

EXPERIMENTAL EXPOSURE OF NAIVE BANK VOLES (*CLETHRIONOMYS GLAREOLUS*) TO THE CHORNOBYL, UKRAINE, ENVIRONMENT: A TEST OF RADIORESISTANCE

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Abstract—Previous studies have demonstrated no difference in micronucleus (MN) frequencies between wild rodents chronically exposed to the environmental radiation contamination of the Chernobyl (Ukraine) exclusion zone and those inhabiting reference populations. The aim of the present study was to test the hypothesis that a population of bank voles (*Clethrionomys glareolus*) has developed radioresistance as a result of 14 years of chronic, low-dose radiation exposure. Naive voles were placed in environmental enclosures in the Red Forest region of the exclusion zone for 30 d. Blood samples were obtained at regular intervals, and the MN assay was used to assess chromosomal damage. Additionally, radionuclide uptake was monitored throughout the study, and dose was documented for each individual as well as for their offspring. Total dose for the voles experimentally exposed in this environment averaged 1.09 Gy (36.20 mGy d⁻¹) for the 30-d study period. Our results indicate that exposure to radiation levels well above regulatory statutes did not result in an increased MN frequency. Furthermore, our results do not support the hypothesis that voles chronically exposed to these radiation levels have developed a genetic basis for radioresistance that is unique from that present in naive populations. The use of *C. glareolus* as a sentinel species for environmental studies of radiation contamination and the question of whether the MN assay is an appropriate endpoint for studies of low-dose, chronic radiation exposure are also discussed.

Keywords—Radiation Chernobyl Chernobyl *Clethrionomys* sp. Micronucleus assay

INTRODUCTION

The environmental contamination resulting from the Chernobyl Nuclear Power Plant disaster (April 26, 1986) offers a unique opportunity to examine in vivo biological effects of chronic, low-dose exposure to ionizing radiation. The effects of ionizing radiation at the chromosomal and molecular levels have been well documented for acute laboratory exposures [1–4]. Radiation protection measures have been adopted based on the results of laboratory investigations regarding low-dose radiation exposures, which suggest a linear, no-threshold, cumulative response. However, most low-dose laboratory exposures to radiation [3,5,6] are orders of magnitude greater than recent environmental levels of the Chernobyl exclusion zone, one of the most radioactive environments in the world.

Several studies have challenged cumulative effects and linear no-threshold hypotheses and, instead, have reported hormesis from exposure to low doses of ionizing radiation [7–9]. Induction of repair systems has been demonstrated in response to radiation doses as low as 0.01 Gy [8]. Stimulatory effects of exposure to low-dose radiation have been shown to increase longevity, fertility, and defense mechanisms against disease in mammals [7,10]. Endpoints used to assess adaptation to chronic doses include chromosomal aberrations, DNA strand breaks, cell survival, and micronucleus (MN) formation [8,11]. Adaptive response and radioresistance have been demonstrated in vitro for mouse [12] and human [13–15] cultured cells and

have been suggested in vivo for sentinel wildlife species, such as *Clethrionomys* sp. [16,17].

Clethrionomys glareolus collected from the Red Forest region of Chernobyl have consistently demonstrated the highest concentration of radionuclides of any native species sampled from the exclusion zone. Voles in the Red Forest have average ¹³⁷Cs concentrations in muscle of 25 kiloBecquerels per gram (KBq/g) for an average internal dose of 18 mGy d⁻¹. Dose rates for all species of small mammals collected in the Red Forest average 10 mGy d⁻¹ [18]. The maximum allowable dose for terrestrial vertebrates, according to International Atomic Energy Agency (Vienna, Austria) guidelines, is 1.0 mGy d⁻¹ [19], yet in previous studies using chromosomal [20,21] and molecular endpoints [22], we have been unable to document a negative effect of chronic environmental exposure to these radiation levels, either in individuals or in the population as a whole.

The aim of this study was to test the hypothesis that selective pressure from chronic exposure to ionizing radiation has produced resident voles (i.e., voles living in close proximity to Reactor 4) that are radioresistant. In this case, radioresistance would be defined as the ability to efficiently repair DNA lesions resulting from both direct and indirect effects of radiation exposure. Fourteen years seems to be adequate for selection, given the short life span of voles. Initial assumptions included in the experimental design were (1) levels of contamination in the Chernobyl exclusion zone [18] are of the magnitude capable of eliciting a response, (2) MN formation is an appropriate endpoint of environmental exposure to ion-

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izing radiation [23,24], and (3) if the Red Forest population of *C. glareolus* has adapted to repair the damage from exposure, the frequency of micronucleated erythrocytes should be increased in naive voles exposed to the Chernobyl environment.

MATERIALS AND METHODS

Study sites

Nedanchichy, Ukraine, a village located approximately 45 km north/northeast of Reactor 4, received minimal fallout from the Chernobyl accident [25]. *Clethrionomys glareolus* from a forest west of Nedanchichy (UTM: 36 336455 U5707606) were collected for transplant studies and introduction into environmental enclosures in the Chernobyl exclusion zone. Enclosures for the naive voles were placed in the Red Forest region of the exclusion zone approximately 1.5 km west/southwest of Reactor 4 (UTM: 36 295545 U5697040). This experimental site was chosen because in previous studies of native species, rodents collected in the Red Forest have consistently demonstrated the highest concentrations of radiocesium and radiostrontium [18].

During May 1999, enclosures measuring $1 \times 0.67 \times 0.67$ m were constructed from untreated red cedar and galvanized wire mesh and placed in the Red Forest. Hinged tops were fastened with bolts and wing nuts to allow access to the animals during periodic sampling. The enclosures were placed on a site excavated to a depth of approximately 30 cm. After an enclosure was in place, the soil and vegetation that had been removed from the placement site were returned to the enclosure. Soil was seeded with alfalfa and native mosses and watered to encourage growth of cover inside the enclosure before introduction of the study animals. Each enclosure was supplied with a water bottle and a nest box. A total of 11 enclosures were placed in a 30- \times 20-m area of the Red Forest (UTM: 36 295545 U5697040).

Sampling

In July 1999, *C. glareolus* ($n = 11$) were captured from a forest west of Nedanchichy using Sherman live traps (H.B. Sherman, Tallahassee, FL, USA) baited with rolled oats. Animals were returned to the lab, where they were sexed, weighed, measured, and assigned a voucher number. A unique toe clip was given to each animal for further identification. At that time, a blood sample was obtained, and the toe was preserved in lysis buffer [26]. These samples were used to establish initial MN frequencies for each individual. Whole-body counts were performed using a 7.6-cm NaI crystal (Canberra Industries, Meridian, CT, USA) enclosed in lead housing. Each vole was counted for 3 to 10 min. Although longer reading times would have provided more accurate estimates of initial radioactivity, efforts were made to reduce stress to the animal by limiting its confinement in the 4- \times 6-cm cylindrical scintillation jar used for the count. Background assessments were made after every third count. The counting methods, calibration, and standardization were as described by Chesser et al. [18]. Data were recorded and analyzed using a Libretto laptop computer (Toshiba American Information Systems, Irvine, CA, USA) and Gamma Vision software package (E&G Ortec, Oak Ridge, TN, USA). Male and female voles were paired, and the five pairs were placed into five separate cages in the lab and monitored for overall health and compatibility for 24 h. One female that was determined to be pregnant by palpation was housed separately for the 24-h period.

On July 22, 1999, the pairs of voles and the pregnant female were introduced into six separate enclosures in the Red Forest. Lab chow, apple, potato, cucumber, and water were supplied ad libitum. Mice were recaptured and returned to the lab for sampling every 10 d. The pregnant female was left undisturbed (except for replenishing food and water) in the enclosure for the duration of the study period. On the evening before sampling, Sherman live traps were set in the enclosures supplied with oats and a nestlette for bedding. Voles not caught in the traps were removed by excavating their burrow systems. All animals were returned in live traps containing food and bedding to the lab facility at Chernobyl City, where they were then placed in cages. Animals were monitored for overall health, whole-body counts and body mass were measured, and a blood sample was taken. Animals were returned to their enclosures during the evening of their day of capture.

Offspring were collected from four of the five enclosures during the course of the study. Newborns were removed from the enclosure at the time of discovery, returned to the lab, and euthanized as previously described by Baker et al. [20]. Whole-body counts and weights were recorded, blood samples were taken, and voucher numbers were assigned. Half of each neonate was cryopreserved, and half was preserved in lysis buffer [26]. At the termination of the study, all animals were anesthetized and euthanized. Bone and muscle samples were taken for radiocesium and radiostrontium analysis, respectively. The results of these analyses are reported in a separate study [27]. Voucher specimens and vital tissues are housed at the Museum of Texas Tech University (Lubbock, TX, USA).

Accumulated dose calculations

The activity of ^{90}Sr from bone and soil samples and of ^{137}Cs from muscle samples were determined according to the methods described by Chesser et al. [18]. Uptake rates and accumulated dose rates in the enclosures through biotic and abiotic pathways are the subjects of a separate study and detailed in Chesser et al. [27].

MN assay

Blood smears were returned to the laboratory at Texas Tech University and stored, stained, and scored as previously described [21]. Slides were randomized and coded, and a single investigator analyzed 5,000 polychromatic erythrocytes (PCEs) per individual per sampling period.

RESULTS

Study animals

All voles survived the study period and appeared to be in good general health at termination of the study. Offspring were born to four of the five pairs of voles. In total, 21 young were born in the enclosures. Radionuclide concentrations of mothers and their young are reported in Table 1. Because the gestation period of *C. glareolus* is 21 d, young collected after August 11, 1999, were most likely conceived in the enclosures ($n = 17$). The fifth paired female was pregnant at the termination of the study.

The pregnant female that was placed alone in an enclosure was recaptured at the end of the study along with four young. The juveniles were fully furred and moving freely about the enclosure, but they were not fully weaned (one was nursing at the time of capture). The ^{137}Cs activity and concentrations for this mother (TK81530) and her offspring are included in Table 1.

Table 1. Specific activity of ^{137}Cs and dose in female bank voles and their offspring born in enclosures in the Red Forest near Chernobyl, Ukraine

Mother's TK ^a number	Enclosure number	Mother's specific activity (Bq/g)	Mother's dose (mGy d ⁻¹)	Newborn TK number	Newborn specific activity (Bq/g)	Newborn dose (mGy d ⁻¹)
81541	2	240.27	0.17	82501	124.82	0.09
				82502	121.32	0.09
				82503	123.89	0.09
				82504	130.25	0.10
81540	3	69.35	0.05	82518	57.08	0.04
				82519	55.67	0.04
81539	9	34.91	0.03	82510	18.32	0.01
				82511	20.89	0.00
				82512	26.72	0.02
				82531	48.02	0.04
				82532	45.41	0.03
81538	10	59.55	0.04	82533	62.17	0.05
				82513	20.21	0.02
				82514	27.04	0.02
				82415	19.89	0.01
				82516	15.04	0.01
				82517	17.49	0.01
81530	11	186.24	0.14	82534	312.97	0.23
				82535	200.54	0.15
				82536	220.20	0.16
				82537	448.90	0.33

^a TK numbers are individual Texas Tech University Museum voucher identification numbers.

Dose accumulation

Empirical values for ^{137}Cs and ^{90}Sr activities and concentrations for the voles at initiation of the study and subsequent sampling periods are presented in Table 2. Variation in the sample size results from an occasional inability to recapture an animal without subjecting it to undue stress or excessively disturbing the enclosure. The dose rates presented here are discussed in detail in the companion paper by Chesser et al. [27].

Internal dose

The accumulation of ^{137}Cs in *C. glareolus* averaged 1.57 kBq g⁻¹, corresponding to an accumulated dose of 98 mGy from intramuscular ^{137}Cs at the end of the 30-d study period. Approximately 1.50 mGy d⁻¹ of ^{90}Sr was incorporated during captivity in the enclosure, resulting in an accumulated dose of 18.64 mGy from ^{90}Sr . Doses from internally deposited ^{137}Cs and ^{90}Sr during the enclosure study averaged 116.70 mGy.

External dose

External dose rates were calculated as 18.10 mGy d⁻¹ from ^{137}Cs and 14.24 mGy d⁻¹ from ^{90}Sr in the soil. Therefore, the

estimated accumulated external doses during the 30-d study period were 543.30 mGy from ^{137}Cs and 427.20 mGy from ^{90}Sr .

Total dose

Total dose and contributions from ^{137}Cs and ^{90}Sr are presented in Table 3. The total dose resulting from internal and external sources of radiation was 1,087 mGy during 30 d of exposure to the Red Forest environment.

MN frequencies

Mean MN frequencies for each sampling period and corresponding ^{137}Cs levels are presented in Table 2. The initial frequency of micronucleated PCEs (MNPCEs) ranged from 0 to 0.40%, with a mean of 0.20%. Day 10 sample frequencies ranged from 0.02 to 0.25%, with a mean of 0.10%. After the initial decrease observed in the day 10 sample ($\chi^2_3 = 24.66$, $p < 0.001$), frequencies of MN remained below initial frequencies for the duration of the study (Fig. 1). The number of MNPCEs from day 10 to day 30 did not differ significantly ($\chi^2_2 = 0.167$, $p = 0.92$). No relationship between MN frequency and accumulated dose was observed.

Table 2. The mean number of polychromatic erythrocytes (PCEs), percentage of micronuclei (MN), and corresponding activity levels and concentrations of ^{137}Cs for bank voles held in enclosures in the Red Forest at Chernobyl, Ukraine

Sample period	Mean PCEs	Mean % MN	Specific activity (Bq/g)	^{137}Cs	
				g/vole	μg/g
Day 0 ($n = 11$)	5,256	0.19 (±0.08) ^a	43.64 (29.4)	5.46×10^{-12} (3.68×10^{-12})	5.46×10^{-6} (3.68×10^{-6})
Day 10 ($n = 11$)	5,046	0.1 (±0.05)	1,079.85 (276.6)	1.92×10^{-11} (1.23×10^{-11})	1.91×10^{-5} (1.23×10^{-5})
Day 20 ($n = 10$)	4,166	0.14 (±0.05)	1,594.89 (430.7)	1.99×10^{-10} (5.38×10^{-11})	1.99×10^{-4} (5.38×10^{-5})
Day 30 ($n = 9$)	5,033	0.12 (±0.07)	1,570.56 (339.9)	1.96×10^{-10} (4.23×10^{-11})	1.96×10^{-4} (4.23×10^{-5})

^a Values in parentheses are standard errors.

Table 3. Estimated contributions of ^{137}Cs and ^{90}Sr to internal and external dose in bank voles maintained in enclosures in the Red Forest near Chernobyl, Ukraine for a 30-d period^a

Sample period	External	Internal	External	Internal
	^{137}Cs (18.1 mGy d ⁻¹)	^{137}Cs (mGy d ⁻¹)	^{90}Sr (14.24 mGy d ⁻¹)	^{90}Sr (mGy d ⁻¹)
Day 0 (<i>n</i> = 11)	~ ^b	~	~	~
Day 10 (<i>n</i> = 11)	181	~	142	~
Day 20 (<i>n</i> = 10)	362	~	285	~
Day 30 (<i>n</i> = 9)	543	98	427	19
Total dose	641 mGy d ⁻¹ ^{137}Cs		446 mGy ⁻¹ ^{90}Sr	
Combined dose	1,087 mGy d ⁻¹			

^a Strontium-90 was calculated at the termination of the study.

^b Undetectable amounts of ^{137}Cs or no value calculated for ^{90}Sr .

DISCUSSION

In this study, we made several assumptions. First, we assumed that the magnitude of exposure to ionizing radiation in individuals living in the Red Forest was sufficient to induce chromosomal damage. Second, we assumed that the MN assay was an appropriate endpoint with which to document chromosomal breakage [23,24,28,29]. Finally, we assumed that if the Red Forest population of *C. glareolus* had adapted to repair damage from radiation exposure, then one should observe a higher frequency of micronucleated erythrocytes in naive voles exposed to the Chernobyl environment.

Our results indicate that exposure to radiation levels well above the regulatory guidelines does not result in an increased frequency of MNPCEs. Furthermore, our results do not support the hypothesis that voles resident in the Red Forest are radio-resistant relative to naive voles, at least in terms of MN formation. However, we cannot reject the hypothesis that *C. glareolus* has a unique level of radioresistance inherent to the species. Additionally, data presented here raise questions of whether *C. glareolus* is an appropriate sentinel species for environmental studies of radiation contamination and whether the MN assay is an appropriately sensitive endpoint for studies of low-dose, chronic exposure to radiation.

Dose rates

The dose rates presented here and estimated in the companion paper by Chesser et al. [27] are far in excess of the International Atomic Energy Agency guidelines of 1.0 mGy

d⁻¹, the upper limit for terrestrial vertebrates [19]. Reproductive inhibition in mammals has been reported at 1.0 mGy d⁻¹ [30]. Total dose for *C. glareolus* experimentally exposed to the Chernobyl environment averaged 1.09 Gy (32.60 mGy d⁻¹) for the 30-d study period. If the impact of radiation dose is cumulative, as is widely held, then detrimental effects from such doses would be expected, because a vole living in the Red Forest would receive a total dose of more than 13,224 mGy/year. This annual dose exceeds the lethal dose for 50% of the population within 30 d (LD50/30) if administered acutely, but no mortality was observed. However, the scientific literature indicates that reproductive inhibition would be expected [30]. Instead, naive voles successfully bred and reproduced in this environment. A total of 21 progeny, 17 of which were conceived while the voles were living in the Red Forest enclosures, were born during the study to individuals newly introduced to radiation exposure. Previous studies have documented that resident *C. glareolus* successfully reproduce in the Red Forest, and in fact, our field team [20,31,32] has collected fecund females of all rodent species.

MN assay

Micronucleus formation has been widely used as an endpoint for genetic damage in environmental toxicologic studies [28,29,33–35], and its sensitivity to low-dose radiation has been demonstrated in laboratory studies [8,12]. Therefore, we concluded that MN formation was an appropriate endpoint for this study. Even so, that we were unable to document significantly higher MN frequencies in previous studies [21] or in animals experimentally exposed to the Red Forest environment raises questions regarding the sensitivity of this endpoint in documenting the effects of chronic, low-dose exposure to environmental radiation (at least in some species). Our experimental design did not allow us to take blood samples daily. Therefore, a rapid but short-term cellular response to exposure, resulting in an increased MN formation after 3 to 5 d of exposure, is possible. Given the typical time frame of erythroblast formation, shorter sampling periods might have revealed this, but such sampling periods needed to be balanced against the stress of daily disturbance to the voles, which we tried to avoid (especially during the early days of the study).

The observed decrease in MN frequencies (Table 2 and Fig. 1) may be indicative of enhanced expression of a repair system in response to damage during the early days of the study. Although a slight overlap was found in the confidence intervals (Fig. 1) between day 0 and day 10, contingency χ^2 analysis of MN and PCEs across the four time periods showed a highly significant reduction in MN between day 0 and day 10 ($\chi^2_3 = 24.66, p < 0.001$). Removal of the day 0 class from the contingency table showed that the remaining sample periods were not significantly different ($\chi^2_2 = 0.167, p = 0.92$). Therefore, the difference across samples was due to a decrease in MN from day 0 to day 10.

Radioresistance

Radioresistance could be explained by two possible responses to chronic radiation exposure. First, multigenerational selective pressures on a population from chronic exposure to ionizing radiation for alleles that increase survival (i.e., fitness) could produce individuals with new genotypes that would have greater resistance to the effects of radiation. Alternatively, individual response to an environmental toxicant by initiation of cellular feedback mechanisms or repair systems might also

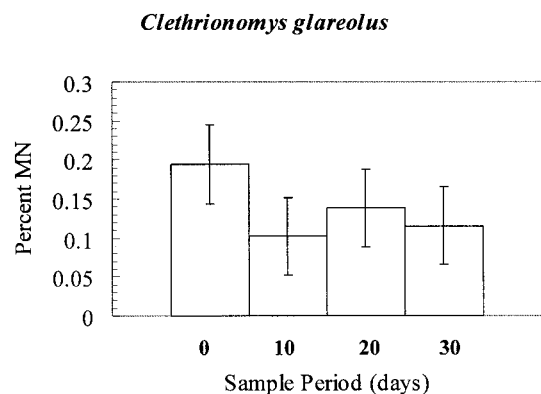


Fig. 1. Mean percentage micronucleated (MN) polychromatic erythrocytes (PCEs) for the four sample periods in bank voles (*Clethrionomys glareolus*) experimentally exposed to the Chernobyl (Ukraine) environment. Error bars represent 95% confidence intervals.

offer protection (to individuals). These two potential responses are not necessarily mutually exclusive. In fact, the natural selection brought about by chronic exposure to a toxicant ultimately enhances survival in a polluted environment.

We found no evidence that, at the dose levels encountered in our study, resident *C. glareolus* can more effectively repair chromosomal damage than naive voles. If radioresistance is present in residents of the Red Forest, we would expect an elevation of MN frequencies in the introduced animals that would remain elevated through the life of the individual. However, no elevated MN count was found in naive mice introduced to the exclusion zone. Therefore, we reject the hypothesis that naive mice will respond differently to this environment than individuals that are progeny of populations with multigenerational exposure. The second hypothesis, that a normal MN count is the result of feedback activation of repair in response to low-dose radiation, cannot be eliminated by our data.

Radioresistance may be an inherent quality of *C. glareolus*. This possibility, and the subsequent value of this species as a sentinel in environmental studies of radiation contamination, should be re-evaluated. The LD_{50/30} for *C. glareolus* is 1,100 rads [36], yet these animals received, on average, 108 rads (36.20 mGy d⁻¹) in this study from exposure to one of the most radioactive environments in the world (Table 3). Even so, this species has been reported previously to demonstrate increased MN formation in response to much smaller radiation doses than those reported here [29]. Cristaldi et al. [29] admit that the ¹³⁷Cs levels reported for *C. glareolus* collected in Rome were too low to explain the increase in MN formation, yet the response was concluded to result from exposure to radioactive fallout from Chernobyl (whereas heavy metal levels in soil were discounted as being negligible). Interestingly, pollution from traffic emissions in Rome is of sufficient level to elevate heavy metal content in tissues of mice living in the city [37], and a corresponding increase in MN formation has been observed. These studies should be re-evaluated, considering both the possibility of a synergistic effect between additional heavy metal contamination and radioactive fallout [38] and whether the use of *C. glareolus* as a sentinel species in environments with low-level radiation contamination is appropriate.

Finally, what is obvious from this study, as well as from others, is the need for comprehensive analysis of data from both chronic and acute exposures in field and laboratory studies, employing multiple endpoints, to reduce the likelihood of sounding genetic false alarms [39] regarding the biological effects of radiation exposure. Current studies by our research group are underway to examine species more closely related to the benchmark species *Mus musculus* as well as radiosensitive strains of laboratory mice to determine their utility in environmental toxicologic studies of radiation contamination.

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