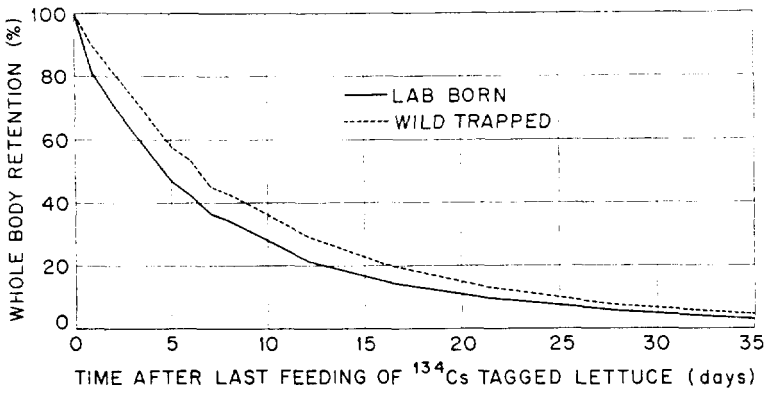

FIG. 3. Whole body retention of ^{134}Cs following termination of a thirty-day chronic ingestion of tagged lettuce.

approached the divergence became highly significant. The uptake curve for both groups was a multicomponent curve when plotted on log/log paper. The first (fast) component occurred from the 16th to about the 208th hr. Regression equations for each group are as follows:

wild trapped: $Y = 0.7727 \cdot 10^{-2} X^{0.5614}$;

laboratory born: $Y = 0.7746 \cdot 10^{-2} X^{0.5304}$;

where Y equals microcuries absorbed and X equals time in hours after the initial administration. The second major component began at the 208th hr and continued to the 544th hr:

wild trapped: $Y = 0.4039 \cdot 10^{-2} X^{0.3448}$

laboratory born: $Y = 0.4327 \cdot 10^{-2} X^{0.3278}$.

After the 544th hr the rate increase was so slight that it was considered to be zero. The designation of the uptake curve as multicomponent may be misleading. It is highly unlikely that each component is discretely separate from the other. It is more probable that a smoother transition between components would be made if smaller counting intervals were utilized.

Table 3 gives means and standard errors for whole-body accumulation and excreta. T-tests were run on the whole-body sample means of the two experimental groups, and a significant difference was noted on the 64th hr at the 99.0% level and a gradual increase in the divergence of the two curves occurred throughout the remaining hours. Significance at the 99.5% level was noted by 712 hr.

After the 712th hr count, feeding of ^{134}Cs-tagged lettuce was discontinued. Using the equilibrium level as 100% absorbed dose, retention curves (Fig. 3) for both groups were plotted. The resulting retention levels, Table 4, are expressed as percentages of initial activity remaining at any time T_n. The retention curves seem to be composed of two components. Component one, from day 1 to day 7, is probably a reflection of ^{134}Cs clearance from systems such as the liver and intestinal tract. The retention equation and T_b for both groups are as follows:

laboratory born: $Y = 92.8e^{-0.1332X}$
$T_b = 5.20$ days

wild trapped: $Y = 100.8e^{-0.1116X}$
$T_b = 6.21$ days

where Y equals % remaining and X equals time in days after last feeding. The second component (day 8 to day 35) is believed to be indicative of the longer compartments:

laboratory born: $Y = 61.7e^{-0.0853X}$
$T_b = 8.12$ days

wild trapped: $Y = 79.0e^{-0.0827X}$
$T_b = 8.38$ days

A significant difference (Table 4) between sample means of the two groups is evident throughout the 35 day excretion period.

During the uptake phase the quantity of radiocesium absorbed by the gastrocnemius muscle was low and did not reach its greatest concentration until the 208th hr, in contrast to

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Table 3. Uptake of ^{134}Cs *by lab-born and wild-caught* Sigmodon hispidus *under a chronic feeding regimen*

Hours after initial feeding	Group (lab-born or wild-caught)	Weight (g)	Whole body accumulation (μCi)	Probability of $\bar{x}$ lab and $\bar{x}$ wild being different	Urine excreted (μCi)	Feces excreted (μCi)	Ratio of urinary: fecal ^{134}Cs
16	Lab	114.73 ± 6.23 (13)*	0.0334 ± 0.0008 (13)	$0.1 < P$	0.0241 ± 0.0009 (13)	0.0030 ± 0.0004 (13)	8.0:1
	Wild	110.38 ± 8.21 (13)	0.0368 ± 0.0015 (13)		0.0210 ± 0.0011 (13)	0.0024 ± 0.0003 (13)	8.8:1
40	Lab	119.58 ± 7.05 (13)	0.0568 ± 0.0016 (13)	$0.1 < P$	0.0332 ± 0.0014 (12)	0.0047 ± 0.0007 (12)	7.1:1
	Wild	111.81 ± 8.24 (13)	0.0609 ± 0.0016 (13)		0.0316 ± 0.0009 (12)	0.0048 ± 0.0006 (12)	6.6:1
64	Lab	104.15 ± 11.01(13)	0.0728 ± 0.0004 (13)	$0.01 < P$	0.0404 ± 0.0010 (12)	0.0050 ± 0.0007 (12)	8.1:1
	Wild	111.58 ± 8.60 (13)	0.0796 ± 0.0023 (13)		0.0384 ± 0.0016 (12)	0.0055 ± 0.0006 (12)	7.0:1
88	Lab	117.96 ± 6.23 (13)	0.0856 ± 0.0019 (13)	$0.005 < P$	0.0444 ± 0.0014 (12)	0.0047 ± 0.0006 (12)	9.4:1
	Wild	108.62 ± 8.06 (13)	0.0950 ± 0.0020 (13)		0.0413 ± 0.0018 (12)	0.0056 ± 0.0006 (12)	7.4:1
112	Lab	118.31 ± 3.61 (13)	0.0996 ± 0.0027 (13)	$0.01 < P$	0.0461 ± 0.0015 (12)	0.0068 ± 0.0007 (12)	6.8:1
	Wild	107.04 ± 6.59 (13)	0.1109 ± 0.0027 (13)		0.0431 ± 0.0013 (12)	0.0069 ± 0.0007 (12)	6.2:1
136	Lab	113.69 ± 6.13 (13)	0.1071 ± 0.0039 (13)	$0.005 < P$	0.0495 ± 0.0013 (11)	0.0050 ± 0.0008 (11)	9.9:1
	Wild	106.77 ± 8.41 (13)	0.1230 ± 0.0027 (13)		0.0464 ± 0.0012 (11)	0.0070 ± 0.0007 (11)	6.6:1
160	Lab	116.21 ± 6.26 (12)	0.1172 ± 0.0040 (12)	$0.005 < P$	0.0509 ± 0.0008 (11)	0.0065 ± 0.0010 (11)	7.8:1
	Wild	105.79 ± 7.95 (14)	0.1296 ± 0.0037 (14)		0.0475 ± 0.0011 (11)	0.0073 ± 0.0008 (11)	6.5:1
184	Lab	116.00 ± 6.46 (12)	0.1234 ± 0.0028 (12)	$0.001 < P$	0.0524 ± 0.0009 (11)	0.0063 ± 0.0007 (11)	8.3:1
	Wild	107.86 ± 7.60 (14)	0.1442 ± 0.0037 (14)		0.0470 ± 0.0015 (11)	0.0069 ± 0.0009 (11)	6.8:1
208	Lab	116.75 ± 7.97 (12)	0.1337 ± 0.0049 (12)	$0.005 < P$	0.0524 ± 0.0017 (11)	0.0064 ± 0.0008 (11)	8.2:1
	Wild	112.68 ± 6.28 (14)	0.1568 ± 0.0046 (14)		0.0495 ± 0.0014 (11)	0.0073 ± 0.0007 (11)	6.8:1
232	Lab	116.50 ± 6.40 (12)	0.1360 ± 0.0040 (12)	$0.001 < P$	0.0525 ± 0.0005 (11)	0.0064 ± 0.0009 (11)	8.2:1
	Wild	111.57 ± 8.06 (14)	0.1602 ± 0.0037 (14)		0.0546 ± 0.0013 (11)	0.0081 ± 0.0008 (11)	6.7:1
256	Lab	116.50 ± 6.24 (12)	0.1442 ± 0.0049 (12)	$0.001 < P$	0.0546 ± 0.0022 (11)	0.0062 ± 0.0009 (11)	8.8:1
	Wild	116.21 ± 9.22 (14)	0.1700 ± 0.0037 (14)		0.0562 ± 0.0013 (11)	0.0080 ± 0.0011 (11)	7.0:1
328	Lab	115.46 ± 6.74 (12)	0.1518 ± 0.0064 (12)	$0.005 < P$	0.0501 ± 0.0013 (11)	0.0073 ± 0.0008 (11)	6.7:1
	Wild	112.00 ± 8.87 (12)	0.1792 ± 0.0057 (12)		0.0468 ± 0.0018 (11)	0.0090 ± 0.0011 (11)	5.2:1
376	Lab	118.83 ± 6.11 (12)	0.1624 ± 0.0068 (12)	$0.005 < P$	0.1115 ± 0.0019 (11)	0.0151 ± 0.0014 (11)	7.4:1
	Wild	110.75 ± 8.49 (12)	0.1933 ± 0.0068 (12)		0.1085 ± 0.0021 (11)	0.0176 ± 0.0016 (11)	6.2:1
424	Lab	119.54 ± 6.69 (12)	0.1679 ± 0.0065 (12)	$0.005 < P$	0.1150 ± 0.0023 (10)	0.0154 ± 0.0018 (10)	7.5:1
	Wild	113.46 ± 8.74 (12)	0.1980 ± 0.0062 (12)		0.1122 ± 0.0025 (11)	0.0170 ± 0.0018 (11)	6.6:1
544	Lab	122.58 ± 8.59 (12)	0.1824 ± 0.0092 (12)	$0.005 < P$	0.2684 ± 0.0056 (10)	0.0476 ± 0.0042 (10)	5.6:1
	Wild	116.17 ± 6.79 (12)	0.2184 ± 0.0085 (12)		0.2580 ± 0.0063 (11)	0.0467 ± 0.0037 (11)	5.5:1
712	Lab	122.50 ± 7.08 (11)	0.1853 ± 0.0090 (12)	$0.005 < P$	0.3572 ± 0.0069 (10)	0.0728 ± 0.0070 (10)	4.9:1
	Wild	116.46 ± 7.45 (14)	0.2208 ± 0.0108 (14)		0.3542 ± 0.0079 (11)	0.0739 ± 0.0069 (11)	4.8:1

* Values are $\bar{x}$ ± 1 S.E.; numbers in parentheses are samples numbers.

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Table 4. Excretion of ^{134}Cs *in lab-born and wild-caught* Sigmodon hispidus *following a chronic feeding regimen*

Days after last feeding	Group (lab-born or wild-caught)	Weight (g)	Whole body activity (μCi)	Initial activity remaining (%)	Probability of $\bar{x}$ lab and $\bar{x}$ wild being different	Urine excreted (μCi)	Feces excreted (μCi)	Ratio of urinary: fecal ^{134}Cs
1	Lab	122.50 ± 7.08 (11)*	0.1511 ± 0.0091 (11)	81.5	$P > 0.001$	0.0282 ± 0.0006 (11)	0.0044 ± 0.0005 (11)	6.4:1
	Wild	116.46 ± 7.45 (14)	0.1998 ± 0.0073 (14)	90.4		0.0302 ± 0.0008 (14)	0.0050 ± 0.0005 (14)	6.0:1
2	Lab	122.73 ± 7.09 (11)	0.1318 ± 0.0088 (11)	71.1	$P > 0.001$	0.0208 ± 0.0007 (11)	0.0026 ± 0.0004 (11)	8.0:1
	Wild	121.32 ± 7.34 (14)	0.1772 ± 0.0068 (14)	80.3		0.0235 ± 0.0006 (14)	0.0035 ± 0.0003 (14)	6.7:1
5	Lab	126.86 ± 7.06 (11)	0.0870 ± 0.0065 (11)	47.0	$P > 0.001$	0.0397 ± 0.0018 (11)	0.0053 ± 0.0008 (11)	7.5:1
	Wild	118.08 ± 6.71 (12)	0.1279 ± 0.0065 (12)	57.9		0.0486 ± 0.0020 (12)	0.0066 ± 0.0006 (12)	7.4:1
6	Lab	127.82 ± 7.27 (11)	0.0784 ± 0.0062 (11)	42.3	$P > 0.001$	0.0091 ± 0.0003 (11)	0.0011 ± 0.0002 (11)	8.3:1
	Wild	132.54 ± 9.15 (14)	0.1178 ± 0.0063 (14)	53.4		0.0113 ± 0.0006 (14)	0.0015 ± 0.0002 (14)	7.5:1
7	Lab	128.91 ± 7.12 (11)	0.0677 ± 0.0056 (11)	36.5	$P > 0.001$	0.0081 ± 0.0005 (11)	0.0013 ± 0.0002 (11)	6.2:1
	Wild	125.67 ± 8.62 (12)	0.0997 ± 0.0057 (12)	45.1		0.0096 ± 0.0004 (12)	0.0014 ± 0.0001 (12)	6.9:1
8	Lab	128.36 ± 6.86 (11)	0.0630 ± 0.0053 (11)	34.0	$P > 0.001$	0.0073 ± 0.0004 (11)	0.0009 ± 0.0002 (11)	8.1:1
	Wild	123.63 ± 9.14 (12)	0.0944 ± 0.0046 (12)	42.8		0.0090 ± 0.0005 (12)	0.0012 ± 0.0001 (12)	7.5:1
12	Lab	135.90 ± 6.77 (10)	0.0401 ± 0.0033 (10)	21.6	$P > 0.001$	0.0197 ± 0.0008 (10)	0.0027 ± 0.0004 (10)	7.3:1
	Wild	124.64 ± 7.42 (11)	0.0650 ± 0.0034 (11)	29.5		0.0258 ± 0.0012 (11)	0.0033 ± 0.0003 (11)	7.8:1
16	Lab	134.75 ± 6.55 (10)	0.0277 ± 0.0025 (10)	14.9	$P > 0.001$	0.0119 ± 0.0009 (10)	0.0018 ± 0.0003 (10)	6.6:1
	Wild	124.68 ± 7.27 (11)	0.0449 ± 0.0027 (11)	20.4		0.0171 ± 0.0009 (11)	0.0029 ± 0.0003 (11)	5.9:1
21	Lab	138.89 ± 7.55 (9)	0.0183 ± 0.0020 (9)	9.9	$P > 0.005$	0.0107 ± 0.0008 (9)	0.0017 ± 0.0003 (9)	6.3:1
	Wild	127.15 ± 8.25 (10)	0.0292 ± 0.0019 (10)	13.2		0.0151 ± 0.0008 (10)	0.0019 ± 0.0003 (10)	7.9:1
28	Lab	142.56 ± 7.54 (9)	0.0100 ± 0.0012 (9)	5.4	$P > 0.005$	0.0089 ± 0.0007 (9)	0.0017 ± 0.0002 (9)	5.2:1
	Wild	130.00 ± 8.03 (10)	0.0167 ± 0.0013 (10)	7.6		0.0131 ± 0.0010 (10)	0.0018 ± 0.0005 (10)	7.3:1
35	Lab	149.06 ± 7.74 (8)	0.0063 ± 0.0008 (8)	3.3	$P > 0.01$	0.0057 ± 0.0006 (8)	0.0009 ± 0.0002 (8)	6.3:1
	Wild	137.78 ± 8.18 (9)	0.0102 ± 0.0010 (9)	4.6		0.0076 ± 0.0006 (9)	0.0012 ± 0.0002 (9)	6.3:1

* Values are $\bar{x} \pm 1$ S.E.; numbers in parentheses are sample numbers.

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Table 5. Distribution of absorbed ^{134}Cs *in* Sigmodon hispidus *during chronic ingestion. Sample number in all cases is two* (1 *laboratory born,* 1 *wild trapped*)

Tissue		Hours After Initial Administration 16	40	64	88	112	136	208	712
Liver	(μCi)	0.0019	0.0035	0.0023	0.0039	0.0047	0.0034	0.0045	0.0034
	% total*	4.89	5.88	2.99	3.78	3.98	3.33	2.75	2.29
	weight†	3.2983	5.7779	4.1152	4.2797	5.1553	3.1570	4.7199	3.7181
Heart	(μCi)	0.0002	0.0004	0.0003	0.0006	0.0008	0.0006	0.0008	0.0006
	% total	0.51	0.67	0.39	0.58	0.67	0.58	0.48	0.39
	weight	0.4110	0.5268	0.4209	0.4192	0.4272	0.4219	0.4308	0.3335
Blood	(μCi)	0.0001	0.0001	0.0001	0.0005	0.0005	0.0004	0.0005	0.0002
	% total	0.25	0.16	0.13	0.48	0.42	0.39	0.30	0.17
	volume‡	1	1	1	1	1	1	1	1
Stomach	(μCi)	0.0007	0.0009	0.0011	0.0022	0.0019	0.0013	0.0019	0.0016
	% total	1.80	1.51	1.43	2.13	1.61	1.27	1.16	1.09
	weight	0.8218	0.8230	0.8527	0.7619	0.7658	0.6220	0.7560	0.7091
Small intestine	(μCi)	0.0018	0.0020	0.0019	0.0024	0.0041	0.0020	0.0028	0.0027
	% total	4.63	3.36	2.47	2.32	3.48	1.96	1.71	1.81
	weight	1.7967	1.7474	1.4614	1.2476	1.7001	1.4839	1.2913	1.4254
Caecum	(μCi)	0.0005	0.0008	0.0009	0.0010	0.0017	0.0012	0.0011	0.0011
	% total	1.28	1.34	1.17	0.96	1.44	1.17	0.67	0.72
	weight	0.8007	1.3331	1.1445	0.9557	1.4639	0.8101	0.7943	0.8783
Large intestine	(μCi)	0.0005	0.0004	0.0006	0.0007	0.0010	0.0008	0.0009	0.0007
	% total	1.28	0.67	1.78	0.67	0.84	0.78	0.55	0.47
	weight	0.5973	0.5207	0.6143	0.5002	0.5298	0.4302	0.4697	0.5195
Gastrocnemius	(μCi)	0.0003	0.0006	0.0008	0.0015	0.0019	0.0015	0.0022	0.0021
	% total	0.78	1.00	1.04	1.45	1.61	1.47	1.34	1.40
	weight	0.9426	2.0757	0.7301	1.1052	1.0480	0.7392	0.8237	0.7754
Skin	(μCi)	0.0039	0.0048	0.0057	0.0090	0.0109	0.0087	0.0111	0.0108
	% total	10.05	8.06	7.41	8.72	9.25	8.54	6.79	7.31
Residual carcass	(μCi)	0.0289	0.0460	0.0632	0.0813	0.0903	0.0819	0.1376	0.1218
	% total	74.48	77.31	82.18	78.85	76.65	80.45	84.21	82.85

* % total of whole body activity.
† Wet weight (in grams).
‡ Volume, 1 cc.

rapid accumulation of ^{134}Cs by the liver and small intestine (Table 5). For the first 8 days of the excretion phase (Table 6), the percent of the total body ^{134}Cs decreased in all tissues except the muscle, which remained above the equilibrium percentage (Table 5). On day 16 an increase in the percentage of ^{134}Cs was found in all tissues except the liver and skin. The increase at this time was due to much higher tissue percentages in one of the experimental animals than in the other. Following this transient increase a consistent decrease occurred until day 35 when all sample tissues contained less than 0.0001 μCi. Of all tissues sampled blood showed the lowest levels throughout both experimental phases, which substantiates the observation made by Hood and Comar (1953) that cesium was taken up against a concentration gradient.

Discussion

The significantly different levels of ^{134}Cs absorption between the wild-caught and laboratory-born rats cannot be attributed to either sex or weight differences. Other authors [4-7] also report no difference in cesium metabolism

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Table 6. Distribution of ^{134}Cs *in* Sigmodon hispidus *after termination of chronic ingestion. Sample number in all cases is two* (1 *laboratory born*, 1 *wild trapped*)

Tissue		Days After Last Administration 1	2	5	8	16	28	35
Liver	(μCi)	0.0033	0.0024	0.0016	0.0014	0.0005	0.0002	*T*
	% total*	1.82	1.57	1.20	1.28	1.23	0.75	—
	weight†	4.3861	5.0246	7.1335	5.6129	5.5958	4.3573	3.8594
Heart	(μCi)	0.0006	0.0004	0.0003	0.0002	0.0003	*T*(§)	*T*
	% total	0.34	0.25	0.19	0.15	0.74	—	—
	weight	0.3816	0.4261	0.5161	0.4178	0.3809	0.3073	0.3414
Blood	(μCi)	0.0004	0.0003	0.0001	0.0002	0.0002	*T*	*T*
	% total	0.23	0.18	0.08	0.15	0.49	—	—
	volume‡	1	1	1	1	1	1	1
Stomach	(μCi)	0.0013	0.0011	0.0008	0.0007	0.0003	*T*	*T*
	% total	0.74	0.74	0.58	0.59	0.74	—	—
	weight	0.6871	0.7421	1.1287	1.0907	0.6640	0.6729	0.7399
Small intestine	(μCi)	0.0024	0.0022	0.0013	0.0010	0.0004	0.0002	*T*
	% total	1.31	1.45	0.97	0.92	0.98	0.75	—
	weight	1.4239	1.6283	2.4565	1.7334	1.0682	1.4893	1.5184
Caecum	(μCi)	0.0013	0.0007	0.0005	0.0004	0.0003	*T*	*T*
	% total	0.70	0.46	0.37	0.38	0.74	—	—
	weight	0.9381	1.1368	1.2685	0.8799	0.8068	0.8996	1.2533
Large intestine	(μCi)	0.0008	0.0007	0.0003	0.0002	0.0004	*T*	*T*
	% total	0.45	0.44	0.20	0.21	0.98	—	—
	weight	0.5441	0.5790	0.5461	0.5455	0.5343	0.4401	0.4476
Muscle (gastrocnemius)	(μCi)	0.0036	0.0038	0.0017	0.0019	0.0010	0.0003	*T*
	% total	1.98	2.49	1.25	1.75	2.45	1.63	—
	weight	0.8096	1.0364	0.8222	0.9131	0.6948	0.8409	0.8790
Skin	(μCi)	0.0106	0.0079	0.0066	0.0064	0.0018	0.0009	0.0009
	% total	5.83	5.17	4.92	5.88	4.41	7.89	8.35
Residual carcass	(μCi)	0.1561	0.1317	0.1221	0.0967	0.0357	0.0093	0.0063
	% total	86.20	86.61	90.78	88.27	87.50	81.58	80.42

* % total of whole body activity.
† Wet weight (in grams).
‡ Volume, 1 cc.
§ Trace amount, <0.0001 μCi.

between males and females. Weight of the animals did not differ significantly between the laboratory-born and wild-trapped groups and thus cannot be considered as the principal reason for the absorption differences.

WHICKER[4] has reported a more rapid elimination for five-month-old mule deer as compared to adult animals but found no difference in the rates of yearlings and adults. HOOD and COMAR[6] also found a higher excretion rate in young rats than in older ones. Since the age of the wild-trapped cotton rats is unknown, it is not possible to draw any definite conclusions about the correlation of age and ^{134}Cs uptake from our data. However, the excretion data indicates a slightly faster elimination for the laboratory group, which was known to be 6 to 9 months of age. Some authors have indicated that potassium intake in the daily diet has an effect on cesium elimination,[5,8] but only in cases where the diets were potassium deficient or contained very small amounts of potassium; and WHICKER[4] indicates that foliage type and amount of food intake has some bearing on

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elimination of cesium. The amount and type of food available to both groups of cotton rats was standardized and thus any marked effect cannot be attributed to food differences.

It appears that an inherent difference exists in the initial uptake of ^{134}Cs by the wild-trapped and laboratory-born groups. Since the muscle is the critical organ[4,6,7,9–11], it may not be inappropriate to assume a difference in the musculature of the two groups.

Biological half-lives for the groups receiving a single administration of simulant were shorter than the second component half-lives for the groups chronically ingesting contaminated lettuce. The latter, in turn, were similar to the 8.1-day half-life reported by BAKER *et al.*[1] for the same species under similar laboratory circumstances using a single intraperitoneal injection and calculating excretion rates on the basis of second-day activity as 100% absorption. It is our belief that calculations of biologically important phenomena when the isotope is at an equilibrium level yield smoother elimination curves than curves obtained by a single oral dose or intraperitoneal injection. The almost complete disappearance of the extracellular fraction of the isotope eliminates the need for selecting some arbitrary time after administration and designating it as 100% of the absorbed dose.

Although there were statistically significant differences in uptake and excretion between the wild-caught and laboratory-born rats, these differences are not large enough to preclude use of laboratory-born rats, which can be provided as uniform groups raised in the same environment.

CONCLUSIONS

The metabolism of radiocesium following contamination by fallout in the environment must be considered from three aspects. First, absorption rates from the two pathways of exposure, ingestion of fallout particles per se and ingestion of contaminated foods, must be measured. The reason for the shorter ^{134}Cs biological half-lives for the fallout simulants as compared to the T_b for the chronic exposure very well may be due to the low amounts of the radioisotope available for absorption by the longer compartments, i.e., muscle. Since the short time interval (5.8 days) over which reliable measurements could be made for the simulant coincides with the time required for the fast component to clear in the chronic study, the λ_b and T_b reported for the simulant may be appropriate mainly for short compartments such as the liver and intestine. In an actual fallout situation or in our future studies with fallout simulant, radioactive particles will be ingested chronically and radiocesium from this source will build up to equilibrium levels along with the radiocesium from contaminated food.

Secondly, it is necessary to understand the effects of the interaction of the pathways. We do not know, for example, the effect of the particulate matter on the absorption and retention of ^{134}Cs ingested with vegetative material and vice versa. The third and most important aspect, however, will be the influence of environmental factors on the accumulation and elimination of radiocesium. Field studies are now underway in an attempt to identify these factors.

Since many small mammals reingest part of their fecal material (a special "soft feces") as it is expelled, it is probable that reingestion of radiocesium via this route occurs. We do not know to what degree our rats practiced coprophagy or if radioactive particles, particularly the simulant, were segregated in or from the soft feces.

The differing rates of radiocesium uptake in the tissues mean that food-chain transfers to predators of small prey species such as cotton rats will differ according to feeding habits of the predators. Carnivores such as foxes, bobcats, and snakes which swallow all of the prey will be exposed to the radionuclides in digestible tissues, including the nuclides available on radioactive particles in the digestive tracts of the prey. Shrews, on the other hand, mostly ingest soft tissues such as muscle, brain, heart, liver, etc., but normally do not eat the intestines, bones, or skin. Hawks and owls ingest most of such small prey, but indigestible parts such as hair, bone, and teeth are regurgitated in pellets. Thus, it seems likely that body burdens in predators will depend greatly on feeding habits of the predators as well as on the isotope concentrations in various tissues of the prey, including the GI-tract contents.

Calculation of internal dose received by the cotton rats from the radioactive particles was

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not attempted. Additional requisite data for such calculations include transit times of the particles through various parts of the gut, particulate sorting, dimensions of the GI tract, shielding afforded by tract contents, coprophagic rates, etc. Similarly, sophisticated estimates of internal dose will require measurements of tissue dimensions and configurations, and radioactivity levels in differentiated zones of certain tissues and organs.

The development of values in the laboratory is important in predicting mammalian responses to radiation insult and nuclide accumulation in case of a nuclear holocaust or accidental releases of radioisotopes into environments. While results from this study will aid in interpretation of field data, these findings should be confirmed and extended by actual field experimentation. Discrepancies between laboratory predictions and actual values in field studies were shown by KAYE and DUNAWAY[13] when measuring bioaccumulation of radionuclides by small mammals in a contaminated area. Our projected experimentation in field enclosures contaminated with simulated fallout and concomitant laboratory studies will answer some of the questions raised in this paper.

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