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RADIATION EFFECTS AND RADIONUCLIDE EXCRETION IN A NATURAL POPULATION OF PINE VOLES[1]

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ABSTRACT

Excretion rates of ^{60}Co and ^{54}Mn and the effects of acute gamma irradiation were measured in two groups (one in the field and one in the laboratory) of a population of pine voles (*Microtus pinetorum*). Field values were compared with laboratory data to ascertain if interactions among radiation and natural environmental factors caused responses which were different from those of animals in the laboratory.

Ninety adult voles were live trapped in a 1-ha study area. They were divided and treated according to the following experimental design:

Number of animals	Sex	Irradiated (700 rads)	Nonirradiated	Injection (μCi) ^{60}Co	Injection (μCi) ^{54}Mn
Field study (66)					
17	F	X		1.0	
16	M	X		none	
17	F		X		1.0
16	M		X	none	
Laboratory study (24)					
3	F	X		1.05	
3	M	X		1.05	
3	F	X			1.05
3	M	X			1.05
3	F		X	1.05	
3	M		X	1.05	
3	F		X		1.05
3	M		X		1.05

In the field study, numbers of individual irradiated and nonirradiated male voles recaptured during five months were not statistically different. Numbers of recaptures for irradiated females were significantly less ($P < 0.01$) than recaptures of unirradiated females. Reproduction continued in both nonirradiated and irradiated females, but young animals were rarely captured. Both initial and long-term excretion of ^{54}Mn and ^{60}Co was greater and internal irradiation dose less in the field than in the laboratory. The near-lethal dose of 700 rads caused no change in ^{60}Co excretion in the laboratory and only a slight reduction in ^{54}Mn excretion.

Results indicate that (1) radiation effects in the natural population were not significantly different from effects anticipated from laboratory experiments, (2) excretion of ^{60}Co and ^{54}Mn was more rapid under field conditions than in the laboratory environment, and (3) environmental factors were more important than the radiation insult in determining radionuclide loss rate.

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INTRODUCTION

Considerable speculation has arisen about the possible interactions of natural environmental factors with ionizing radiation which may cause effects in free-ranging mammals to differ from those manifested in captive mammals (Dunaway and Kaye 1962 and 1964, French and Kaaz 1968, Pelton and Provost 1969, Markham and Whicker 1970). Some research has been done with small mammals in enclosures (Golley and Gentry 1969, Pelton and Provost 1969, French 1970, and DiGregorio et al. 1971), and some studies examined populations on radioactive areas (Dunaway and Kaye

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1961, 1963, and 1964; Childs and Cosgrove 1966, Paglia 1968) and around an unshielded reactor (Schnell 1963). Until recently (Markham and Whicker 1970, O'Farrell et al. 1972), no effects have been measured in free-ranging populations of mammals in natural environmental designs which permitted direct comparison with data for the same species in the laboratory or in outside enclosures.

Concern also has been expressed (Reichle et al. 1970) about the need for characterizing the influences of environmental factors on radionuclide movement in ecological systems. A considerable body of information about biological half-lives, concentration factors, and metabolism of radionuclides is available from laboratory studies, contaminated areas, and enclosure studies. However, virtually no information is available for (1) radionuclide turnover in a natural population of animals after they have received a known concentration of radionuclides or (2) irradiation effects in natural populations (Dunaway et al. 1969).

The objectives of the study presented here were (1) to examine the effects of radiation on a field population of pine voles, *Microtus pinetorum auricularis* V. Bailey; (2) to measure excretion rates of ^{54}Mn and ^{60}Co in members of this population; and (3) to compare experimental results for the field population with results for pine voles in a laboratory environment.

Pine voles were selected for study because populations of this species were abundant in the study area, and little research on radionuclide turnover and radiation effects has been done with members of this large and ecologically important rodent subfamily. Radionuclides of manganese and cobalt were selected because, physiologically, manganese is important as an activator in many enzyme systems, and cobalt is important for vitamin B_{12} synthesis. Wangersky (1963) reviewed the role of manganese in ecology, and Lowman (1963) provided a similar review for cobalt. Relatively little, however, is known about metabolism of these elements in free-ranging homoiotherms.

METHODS

The 1-ha study area is in the AEC Oak Ridge Reservation and was located approximately 20 m NW of Tennessee Highway 95 and 150 m NE of Watts Bar Lake. Dominant vegetation was tall fescue (*Festuca arundinacea*) and sericia lespedeza (*Lespedeza capitata*), with blackberry (*Rubus allegheniensis*), Japanese honeysuckle (*Lonicera japonica*), Johnson grass (*Sorgum halepense*), aster (*Aster pilosus*), and other early-successional-stage vegetation scattered over the area.

Trapping and recapture. Sherman live-traps were used to capture the pine voles. Other small mammals trapped were cotton rats (*Sigmodon hispidus*) (31), white-footed mice (*Peromyscus leucopus*) (77), a golden mouse (*Ochrotomys nutalli*), a rice rat (*Oryzomos palustris*), short-tailed shrews (*Blarina brevicauda*) (23), and eastern harvest mice (*Reithrodontomys humulis*) (2). Traps were baited with a mixture of peanut butter and rolled oats, and pieces of carrot were added to supply moisture to the trapped animals. Fifty traps were used July 6–8, 1970, to catch 90 adult voles, which were brought to the laboratory, marked by toe-clipping, and caged.

After treatment, the voles allocated to the field study were returned to the same sites where they were first caught. No recapture trapping was done until day 14 posttreatment to avoid adding trap stress to irradiation effects during that period. Trapping was conducted at various times thereafter for 162 days. For the first four periods, one trap was used at each of 50 grid stakes with a trapping period of one night. For the fifth and for all subsequent trapping periods, two traps were set at each stake for two consecutive nights.

Irradiation and radioisotope counting. A ^{60}Co Gammacell-200 was used for irradiations. Dose rates were 373.7 rads/min for the field experiment and 364.5 rads/min for the laboratory experiment, with a total irradiation of 700 rads for each animal. Animals were confined within a plastic holder to keep them within a uniform radiation field. Controls were sham-irradiated.

Whole-body radioactivity was measured with a 400-channel Packard pulse-height spectrometer coupled to a Tl-activated NaI crystal (7.6 cm high X 7.6 cm diam). Output from this spectrometer was punched on tape, and a computer analysis of this tape with the RESAP program (Brooks et al. 1970) provided estimates of radioactivity in the animals. The program corrected for physical decay of the radioisotopes. Details of the counting procedure are described by Mathies (1971).

Field study. Irradiation and radioisotope injection of the 66 voles used in the field study were done July 9 (the day after initial trapping was completed). The animals were divided into two groups, each containing 17 females and 16 males, and were treated according to the following schedule:

Treatment group	Radiation dose	Isotope injected
I, 17 females	None	1.0 μCi of ^{54}Mn
16 males	None	None
II, 17 females	700 rads	1.0 μCi of ^{60}Co
16 males	700 rads	None

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Only females were injected so radioactivity could be used to identify maternal parentage as well as to measure nuclide excretion. All 66 voles were returned to the study area when treatments were completed.

Laboratory study. The wild-caught voles were acclimated for 21–90 days in a colony room before the laboratory experiments began. Animals were caged singly in plastic cages (28 × 17 × 13 cm) with grate tops and about 2 cm of Sterolit covering the bottom. In addition to Purina Laboratory Chow and water available ad libitum, about 20 sunflower seeds and 1.0 g (dry weight) of fresh carrot were supplied each day. Clean cages and fresh grass (~40 g, dry wt) for food and nesting material were provided as required. Temperature was 22 ± 1C, light and dark periods were 0600–1800 and 1800–0600 hr, respectively, and relative humidity was controlled to prevent decreases below 50%.

Six voles (3 male and 3 female) were used for each of four treatment groups. The experimental design was:

Treatment group	Radiation dose	Isotope injection
I	None	1.05 μCi of ^{60}Co
II	None	1.05 μCi of ^{54}Mn
III	700 rads	1.05 μCi of ^{60}Co
IV	700 rads	1.05 μCi of ^{54}Mn

The experiment with the ^{54}Mn-injected animals started on 15 September, 1970; the experiment with the ^{60}Co-injected voles on 2 November, 1970.

RESULTS

Excretion of ^{54}Mn and ^{60}Co and internal dose. Irradiation with 700 rads caused little or no change in excretion of ^{54}Mn and ^{60}Co from voles in the laboratory (Table 1). Excretion of ^{60}Co from nonirradiated males was consistently less than from nonirradiated females, but not significantly so. Excretion of ^{60}Co was essentially identical in irradiated and nonirradiated males, but the loss was greater (also not significantly) in irradiated than in nonirradiated females. The ^{60}Co loss was, however, less in nonirradiated males than in the other three groups.

In the laboratory, excretion of ^{60}Co was more rapid than that of ^{54}Mn for the short component (days 1–19, Figs. 1 and 2), but long-term excretion of ^{60}Co was slower than excretion of ^{54}Mn (Table 1). Significantly greater excretion of both ^{54}Mn and ^{60}Co was measured for the females in the field than for their counterparts in the laboratory (Table 1). Loss rates were not significantly different for the longer component slopes (b) for the laboratory (days 43–107) and field (days 49–105) were 0.0122 and 0.0148, respectively, for ^{60}Co and were 0.0197 and 0.0315, respectively, for ^{54}Mn. Excretion of ^{60}Co and ^{54}Mn in the field followed the same pattern as for the laboratory measurements. However, losses of ^{60}Co from irradiated females in the laboratory after 107 days cannot be compared equitably with losses from the irradiated females in the field, because only one female survived in the laboratory to the next counting period.

Two offspring were trapped which apparently were born on the field area to radioactive females. One was a 35-g pregnant female which was captured on day 84 and contained 1.71×10^{-3} μCi of ^{60}Co. The other was a 29.1-g male, caught on day 133, which contained 2.58×10^{-4} μCi of ^{60}Co. In the field group, two young were born in the laboratory just before the mother was injected with ^{54}Mn. The mother and her young were released on the area with the other voles, and on day 28, one of the young (weighing 16.1 g) was trapped and showed a body burden of 1.79×10^{-3} μCi of ^{54}Mn and 1.84×10^{-3} μCi of ^{60}Co. The presence of the ^{60}Co indicated that this offspring apparently received the radioisotope via nursing a female vole other than its mother. Two other young were born to another female of the field group just prior to injection of ^{60}Co. One of these young (weighing 11.9 g) was captured on day 28 and contained no radioactivity. A 39.0-g ^{54}Mn-injected pregnant female died in a trap on day 28. The two near-term (2.5 and 2.7 g) fetuses together contained 1.85×10^{-3} μCi of ^{54}Mn, or 2.9% of the whole-body count (including fetuses) for the female.

More rapid excretion of the radioisotopes by voles in the field resulted in less internal irradiation dose to the field animals. For example, the voles in the natural population from day 21 to 106 received an average of only 0.10 rad from ^{54}Mn and 0.24 rad from ^{60}Co. The voles in the laboratory received 0.23 rad from ^{54}Mn and 0.45 rad from ^{60}Co during the same period. The larger long-term doses to the voles containing ^{60}Co were attributable mainly to the beta radiation (none in ^{54}Mn) and the longer half-life of the ^{60}Co.

Short-tailed shrews supposedly kill and eat such species as meadow voles, *Microtus pennsylvanicus* (Martinsen 1969), which are considerably larger than pine voles. Mathies (1971) suggested that these shrews seldom kill adult white-footed mice, which are more comparable to the pine voles. We counted two *Blarina* on day 28, one on day 64, and five on days 84–85 to determine whether they had fed on radioactive voles they killed or found dead. No ^{60}Co or ^{54}Mn was detected in these shrews, and it is unlikely that those shrews had eaten radioactive adult or young pine voles.

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Table 1. Retention of ^{54}Mn and ^{60}Co by irradiated or nonirradiated pine voles in the laboratory and field. Retention values are means ± 1 SE.

Location	Number	Sex	Treatment: Irradiation (rads)	Treatment: Injection	Retention (% remaining) after 1 day	2 days	3 days	6 days	10 days	14 days	19 days	27 days	34 days	42 days	50 days	59 days	69 days	71 days	90 days	99 days	114 days	133 days	161 days
Lab	3	F		^{54}Mn	78.66 ±0.61	72.42 ±3.78	62.95 ±2.24	47.26 ±1.98	33.09 ±1.88	24.91 ±1.43	18.36 ±1.31	13.45 ±0.77	10.45 ±0.74	8.00 ±0.51	6.48 ±0.43	5.14 ±0.32	4.10 ±0.20	3.32 ±0.14	2.69 ±0.10	2.26 ±0.06	1.85 ±0.05	1.46 ±0.05	1.10 ±0.05
	3	M		^{54}Mn	80.90 ±3.79	74.33 ±3.18	65.47 ±2.30	52.55 ±2.32	38.76 ±1.98	31.59 ±2.29	23.88 ±2.31	17.91 ±2.06	14.42 ±1.93	11.31 ±1.63	9.33 ±1.38	7.42 ±1.20	5.79 ±0.97	4.80 ±0.87	3.91 ±0.74	3.32 ±0.72	2.60 ±0.59	1.95 ±0.45	1.30 ±0.32
	6	Combined		^{54}Mn	79.78 ±1.79	73.37 ±2.25	64.21 ±1.54	49.91 ±1.81	35.93 ±1.76	28.25 ±1.92	21.12 ±1.71	15.68 ±1.40	12.43 ±1.28	9.66 ±1.06	7.90 ±0.91	6.28 ±0.76	4.95 ±0.58	4.06 ±0.52	3.30 ±0.43	2.79 ±0.40	2.22 ±0.31	1.71 ±0.23	1.20 ±0.15
Lab	3	F	700	^{54}Mn	73.68 ±4.92	64.80 ±6.62	51.94 ±3.90	37.69 ±3.33	27.40 ±1.96	20.56 ±1.51	15.77 ±0.46	11.71 ±0.11	9.35 ±0.21	7.53 ±0.30	6.19 ±0.36	4.88 ±0.46	3.93 ±0.43	3.28 ±0.42	2.69 ±0.42	2.37 ±0.40	1.87 ±0.33	1.45 ±0.28	1.13 ±0.23
	3	M	700	^{54}Mn	78.99 ±1.14	67.38 ±4.43	56.06 ±3.49	40.07 ±2.84	30.27 ±4.36	21.74 ±2.01	16.57 ±1.58	12.29 ±1.32	9.83 ±1.01	7.82 ±0.99	6.16 ±0.59	4.82 ±0.51	3.88 ±0.41	3.22 ±0.35	2.62 ±0.31	2.27 ±0.26	1.80 ±0.21	1.42 ±0.18	1.08 ±0.08
	6	Combined	700	^{54}Mn	76.34 ±2.55	66.09 ±3.61	54.00 ±2.52	38.88 ±2.03	28.84 ±2.23	21.15 ±1.16	16.17 ±0.78	12.00 ±0.61	9.59 ±0.47	7.68 ±0.47	6.18 ±0.31	4.85 ±0.31	3.90 ±0.27	3.25 ±0.25	2.66 ±0.23	2.32 ±0.22	1.84 ±0.18	1.43 ±0.15	1.11 ±0.11

Location	Number	Sex	Treatment: Irradiation (rads)	Treatment: Injection	Retention (% remaining) after 1 day	2 days	3 days	7 days	10 days	14 days	18 days	22 days	28 days	35 days	43 days	51 days	65 days	85 days	107 days	133 days
Lab	3	F		^{60}Co	22.47 ±4.03	14.93 ±2.36	11.60 ±1.85	5.63 ±0.79	4.36 ±0.64	3.39 ±0.46	2.84 ±0.35	2.48 ±0.28	2.13 ±0.24	1.83 ±0.20	1.58 ±0.18	1.43 ±0.16	1.22 ±0.16	1.01 ±0.13	0.79 ±0.09	0.68 ±0.08
	3	M		^{60}Co	23.94 ±0.22	16.35 ±0.38	12.24 ±0.40	6.06 ±0.42	4.55 ±0.35	3.61 ±0.32	3.07 ±0.28	2.69 ±0.30	2.34 ±0.24	2.04 ±0.23	1.75 ±0.20	1.59 ±0.19	1.35 ±0.17	1.12 ±0.15	0.89 ±0.09	0.73 ±0.08
	6	Combined		^{60}Co	23.21 ±1.83	15.64 ±1.11	11.92 ±0.86	5.48 ±0.41	4.46 ±0.33	3.50 ±0.26	2.95 ±0.21	2.59 ±0.19	2.23 ±0.16	1.94 ±0.14	1.66 ±0.13	1.51 ±0.12	1.28 ±0.11	1.06 ±0.09	0.84 ±0.06	0.71 ±0.05
Lab	3	F	700	^{60}Co	27.04 ±1.95	16.96 ±0.92	12.32 ±1.04	5.67 ±0.74	4.30 ±0.66	3.33 ±0.58	2.87 ±0.49	2.52 ±0.47	2.12 ±0.41	1.80 ±0.38	1.54 ±0.39	1.36 ±0.33	1.14 ±0.33	0.87 ±0.27	0.71 a	0.87 b
	3	M	700	^{60}Co	30.11 ±2.08	20.10 ±1.16	14.60 ±0.49	6.57 ±0.27	4.68 ±0.33	3.70 ±0.29	3.17 ±0.32	2.78 ±0.30	2.38 ±0.27	2.06 ±0.25	1.82 ±0.23	1.63 ±0.24	1.37 ±0.21	1.10 ±0.19	0.91 ±0.16	0.74 a
	6	Combined	700	^{60}Co	28.58 ±1.45	18.52 ±0.96	13.46 ±0.72	6.12 ±0.41	4.49 ±0.34	3.52 ±0.30	3.02 ±0.27	2.65 ±0.26	2.25 ±0.23	1.93 ±0.21	1.68 ±0.21	1.50 ±0.19	1.26 ±0.18	0.98 ±0.16	0.83 ±0.15	0.78 ±0.15

Location	Number	Sex	Treatment: Irradiation (rads)	Treatment: Injection	Retention (% remaining) after 14 days	21 days	28 days	36 days	49 days	63 - 64 days	84 - 85 days	105 - 106 days	132 - 133 days	161 - 162 days
Field	17	F		^{54}Mn	13.73 ±1.22(6)[c]	8.48 ±0.52(9)	6.80 ±0.28(5)	4.36 ±0.51(4)	2.26 ±0.27(5)	1.84 ±0.48(3)	1.02 ±0.12(7)	0.71 ±0.10(6)	0.48 ±0.07(6)	0.29 ±0.01(3)
Field	17	F	700	^{60}Co	2.72 (2)	1.35 (1)	1.12 ±0.06(3)	0.85 (2)	0.84 (2)	0.72 ±0.14(3)	0.44 ±0.04(3)	0.39 ±0.03(4)	0.26 ±0.02(4)	0.24 (2)

[a] One animal dead.
[b] Two animals dead.
[c] Numbers in parentheses indicate number of animals sampled during trapping period.

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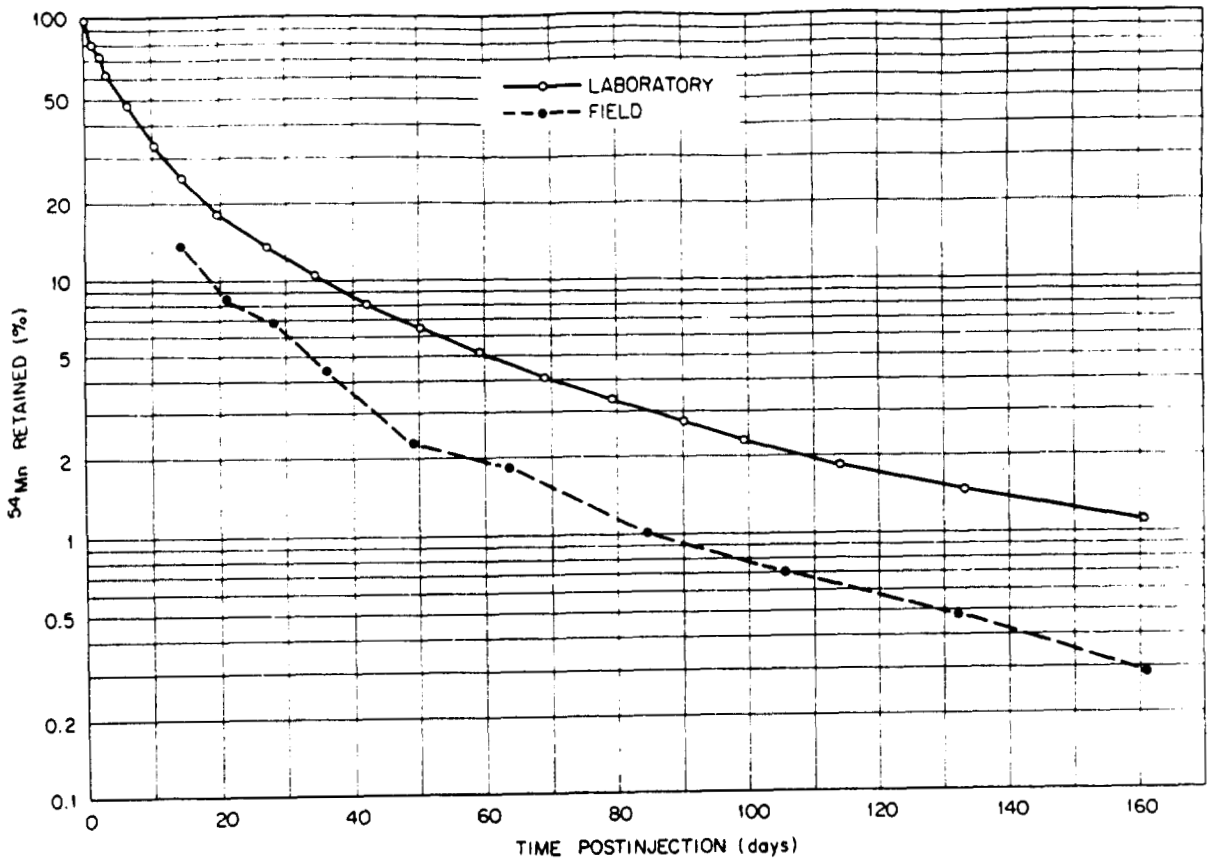

Fig. 1. Retention of ^{54}Mn in nonirradiated pine voles in the laboratory and in a field population.

Radiation effects. During the recapture period after the 66 experimental animals were returned to the study area, 138 individual voles were trapped. Of this number, 21 were from the irradiated group and 24 from the nonirradiated experimental group. The total number of captures was 311, and 175 of these were for the 45 experimental voles. One irradiated male, one irradiated female, and two nonirradiated females died in traps or in counting tubes during the study.

More nonirradiated male voles than irradiated males were captured during the first two trapping periods, but eventually as many irradiated as nonirradiated males were caught (Fig. 3). More nonirradiated females were caught during the first two trapping periods than irradiated females (Fig. 4). Unlike the males, however, the total number of irradiated females caught during the entire study was only 68.6% of the number of nonirradiated females trapped. The total number of recaptures for irradiated females (33) was significantly less (<0.01) than total recaptures of nonirradiated females (65), but the number of recaptures of irradiated males (35) was not significantly different from recaptures of nonirradiated males (40).

Data for the experimental voles and other voles on the area show that reproduction continued in the population, even in the irradiated voles. Irradiated females were pregnant or lactating 9 times out of 20 captures (45.0%) from day 28 to 106, and nonirradiated females evinced reproductive activity in 19 out of 36 captures (52.8%). Two irradiated females had one young each (one on day 64 and one on day 106) after recapture and before they were returned to the area. Since only two radioactive young were captured, and only ten voles weighing <20 g were trapped, the effects of irradiation on reproduction could not be judged in terms of young appearing in the population.

Weights of irradiated ^{54}Mn-injected voles in the laboratory decreased (11.6%) to day 14 from their preirradiation weights, and only once (day 90, +2.1%) during the subsequent 13 sampling periods did their weights return to or above the preirradiation weights. The greatest weight loss in the nonirradiated ^{54}Mn-injected voles in the laboratory during two weeks was only 3.9% (day 2), and at no time after day 14 were weights below preirradiation weights (increases were between 3.5 and 16.2%).

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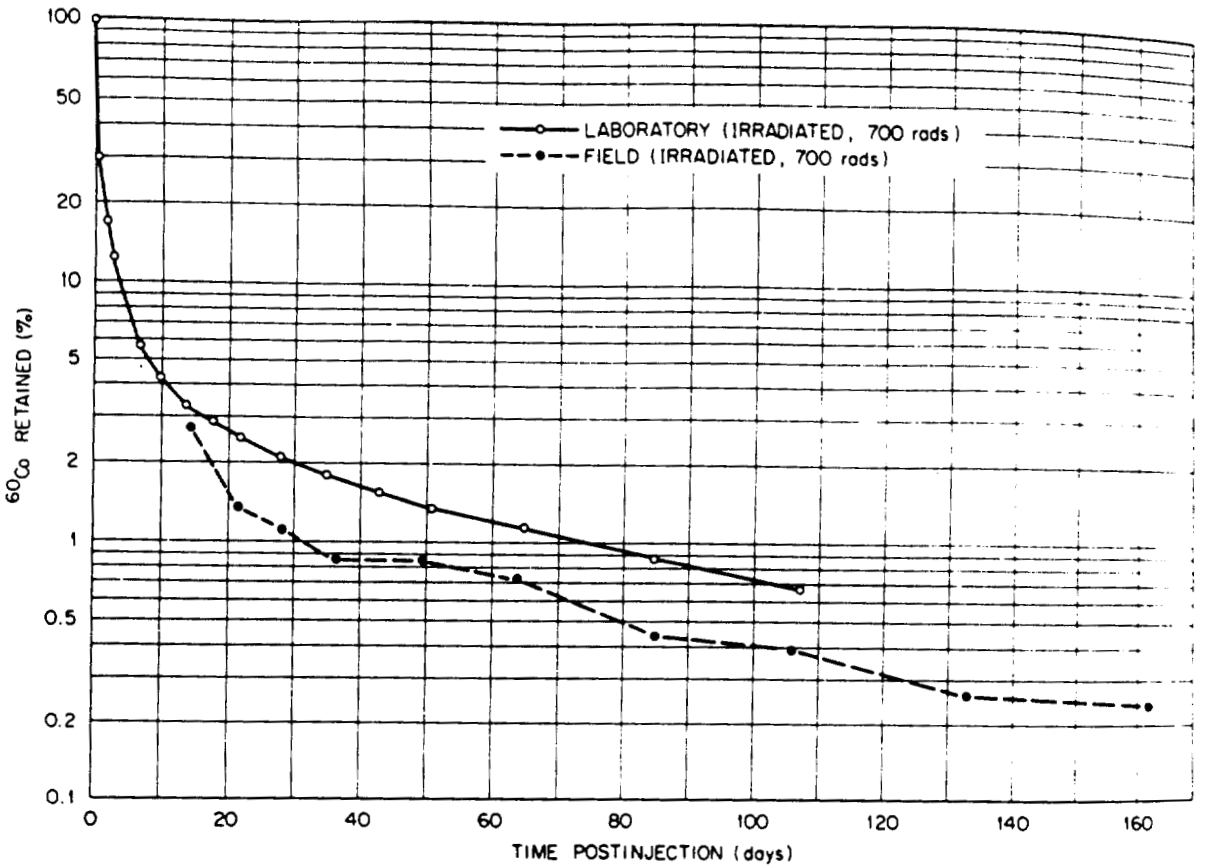

Fig. 2. Retention of ^{60}Co in irradiated pine voles in the laboratory and in a field population.

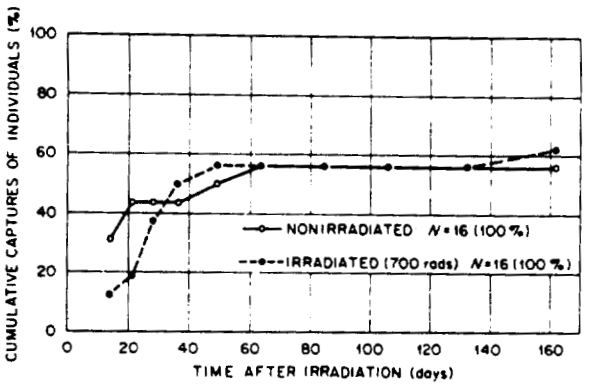

Fig. 3. Capture success of nonirradiated and irradiated male pine voles.

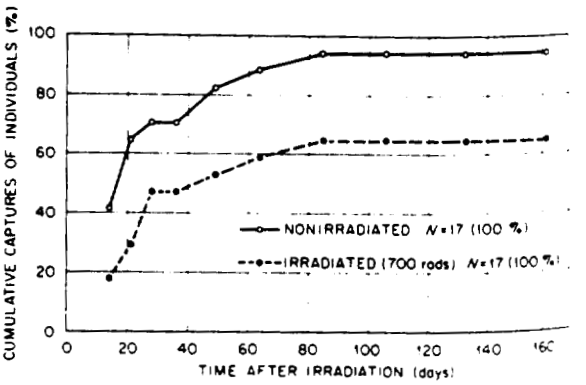

Fig. 4. Capture success of nonirradiated and irradiated female pine voles.

Weights of irradiated ^{60}Co-injected voles decreased to a loss of only 6.0% by day 14, and during the subsequent ten weighing periods were below the original weights five times (range was from 0.6 to 7.5% below). Essentially the same results were obtained for the nonirradiated ^{60}Co-injected voles in the laboratory; weights decreased 6.3% by day 14, and weights were between 1.8 and 4.8% below original weights in seven of the ten sampling periods.

In the natural population, weights of the irradiated ^{60}Co-injected females and the nonirradiated ^{54}Mn-injected females at first recapture on day 14 were 1.1 and 3.9%, respectively, above weights at the start of the experiment. Only once during the nine subsequent

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sampling periods were decreases found for each group – down 4.7% on day 49 for the irradiated voles and down 0.7% on days 161–162 for the nonirradiated animals.

None of the weight changes were statistically significant at any given time, but there was a consistent indication of a slight weight loss in all four laboratory groups during the first two weeks. There was also a more consistent trend of less weight loss in the field population than in the laboratory voles.

The 700-rad dose caused graying of fur on voles in both the laboratory and field experiments, but graying occurred at different times in the irradiated groups. Graying by days 105–106 in five out of seven irradiated field animals ranged from slight graying on head, back, and flanks to moderate graying all over. In the irradiated ^{60}Co-injected laboratory voles, four out of five showed graying by day 107 ranging from slight graying around the left eye to moderate graying on the sides of head and on shoulders and flanks. In contrast, no irradiated ^{54}Mn-injected voles in the laboratory showed graying by day 114.

DISCUSSION

Radioisotope elimination. Results of the radioisotope measurements indicate that greater loss of both ^{54}Mn and ^{60}Co occurred in the field population of voles than in the laboratory colony during the early excretion phase (days 1–21). These differences probably did not result from temperature variations between the field and the laboratory. We do not know the microhabitat temperatures to which the voles in the field were exposed, but even if they spent most of the time in cool temperatures underground, previous studies (Baker and Dunaway 1969, Mathies 1971) indicate that the temperature differential would not have been enough to cause the decrease observed.

Perhaps increased activity by the voles in the field was responsible for the greater loss of the ^{54}Mn and ^{60}Co. Chew (1971) showed that exercised *Peromyscus polionotus* excreted ^{65}Zn faster than nonexercised old-field mice. Kitchings et al. (1969) showed that chronic ^{134}Cs accumulation under laboratory conditions was greater and excretion slower in wild-caught than in laboratory-born cotton rats. The excretion data from cotton rats appear to contradict our results for pine voles and the data of Chew for old-field mice. However, it may be that the wild-caught cotton rats had high metabolic rates in the wild, but when they were confined their metabolic rates decreased to a level that was lower than that of *Sigmodon* acclimated to laboratory conditions. It is also not equatable to compare results for excretion from animals receiving radioisotopes acutely (as our pine mice or in Chew's experiment) versus chronically (as in the cotton rat study). Mathies (1971) showed that losses of ^{60}Co and ^{137}Cs from white-footed mice were slower from body burdens acquired chronically, and Kitchings et al. (1969) found a similar phenomenon for cotton rats. Differences between the diets of the laboratory and field voles may also have affected radionuclide excretion. French (1967) discusses possible effects of type or form of vegetation on element uptake, but his discussion is oriented toward ingested elements.

Whatever the reasons for the more rapid early excretion of ^{54}Mn and ^{60}Co from the free-ranging pine voles, an obvious consequence was a considerable reduction in internal irradiation dose. For radioisotopes with relatively long half-lives, health physicists are particularly interested in the "long component" of excretion, which contributes heavily to internal dose. However, if metabolic processes cause a more rapid early loss of a radioisotope from free-ranging animals than in confined animals, then the irradiation dose will be less in the former even though effective half-lives of the "long component" may not be significantly different (as in this study). Even though the half-lives of the radioisotopes (^{60}Co, 5.2 years; ^{54}Mn, 0.85 year) steadily reduce internal dose, the slow monotonic decrease in long-term biological excretion of these radioisotopes means that considerable chronic dose will be delivered.

One explicit assumption has been that radionuclide excretion depends in large part on metabolic rate. Earlier studies were unsuccessful in quantitatively correlating the long component of excretion with metabolism (Orr 1967, Pulliam et al. 1969, Baker et al. 1970, Chew 1971). In retrospect, it seems logical that the early components of radionuclide excretion curves should reflect metabolic rates better than the long components, because, ipso facto, the tissues and organs most active in releasing elements during early excretion generally are those which are most active metabolically in excreting unincorporated materials.

The lack of ^{60}Co and ^{54}Mn in the short-tailed shrews indicated that the shrews were not preying on adult or young voles used in the experiment, and these results are similar to those of Mathies (1971), who found no indication of *Blarina* feeding of radioactive *P. leucopus* in a forest.

Radiation effects. Most studies of small mammals in outside enclosures or in free-ranging populations have described radiation effects which differ little from effects in the same species in the laboratory. Few of

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these studies have examined the influence of severe environmental factors such as climatic changes or high population densities on the organism's response to radiation. Darenskaya et al. (1967) found seasonal changes in radiation-induced mortality in domesticated rabbits and dogs, even in laboratory colonies. Dunaway et al. (1970) found mortality rates and survival time of irradiated white-footed mice caged in an outside environment to be about the same as the 50% mortality and 8.2-day survival time in the laboratory during the warm parts of the year. However, the mortality rate of the mice increased to about 85% and survival time decreased to 5.3 days during November and December.

The LD_{50-30} of male and female *Microtus* in the laboratory was 883 and 1004 rads, respectively (Dunaway et al. 1969), and none died within 30 days at a dose of 700 rads during that study or in the laboratory part of this study. "Radiation sickness" would, however, be expected at 700 rads, and the fewer number of captures of both sexes during the first two trapping periods may have been the result of radiation sickness. Perhaps the relatively few captures of both nonirradiated and irradiated males was to be expected, since some small-rodent males wander during the breeding season (Dunaway and Kaye 1961, Dunaway 1968). On the other hand, adult females occupy relatively fixed territories during the breeding season. The disappearance of irradiated females from the area may not reflect irradiation deaths per se but may result from loss of territory during the period of radiation sickness when irradiated females would be less able to defend their territories. If such an effect does occur, it would be more evident in dense breeding populations, where competition for territory among adult females would be severe. The structure of the trappable population was predominantly adult, as evinced by the fact that only ten out of 311 captures were voles that weighed less than 20 g.

Pelage graying is a common phenomenon in mammals irradiated with sublethal doses (Chase 1949, Dunaway et al. 1969). This graying results when unpigmented hair from damaged follicles replaces molted pigmented hair (Chase 1949). The more rapid graying of the animals in the field than in the laboratory may have reflected normal molting of the field animals in response to natural environmental cues. In the laboratory the environment was unchanging. Graying did not seem to increase the predation rate on voles in the free-ranging population, although evidence compiled by Cott (1957) suggests that prey species whose pelage contrasts with the environment would be more vulnerable to predators. Survival of semifossorial species, such as the pine vole, after graying may differ from other species more exposed to the view of predators, but the data of O'Farrell et al. (1972) indicate that grayed pocket mice (*Perognathus parvus*) survive in natural populations about as well as pocket mice with normal pelage.

The consistently, although statistically nonsignificant, greater weights of the females in the field compared with those in the laboratory are a reflection of pregnancies in the field animals. The voles in the laboratory were not allowed to reproduce. The slight but consistent weight losses in the laboratory animals during the first 14 days presumably were caused by handling of the animals, a phenomenon noted before (Dunaway et al. 1969). In general, the findings indicate that irradiation with 700 rads caused little weight loss, in contrast to the 21% loss in voles dying at doses of 860–930 (Dunaway et al. 1969).

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