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CESIUM-137 ACCUMULATION, DOSIMETRY, AND RADIATION EFFECTS IN COTTON RATS

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ABSTRACT

Cesium-137 accumulation, dosimetry, and radiation effects were determined in cotton rats living in their natural environment, which was contaminated with ^{137}Cs-labeled sand. Cesium-137 levels were relatively high 6 months after application of the fallout simulant but decreased as the simulant descended from the vegetation toward the ground. Radioactivity levels in organs and tissues, in general, paralleled those of the whole body. Dose rate to cotton rats paralleled radioactivity levels in the whole body. No effects on peripheral blood or body weight due to irradiation were observed in this study.

In natural environments contaminated by nuclear fallout debris, mammals receive both external and internal radiation, the latter resulting primarily from ingestion of contaminated food and fallout particles. Both internal and external radiation must be considered in determining the total dose the animal will receive. Radionuclide accumulation is important because it causes tissue irradiation in the individual animal and because each animal occupies a role in the food chain and is eventually a contaminated food source.

One of the major radionuclides in fallout is ^{137}Cs. Many studies of radionuclide cycling have demonstrated that wild mammals readily accumulate radiocesium.[1-3] Movement of radiocesium in the food chain was demonstrated by Hanson, Palmer, and Griffin;[4] Pendelton et al.;[5] and Jenkins. Monroe, and Golley,[1] who showed that predators accumulated more ^{137}Cs than did their potential prey in the same geographical area, thus showing increasing ^{137}Cs concentration at the secondary consumer levels of the food chain. Therefore, in addition to evaluating internal dose, we must determine total radionuclide

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accumulation to predict both transfer in food chains and concentration at higher trophic levels.

Information concerning effects of acute and chronic irradiation on caged animals is abundant.[6-8] Accumulation and excretion of radiocesium have also been studied in great detail in caged animals and human volunteers.[9-12] However, ^{137}Cs accumulation and effects of chronic internal and external irradiation in mammals living in natural environments have seldom been investigated under replicated conditions. This paper presents results of a study to determine effects and degree of ^{137}Cs accumulation in cotton rats (*Sigmodon hispidus*) living in outside enclosures contaminated with ^{137}Cs-labeled sand. Of primary concern were measurements of in vivo dosimetry, whole-body radioactivity, radioactivity of internal organs and tissues, radioactivity of gastrointestinal contents, and effects on the hemopoietic system.

MATERIALS AND METHODS

Study Area

In 1968 eight 100-m^2 enclosures were constructed in an existing fescue (*Festuca arundinacea*) community on the U. S. Atomic Energy Commission reservation, Oak Ridge, Roane County, Tenn. Each enclosure was constructed with steel sheeting buried 18 in. and standing 24 in. above ground. Geological, soil, floral, and climatological data of the area have been summarized previously.[13] In August 1968 four of the eight enclosures were contaminated with ^{137}Cs-labeled silica sand particles (particle diameter, 88 to 177 μ) at a mass load of 72 g/m^2; this gave a radioactivity level of 2.2 Ci per enclosure. Details of the fallout-simulant characteristics and application have been described earlier.[14] Our study was conducted in four enclosures (two contaminated and two control) during the period from December 1968 to April 1970. The sides of each enclosure were topped with an electrically charged wire to contain rodents and repel nonavian predators, and each enclosure was covered with a nylon net to preclude avian predation.

Experimental Procedure

Adult, laboratory-born cotton rats were used in this study. Two weeks before being placed in the enclosures, each rat was weighed and bled to determine preexperimental values. Our hematological methods are described in detail elsewhere.[15] Three to four days before rats were placed in the enclosures, two glass-rod dosimeters encased in nylon capsules were injected subcutaneously (one dorsally and one ventrally) in each rat according to the method of Kaye.[16]

Four animals were released into each enclosure at various times during the year and were trapped 30 days later. Sexes were kept in separate contaminated and control enclosures. In the spring and fall of 1969, half the animals trapped

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at the 30-day sample were re-released into the enclosures to be recaptured for a 60-day sample. At time of capture all animals were weighed and then assayed for whole-body radioactivity in a Packard Instrument Co. Armac liquid scintillation detector, and the dosimeters were removed.

Internal organs (heart, liver, spleen, and kidneys) of the radioactive rats were weighed and counted for radioactivity in the whole-body counter. The gastrointestinal (GI) tract was excised from the terminal end of the esophagus to the anus and separated into its four components: stomach, small intestine, cecum, and large intestine. These components were cleared of contents with 1*N* sodium acetate buffer solution, weighed, and counted for radioactivity. Gastrointestinal contents were assumed to be comprised of two components, fallout simulant and organic matter, and separation of contents was based on this assumption. Contents of each GI component were triturated and washed with 30% hydrogen peroxide. Organic matter rose to the top of the hydrogen peroxide, and fallout simulant settled to the bottom. Both fallout simulant and organic matter were then counted as described.

Total in vivo gamma dosimetry from both internal and external sources was determined with Toshiba low-Z glass rods (1 by 6 mm) read on a Toshiba fluoro glass dosimeter, type FGD-38, using National Bureau of Standards standards. Internal beta dose rate (rads/day) was determined from our data by the method of Hine and Brownell,[17] by using the beta and electron mean energies and mean number per disintegration from Dillman.[18] It was assumed that the range of beta particles was small relative to dimensions of the cotton rat; therefore beta energy was assumed to be completely absorbed.[19] Gamma-ray dose rate (rads/day) was calculated from the equation

$$D_\gamma = 51.2CE_t \tag{1}$$

where D_γ = gamma-ray dose rate
51.2 = dis/day × g-rad/MeV
C = isotope concentration (μCi/g)
E_t = total gamma + X-ray energies

Photon energies were determined from Dillman,[18] and absorbed fractions for photon sources were determined for a mass of about 118 g by using the data of Snyder et al.[20] For both internal beta- and gamma-dose-rate calculations, uniformly distributed isotope was assumed.

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RESULTS AND DISCUSSION

Dosimetry

The major contribution to whole-body total dose rate was from external gamma irradiation. Amounts of external and internal irradiation contributing to

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Table 1

CONTRIBUTION OF INTERNAL AND EXTERNAL GAMMA AND INTERNAL BETA IRRADIATION TO THE TOTAL WHOLE-BODY DOSE RATE

Sample period	Number of animals sampled	Total dose rate (gamma + beta), rads/day	External gamma dose rate, rads/day	% of total	Internal gamma dose rate, rads/day	% of total	Internal beta dose rate, rads/day	% of total
February 1969	2	4.41	3.77	85.5	0.075	1.7	0.56	12.7
April 1969	2	3.42	3.04	88.9	0.051	1.5	0.38	11.1
May 1969	4	3.15	2.95	93.7	0.024	0.8	0.18	5.7
July 1969	6	2.72	2.54	93.4	0.021	0.8	0.16	5.9
October 1969	4	2.48	2.41	97.2	0.008	0.3	0.06	2.4
November 1969	4	2.45	2.34	95.5	0.012	0.5	0.09	3.8
January 1970	3	2.44	2.39	98.0	0.005	0.2	0.04	1.6
April 1970	6	2.62	2.57	98.1	0.005	0.2	0.04	1.6

whole-body total dose rate and to GI-tract total dose rate are shown in Tables 1 and 2. Internal beta irradiation contributed more to both the whole-body and the GI-tract total dose rates than did internal gamma irradiation because the size of the cotton rat permitted complete absorption of the beta energy but considerably less of the gamma. During the early months of the investigation,

Table 2

CONTRIBUTION OF GI-CONTENTS GAMMA AND BETA IRRADIATION TO TOTAL GI-TRACT DOSE RATE*

Sample period	Number of animals sampled	Total dose rate (gamma + beta), rads/day	Internal beta dose rate, rads/day	Internal gamma dose rate, rads/day
February 1969	2	0.805	0.71	0.095
April 1969	2	0.555	0.49	0.065
May 1969	4	0.249	0.22	0.029
July 1969	6	0.103	0.09	0.013
October 1969	4	0.215	0.19	0.025
November 1969	4	0.181	0.16	0.021
January 1970	3	0.068	0.06	0.008
April 1970	6	0.113	0.10	0.013

*Beta contribution was 88.3% of the total and gamma contribution 11.7%.

internal beta- and gamma-irradiation contribution to the total whole-body dose rate was 12.7 and 1.7%, respectively, whereas the external gamma contribution was 85.5%. Later, however, when ^{137}Cs intake by the animals was reduced (see discussion in the following paragraphs), internal beta and gamma irradiation contributed only 1.6 and 0.2%, respectively, to the total whole-body dose rate, whereas the external gamma contribution was 98.1%. It appears that internal beta irradiation is of more consequence early after fallout arrival than it is later.

Average gamma dose rates from both external and internal sources in cotton rats ranged from 3.84 rads/day in February 1969 to 2.35 rads/day in November 1969 (Fig. 1). Regression analysis showed that from February to July the dose rates decreased 0.008 rad/day per day but from July to April 1970 there was no significant change. The initial decrease in dose rate probably was caused by changing geometry of the radiation fields in pens as the fallout simulant descended through the vegetation to the ground. Most of the fallout simulant is now on the ground, forming an irregular plane source and resulting in a relatively stable dose rate of approximately 2.46 rads/day.

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Radioactivity

Radioactivity in cotton rats is shown in Fig. 2. The four measurements (whole body, total tissue, organic matter, and fallout simulant), in general,

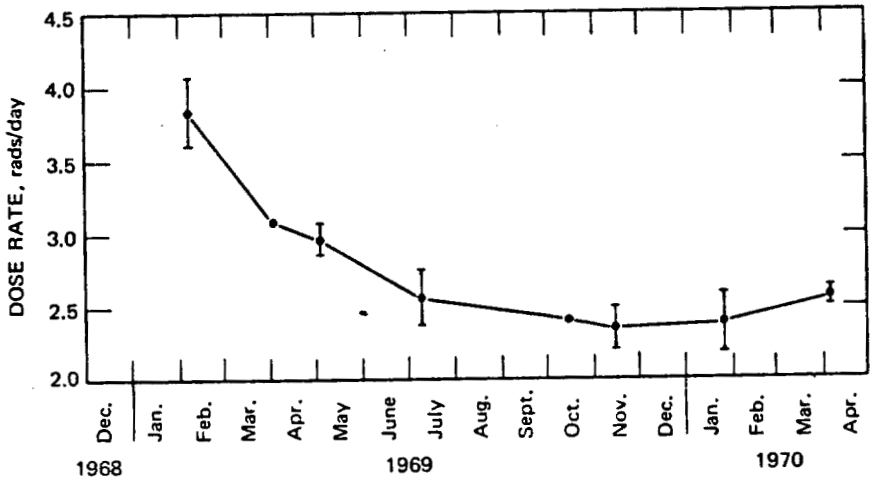

Fig. 1 Gamma dose rate to cotton rats living in ^{137}Cs-contaminated enclosures from February 1969 to April 1970. •, means of dorsal and ventral dosimeters. Vertical lines represent standard error of the mean, and absence of vertical lines denotes standard error too small to plot.

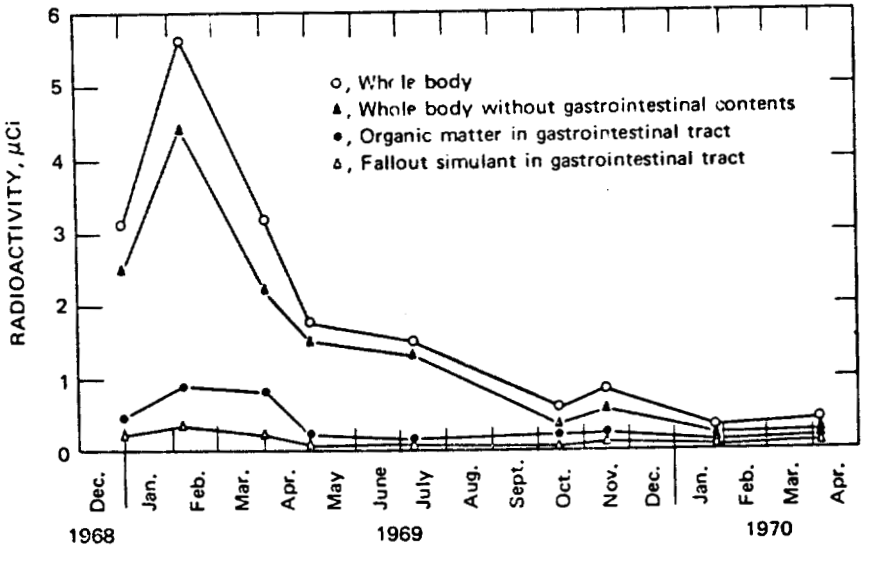

Fig. 2 Total radioactivity (μCi) in cotton rats after chronic ingestion of ^{137}Cs-contaminated fallout simulant and vegetation for 30 or 60 days.

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parallel each other. Radioactivity in all four measurements increased from December 1968 to February 1969, after which time it began to decrease. This initial rise in cotton-rat whole-body radioactivity was probably influenced by relative proportions of living and dead vegetation in their diet since the choice of food in midwinter was influenced by the diminution of living vegetation. As living vegetation decreased, rats foraged closer to the ground; hence their diet consisted of increasing amounts of dead vegetation. Dahlman, Auerbach, and Dunaway[14] reported that radioactivity was considerably greater in dead vegetation than in living vegetation. Therefore descent of fallout simulant to the ground, which results in its availability for ingestion, coupled with the change in food helps to explain the high whole-body radioactivity in cotton rats during midwinter 1969. As time progressed, however, radioactivity levels of living and dead vegetation approached each other; this resulted in a relatively constant body burden in cotton rats. Descent curves of these measurements parallel those of the dosimetry and, again, reflect movement of fallout simulant toward the ground. Whole-body radioactivity remained relatively constant from October 1969 to April 1970, whereas GI-content radioactivity remained relatively constant after May 1969.

Figure 3 shows relative amounts of ^{137}Cs in each of five compartments: internal organs, GI tissue, GI contents (organic matter and fallout simulant), pelt (skin and hair), and residual carcass. These percentages include both 30- and

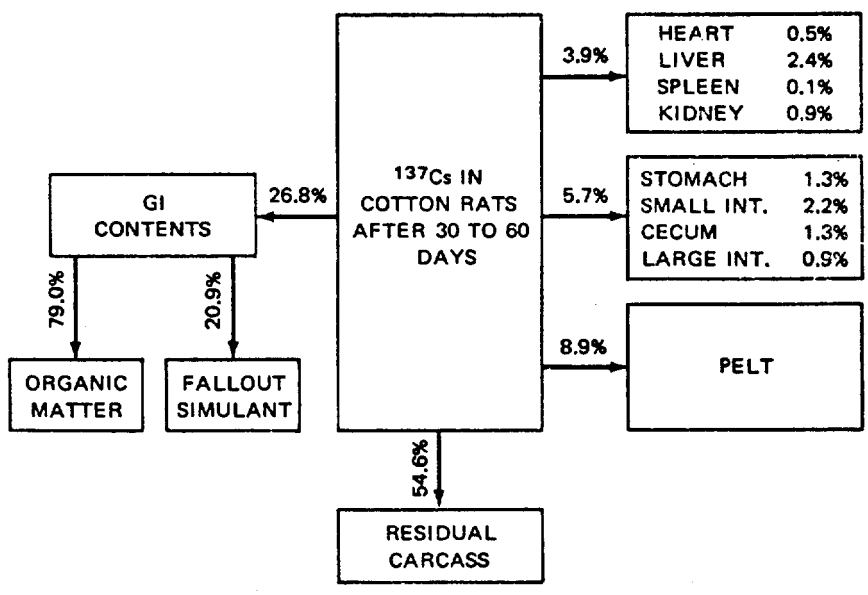

Fig. 3 Percent of radioactivity in various components of cotton rats after 30 to 60 days of chronic ingestion of ^{137}Cs-contaminated fallout simulant and vegetation.

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60-day samples over the entire experimental period because we found no significant increase or decrease from 30 to 60 days. In December 1968, whole-body radioactivity reached a maximum level 3 weeks after animals were placed in the pens.[21] Kitchings, Dunaway, and Story,[12] in a laboratory study, determined equilibrium at 544 hr (22.7 days) after chronically feeding cotton rats ^{134}Cs-tagged lettuce for 30 days. In March 1970 we trapped cotton rats 7 and 10 days after placing them in the contaminated pens. Whole-body radioactivity was 0.3620 and 0.3579 μCi, respectively. These values were not significantly different from 0.3790 μCi determined on day 30. Therefore we feel that cotton rats reached ^{137}Cs equilibrium by 30 days and that gain or loss would be negligible for an additional 30 days.

Radioactivity in the rats was contained mostly in the residual carcass (Fig. 3). The two major compartments of residual carcass are muscles and skeleton, which comprised about 49 and 7%, respectively, of total body wet weight.[22] It is well established that ^{137}Cs is accumulated in muscle in much larger amounts than in any other mammalian tissue.[9,23,24] The data in Table 3 support these findings. Pelt, which includes skin and hair, accounted for 8.9% of the whole-body radioactivity. In terms of weight most of the pelt is muscle. Because of both tissue specificity for ^{137}Cs and amount of muscle in the mammalian body, it is apparent that most of the body burden was contained in muscle.

Average radioactivity in cotton-rat GI-tract contents was 27% of the whole-body radioactivity. Of the total amount of radioactivity in the GI contents, 79% was in organic matter and 20.9% was in fallout simulant. The radioactivity contribution of fallout simulant in the early part of the experiment was approximately 10 times that in April 1970, our last sample period. Weathering caused leaching of ^{137}Cs from the fallout simulant into the native soil and onto the plants. Also, the simulant is becoming mixed with the soil. Consequently ^{137}Cs is still present, but it is not so readily ingestible in the form of fallout simulant. With increasing time vegetation radioactivity will reflect radioactivity levels in the soil; therefore future body burdens of herbivores and saprovores living in the contaminated areas will reflect ^{137}Cs levels in living and dead vegetation.

Radiation Effects

We saw no effects of the ^{137}Cs radiation on either body weight or peripheral blood of cotton rats. Any slight changes in body weight or general blood measurements probably were results of seasonal variations in the general environment since similar measurements were obtained for both control and experimental animals. For cotton rats general environmental fluctuations may be of more immediate consequence than low-level irradiation. Previous studies with cotton rats showed that relatively high acute doses of radiation were required to affect body weight[8] and blood.[25] In January 1970 our animals were exposed to

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Table 3

RADIOACTIVITY AND WEIGHT OF COTTON-RAT ORGANS AND TISSUES AFTER 30 TO 60 DAYS OF CHRONIC INGESTION OF ^{137}Cs-CONTAMINATED FALLOUT SIMULANT AND VEGETATION

Sample period	Number of animals sampled	Whole body	Heart	Liver	Spleen	Kidney	Stomach	Small intestine	Cecum	Large intestine	Pelt	Muscle
						Radioactivity, μCi/g						
February 1969	2	0.0441	0.0361	0.0249	0.0482	0.0485	0.0635	0.0594	0.0510	0.0434	0.0207	0.1054
April 1969	2	0.0298	0.0567	0.0202	0.1587	0.0479	0.0500	0.0361	0.0318	0.0440	0.0255	0.0768
May 1969	4	0.0143	0.0142	0.0089	0.1532	0.0167	0.0200	0.0143	0.0156	0.0133	0.0080	0.0307
July 1969	6	0.0124	0.0115	0.0065	0.0164	0.0139	0.0175	0.0165	0.0120	0.0120	0.0081	0.0232
October 1969	4	0.0046	0.0065	0.0036	0.0071	0.0067	0.0036	0.0037	0.0035	0.0079	0.0033	0.0055
November 1969	4	0.0068	0.0045	0.0036	0.0101	0.0067	0.0038	0.0038	0.0031	0.0029	0.0030	0.0103
January 1970	3	0.0030	0.0029	0.0022	0.0021	0.0039	0.0033	0.0031	0.0026	0.0029	0.0017	0.0060
April 1970	6	0.0031	0.0007	0.0011	0.0004	0.0020	0.0004	0.0006	0.0003	0.0004	0.0018	0.0032
						Wet Weight, g*						
	31	117.1	0.5135	4.9543	0.0774	1.0412	1.2989	2.4680	1.6234	1.3199	17.9157	54.81

*Values are mean weight of 31 animals.

several days of 0°F temperatures and precipitation. After 30 days, only three of eight experimental animals and two of eight control animals were recovered alive. Dunaway and Kaye[26] reported similar mortality in free-ranging cotton rats during cold weather. Percent recovery during the present study was considerably higher in favorable weather.

Ecological Significance

The degree of internal exposure from ^{137}Cs is determined ultimately by the quantity of isotope in the diet,[27] its absorption, and its turnover rate. If ^{137}Cs enters the diet primarily through material deposited on vegetation, internal dose will be proportional to retention of the fallout. If, however, the isotope is incorporated predominantly through the root systems of plants, the dose will be proportional to the total amount of isotope in the soil. Our results support these contentions in part. Tables 1 and 2 and Fig. 2 show the decreasing dose rate with decreasing internal radioactivity as the fallout simulant descends to the ground.

Regardless of the mechanism of incorporation of radioisotope, one of the major consequences of fallout is the creation of a contaminated food source in the food chain. Results of a study with one herbivore, the cotton rat, are presented in this paper, but contamination transfer in the ecosystem will not cease at the vegetation–cotton rat link in the food chain. Jenkins, Monroe, and Golley[1] determined trophic-level-increase ratios for the predator–prey relation involving the gray fox and the cotton rat to be 2.0 and 5.6, the latter determined from an area with "a general lack of potassium." Similarly, from their data, increase ratios for the bobcat–cotton rat relation can be determined as 6.9 and 18.7, the latter again being from the area low in potassium. Analysis of soil in our area indicated no lack of potassium.[28] Since the same predator–prey relations of gray fox–cotton rat and bobcat–cotton rat presumably exist in and around Oak Ridge, contamination levels can be predicted for the gray fox and the bobcat by using the increase ratio of 2.0 and 6.9, respectively. In February 1969, when radioactivity in cotton rats was highest (0.04 μCi/g), radioactivity in gray foxes and bobcats would have been about 0.08 and 0.28 μCi/g, respectively. In November 1969, when cotton-rat radioactivity was lowest (0.007 μCi/g), radioactivity in gray foxes and bobcats would have been about 0.014 and 0.048 μCi/g, respectively. During November 1969 a 7000-g gray fox could accumulate 98 μCi, and a 7000-g bobcat could accumulate 336 μCi (0.336 mCi). The body burden for the bobcat would therefore be approximately 112 times greater than the maximum permissible body burden allowed for man under occupational conditions[29] and even greater than that for man in the nonoccupational category.

CONCLUSIONS

Our results indicate that, for cotton rats in situations similar to ours, we could expect the following:

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1. Within a 30- or 60-day time period, neither weight nor blood will be appreciably affected by chronic low-level radiation (2.44 to 4.41 rads/day) from ^{137}Cs. Changes in these measurements will be caused by changes in environmental factors, such as temperature.

2. Radioactivity levels for whole body, tissues, and GI contents will, in general, parallel each other. Approximately 1 year after fallout arrives, whole-body radioactivity will be only about one-tenth that of early levels but will remain at this lower level for a long period, perhaps years.

3. Such internal organs as heart, liver, spleen, and kidneys will accumulate a relatively small amount of ^{137}Cs.

4. Most of the accumulated ^{137}Cs in tissue will be in muscle because of the relatively high affinity of ^{137}Cs for muscle and the large proportion of muscle in the body.

5. For the first 6 to 12 months after arrival of fallout, dose rate will decrease rather sharply. After this initial decrease equilibrium will be reached and dose rate decrease will be negligible.

6. Although there may be seasonal fluctuations in dosimetry and whole-body radioactivity levels, they will probably be slight.

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