CONCENTRATIONS AND DOSE RATE ESTIMATES OF $^{134,137}$CESIUM AND
$^{90}$STRONIUM IN SMALL MAMMALS AT CHORNOBYL, UKRAINE

RONALD K. CHESSER,++†† DERRICK W. SUGG,‡‡ MICHAEL D. LOMAKIN,‡ RONALD A. VAN DEN B U S S C H E , †#
J. ANDREW DEWOODY,‡‡ CHARLES H. JAGOE,‡ CHAM E. DALLAS,‡‡ F. WARD WHICKER,‡‡ MICHAEL H. SMITH,†‡
SERGEI P. GASCHAK,§§ IGOR V. CHIZHEVSKY,§§ VITALI V. L.YABIK,§§ ELENA G. B U N T O V A , § §
KEVIN HOLLOMAN,†† and ROBERT J. BAKER††
†Department of Genetics, University of Georgia, Athens, Georgia 30602, USA
‡Savannah River Ecology Laboratory, Drawer E, Aiken, South Carolina 29802, USA
§International Research and Development Agency, Kiev-1, PO Box 158, 252001 Ukraine
#Department of Biological Sciences, Texas Tech University, Lubbock, Texas 79409, USA
‡‡Department of Zoology, Oklahoma State University, Stillwater, Oklahoma 74078, USA
†Head, Department of Pharmacology and Toxicology, University of Georgia, Athens, Georgia 30602, USA
‡‡Department of Radiological Health Sciences, Colorado State University, Fort Collins, Colorado 80523, USA
§§Chernobyl Scientific and Technical Center for International Research, Chernobyl, Ukraine

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Abstract—Free-ranging mammals near the Chernobyl nuclear reactor are experiencing substantial radiation dose rates from intramuscular concentrations of $^{134,137}$Cs and skeletal $^{90}$Sr. Radiocesium concentrations averaged 3,200 Bq/g of dry muscle, compared to a mean of 297 Bq/g Sr in bone for mammals in the Exclusion Zone, a region of restricted human activity surrounding the reactor. Estimates of dose rates from intramuscular sources of radiocesium averaged 2.4 mSv/d within 8 km of the reactor and doses to specific tissues are likely much higher. Mammals captured 30 km southeast of the reactor averaged only 2 Bq/g of muscle in areas immediately surrounding the reactor and within and between remeasured and unremediated regions. The variance of $^{90}$Sr that dose rates from external sources of radiation were much greater than the dose rates from internal sources of radiocesium. Estimated dose rates in very small areas of the Chernobyl region exceed those reported to impede reproductive success in mammals.

Keywords—Chernobyl Chernobyl Dose Cesium Strontium

INTRODUCTION

The explosion of the number four reactor at Chernobyl on April 26, 1986, represents a worst-case scenario for the impact of a nuclear accident on risk to the environment and human health. Not only did the explosion eject a large volume of the core into the immediate area of the reactor, but the ensuing 10-day fire propelled an aerosol of radionuclides and particulates high into the atmosphere. An estimated 1 to 2 MCI, or about $4 \times 10^{12}$ Becquerels (Bq; [1–3]) were distributed over a broad geographic area of Eastern Europe, Russia, and Scandinavia [4,5]. Regions immediately surrounding the reactor were particularly contaminated, resulting in the loss of about 400 ha of pine forest [6]. The region around the reactor is now protected by an outer exclusion zone, where there is minimal habitation by man, and a more tightly controlled inner exclusion zone, where there is limited human activity. One reactor (number three) continues to function at the nuclear complex. Although less than three percent of the original radioactivity released during the course of the accident remains, the zones still contain substantial inventories of cesium and strontium. Two isotopes of cesium, $^{134}$Cs and $^{137}$Cs, and strontium ($^{90}$Sr) have relatively long half-lives (2, 30, and 28 years, respec-
tively) and are readily incorporated into biological tissues as homologues of potassium ($^{40}$K) and calcium ($^{40}$Ca).

Mammals are generally more sensitive to ionizing radiation than any other class of organism [7]. Despite the magnitude of this disaster, mammal populations thrive in even the most radioactive regions around the reactor [8,9]. Populations of mammals in the 10-km zone have experienced a strong recovery from areas where they were most certainly extirpated in the months after the explosion [10] by radiation doses exceeding 60 Gy [11]. Presently, mammal densities are higher in the radioactive areas than in nearby habitats, which received much lower amounts of radioactive fallout [11]. Recovery of mammal populations within the Chernobyl Exclusion Zones may, in part, be due to evacuation of about 153,000 people, leaving agricultural and disturbed habitats to succeed to grasslands [7,10]. Portions of habitats near the nuclear complex have undergone extensive remediation. In the Red Forest region, dead pines and approximately one million square meters of topsoil were bulldozed into bermes and covered [12]. Planted grasses and newly emergent birch and pine now cover much of the original forest area. Large tracts of undisturbed habitats remain however, some still strewed with dead pines killed shortly after the explosion (e.g., Glyboke Lake, Red Forest Woodlands). Studies in remediated and undisturbed habitats offer the op-

*To whom correspondence may be addressed (chesser@vri edu).
Fig. 1. Map of collection sites in the 10-km Exclusion Zone around the Chornobyl reactor. Isopeleth lines denote the distribution of radionuclides by the explosion and fire on April 26–May 6, 1986 (numbers are in Ci/km², redrawn from [11]). Other collection sites were 50 km southeast of the reactor in areas receiving relatively low amounts of radioactive fallout.

portunity to examine the effectiveness of remediation efforts on reducing contamination and dose rates on affected fauna and flora.

It is important that we assess the biological and ecological risks brought about by an accident such as the one at Chornobyl. Study of naturally occurring species in the contaminated zones provides insight into the impact of the accident on the resilience of populations and ecosystems. Mammals also provide a likely correlate to biological responses by man if inadvertently exposed to the long-term hazards such as those in the Chornobyl Exclusion Zone. In order to evaluate potential effects, we must estimate the dose to the exposed individuals. To this end, we have determined concentrations of radiocesium in muscle tissues and 90Sr in bone tissue of small mammals living in the immediate vicinity of the Chornobyl reactor. We also assess the variation of radionuclide contamination in remediatted and undisturbed habitats affected by initial plumes released by the reactor explosion and from areas receiving relatively little radioactive fallout (Fig. 1).

MATERIALS AND METHODS

Mammals (N = 596; May 1994–August 1996) were collected by live-trapping from sites that have undergone remediation by removal of topsoil and native trees (Red Forest Grassland and Enclosure sites), grassland and forest regions undisturbed since the April 1986 accident (Red Forest Woodlands, Glyboke Lake, Orchard, and Chistogolovka), and from low-impact areas 30 km southeast of the reactor (Fig. 1) [9]. Muscle samples (N = 471) were taken from specimens immediately after sacrifice and dried in a 40°C drying chamber. Radiocesium concentrations were determined using a Minaxi-5000 gamma counter (Packard, Meriden, CT, USA) equipped with a 3" x 3.25" NaI crystal (well dimensions: 1.7-cm diameter x 7 cm high) set to count photons in the energy range 550 to 760 KeV. This energy range includes 137Cs and a portion of the 134Cs photon energies. Muscle samples were counted for a period of 30 min or until a counting standard deviation of less than 5% was attained. All samples were counted three separate times on the NaI gamma counter, and total radiocesium values for muscle are averages of the three separate counts. All samples were recounted on a Germanium detector (Model GC1519, Canberra, Meriden, CT, USA,) for 2 h each or until a counting standard deviation of less than 5% was attained. The correlation between average values for radiocesium counts determined by the NaI and those with the Ge counter was greater than 0.99 (p < 0.001) with fixed intercept at zero indicating significant conformity among estimates of radiocesium concentrations. For both the Ge and NaI detectors, low-activity standards, traced by the National Institute of Standards and Technology, Gaithersburg, Maryland, USA, whose geometry was similar to that of the samples, were counted before and after groups of five samples. These values were used to calculate detector efficiency. As a final check on the quality of values determined for cesium activities, confirmation of cesium concentrations was achieved by evaluating subsamples (N = 6) chosen to span the range from low to high cesium concentrations on three different detectors (NaI and Germanium counters) and at two different laboratories (Savannah River Ecology Laboratory, Aiken, SC, USA, and Colorado State University, Fort Collins, CO, USA). All samples were evaluated without knowledge of specific locality or species. The coefficient of determination between labs and detectors was greater than 99%, with the intercept at zero, demonstrating strong concordance (r = 0.99, p < 0.001) of values for cesium concentrations. Values are reported in terms of total radiocesium (134Cs,137Cs). Four soil samples collected at each of six locations were counted for 30 min on a 3" x 3.25" NaI crystal. The average ratio of 134Cs:137Cs was 2.7% in both soils and muscle samples, matching closely with predicted values (August 1996) derived from the initial inventory released and half-lives of the isotopes [5].

For strontium analyses, portions of skeletons were dried at 310°C for 3 h and ashed in a muffle furnace at 610°C for 15 h. The ash was dissolved in 1 M HCl at boiling. After filtration, at a pH of 1.0 to 1.2, the 90Y was extracted from the solution with 10% HDEHP (di(2-ethyl-hexyl)phosphoric acid). All monovalent and divalent ions remained in the acid phase. 90Sr was then extracted into 3 M nitric acid and precipitated as hydroxide. The hydroxide precipitate was dissolved in 1 ml concentrated nitric acid, transferred to a liquid scintillation vial, and the Cerenkov radiation from 90Y was counted on a Quantulus liquid scintillation counter [13].

Estimates of the daily absorbed dose were derived separately for cesium, strontium, and from external sources. Because the derivation of the estimated dose contributed by the two radionuclides differ somewhat and because the target tissues may also differ, we present dose rates (DR) associated with each source of radiation. The DR estimates from intramuscular sources of radiocesium (N = 461) were made using the following formula (in milliGy per day [mGy/d]; 1 Gy = 100 rad):  

\[ DR_{Cs} = \frac{T \cdot (Bq/g) \cdot C \cdot (\text{ID/s}/Bq) \cdot E (\text{MeV})}{10^{-6} \text{erg/MeV}} \times (10 \text{ mGy/g}) \times \left( \frac{10 \text{ mGy}}{100 \text{ erg/g}} \right) = T \cdot E \cdot C \cdot (1.3824 \times 10^{-5}) \text{ mGy/d} \]

where T is the number of Becquerels (Bq) measured in a gram of dried sample, D denotes nuclear disintegrations, and s is seconds. The constant C is a scaling factor for adjusting the dry muscle weight to the customary wet weight measurement;
the dry weight was estimated as one fourth that of the wet weight \( (C = 1/4) \) [14]. The parameter \( \bar{E} \) denotes the average energy per disintegration (MeV/D). For \(^{137}\text{Cs} \), \( \bar{E} \) is determined predominantly by the two beta particles \( (\beta_1, \beta_2) \) released in the disintegration of \(^{137}\text{Cs} \); \( \beta_1 \) has a maximum energy of 1.176 MeV but comprises only 6.5% of the beta fraction, while comparable values for \( \beta_2 \) are 0.514 MeV and 93.5%. Because the average energy is approximately [15]

\[
\bar{E} = \frac{E_{\text{max}}}{3} \left( \frac{1 - A^{1/2}}{1 + \frac{E_{\text{max}}}{4}} \right)
\]

where \( E_{\text{max}} \) is the maximum particle energy (0.557 MeV for \(^{137}\text{Cs} \) betas) and \( A \) is the atomic number (55), the mean energy per disintegration for beta is determined to be 0.19 MeV. Practically all beta particles of this energy are absorbed because their penetration in soft tissue is less than 0.4 mm. Assuming the effective radius for a mouse is 1.0 cm, the fraction of the energy absorbed from \(^{137}\text{Cs} \) gamma radiation is only \( \sim 0.039 \) and the total gamma energy absorbed is \( \sim 0.02 \) MeV per disintegration, yielding an overall average energy of \( \bar{E} = 0.19 + 0.02 = 0.21 \) MeV). Inclusion of gamma photons and beta particles from \(^{134}\text{Cs} \) decay did not affect dose rate estimates except beyond the third decimal place. Therefore, the \( DR \) estimate from intramuscular \(^{137}\text{Cs} \) was estimated as

\[
DR_{\text{Cs}} = T \cdot 7.26 \times 10^{-4} \text{ mGy/d}
\]

Estimates for dose rates due to internally deposited \(^{90}\text{Sr} \) \((N = 135)\) were much more complicated than for \( DR_{\text{Cs}} \). Determination of particle energies must account for beta particles emitted by \(^{90}\text{Sr} \) and by its degradation product \(^{90}\text{Y} \). The constant \( C \) is unity in this calculation because fresh bone was used for all analyses. Average particle energy \( \bar{E} \) for each radionuclide was determined from the \( E_{\text{max}} \) for \(^{90}\text{Sr} \) \((A = 38; E_{\text{max}} = 0.546 \text{ MeV}) \); \( E_{\text{max}} = 0.19 \) and \(^{90}\text{Y} \) \((A = 39; E_{\text{max}} = 2.27 \text{ MeV}; E_Y = 0.91) \). For the purposes of this study, we chose to estimate the average dose to the total mass of the organism rather than to a particular organ. \(^{90}\text{Sr} \), however, is not evenly distributed throughout the body. Because the vast majority \((\sim 99\%)\) of \(^{90}\text{Sr} \) and \(^{90}\text{Y} \) is deposited in bone, the dose imparted to surrounding muscle will be limited by the distance over which the particle energy is absorbed. Large fractions of tissue may be unaltered by particles from \(^{90}\text{Sr} \) and \(^{90}\text{Y} \). Beta particles released from \(^{90}\text{Sr} \) will penetrate less than 0.2 mm in bone and 0.4 mm in muscle. Because bone represents approximately 12% of the body mass of a rodent [16] and little energy from \(^{90}\text{Sr} \) is deposited in the total muscle/tissue mass, we multiplied the energy from \(^{90}\text{Sr} \) by 0.12.

In bones the size of a rodent's, a considerable fraction of the energy from \(^{90}\text{Y} \) will be deposited in soft tissues. Energy from \(^{90}\text{Y} \) is dissipated over a larger distance than \(^{90}\text{Sr} \), and a greater volume of muscle/tissue mass is affected. The distance over which half of the energy is absorbed (half-value layer; HVL [17]) in unit density tissue (in mm) is estimated as

\[
\text{HVL} = 0.41\bar{E}^{1.14}
\]

Therefore, one-half of the energy from a disintegration of an \(^{90}\text{Y} \) atom will be absorbed within the first 0.4 mm of muscle tissue \((E_Y = 0.91) \). The above equation can be expanded, assuming one half of the energy remaining is progressively absorbed in subsequent half-value layers [18]. Denoting \( x \) as the number of half-layer penetrations, the percentage of energy absorbed by \( x \) halflayers is \( P = 1 - 2^{-x} \). Solving for \( x \), the number of half-layers necessary for \( P \) percent of energy absorption is

\[
x = \frac{\ln(1 - P)}{\ln(2)}
\]

Using this expression, the depth \((L)\) of penetration of \( P \) percent of the energy of a beta particle in unit density material can be estimated by

\[
L_p = \frac{\ln(1 - P)}{\ln(2)} \times 0.41\bar{E}^{1.14}
\]

Thus, \( 99\% \) of the energy of \(^{90}\text{Y} \) beta particles will be absorbed within 2.5 mm of muscle tissue. It is reasonable, therefore, to assume that virtually all of the energy from \(^{90}\text{Y} \) is absorbed within the body of the rodent. Assuming the mouse is a cylinder of 1-cm radius and that maximum penetration of \(^{90}\text{Y} \) particles of average energy is 4 mm in muscle, then \(^{90}\text{Y} \) beta particles will yield energy to approximately 13% of the muscle/tissue volume (by ratio of cylinder volumes). Together with bone \((\sim 12\%)\) beta particles from \(^{90}\text{Y} \) will affect about 25% of the mass of a rodent. Therefore, we multiplied the energy from \(^{90}\text{Y} \) by 0.25. From the above calculations, the average daily dose rate from internally deposited \(^{90}\text{Sr} \) and \(^{90}\text{Y} \) was estimated as

\[
DR_{\text{Sr+Y}} = T \cdot (0.19(0.12) + 0.91(0.25)) \times 6.6 \times 10^{-6} \text{ (erg/MeV)}
\]

\[
= T \times (3.5 \times 10^{-3}) \text{ mGy/d}
\]

The two measures of \( DR \) may be associated with rather large errors. The depth and position of the radionuclide as well as variable shapes and location of organs and limbs create uncertainties in the estimations. Bone is a particularly heterogeneous material, and dosimetry to bone and surrounding tissue is quite complex [18,19]. Certainly, dose to some specific tissues may be underestimated while others are underestimated by the dose rate estimates calculated above. Such uncertainties are due to insufficient information regarding the geometry of rodent morphology and steps are underway to quantify measures for rodents to attain more accurate estimates to target tissues.

The daily dose rate due to external sources of radiation \((DR_{\text{ext}})\) was measured at one location to examine the relationship between internal and external \( DR \). Sixty-eight Microtus oeconomus were trapped at the Red Forest Enclosure and fitted with collars containing two LiF thermoluminescent dosimeters (TLDs; type TLD 100, Harshaw-Bicron, Newbury, OH, USA). These TLDs absorb radiation in a manner almost equivalent to that of biological tissue [20,21]. Each collar was permanently marked with a unique number and TLDs were housed within a sealed polyethylene tube (0.75-mm wall thickness). Animals were released and allowed to roam freely for 6 to 7 d. Thirteen live mice with intact collars were recaptured. The TLDs were preannealed and read using a Harshaw model QS-3500 TLD reader 9 (Harshaw-Bicron) operated according to the manufacturer's directions. Radiation dose rates were calculated by comparison with calibration dosimeters that were exposed to known amounts of radiation using well-characterized \(^{137}\text{Cs} \) sources. Identical collars carried to the sampling locations but not placed on mice served as controls. As an initial screening of specimens in the laboratory, whole-body counts per minute for total radiation was noted for each mouse.
by placement of a Victoreen 1490 Thiaecounter probe (In-
vasion, Yorba Linda, CA, USA) against the body shortly after
sacrifice. Radiocesium concentrations were determined from
muscle tissue for these individuals as described above. Sta-
tistical differences of means and variances among locations for
dose rates (cesium and strontium) were determined by analysis
of variance and variance ratio (F test) analysis, respectively.
Because dose rates and exposure values were distributed as
log normal for all locations, original values were log trans-
formed prior to statistical analyses.

RESULTS

Values for radiocesium concentrations in muscle from small
mammals at the various collection sites are provided in Table
1 (six animals not shown: one Neomys foides [79 Bq/g] from
Glyboke Lake; two Sicista betulina [55 Bq/g] from Chisto-
galovka, and three Mustela nivalis [13,700 Bq/g] from Red
Forest Grassland). Radiocesium values were log-normally dis-
tributed within species within sites, within species among
sites, among species within sites, and among species among
sites. Clearly, mammals from locations within the 10-km zone have
accumulated strikingly different concentrations of radiocesium.
Mammals at the Red Forest Woodlands had significantly higher
($p < 0.05$) average concentrations than other samples,
with 13,600 Bq/g corresponding to a mean $\text{DR}_{\text{CE}}$ of 9.9 mGy/
d. Mammals from the adjacent Red Forest Enclosure (only about
100 m from the Woodland), however, averaged only 26
Bq/g, yielding an average $\text{DR}_{\text{CE}}$ of 19 $\mu\text{Gy/d}$. The low values
for this location, only 2 km from the reactor, are probably due
to the disturbance and removal of topsoil and trees from the
site during construction of the enclosure walls. More extensive
remediation was carried out at the Red Forest Grassland, which
abuts the Woodland and surrounds the Enclosure. The top layer
(~30 cm) of soil in this former forest was bulldozed and buried
in berms. This region (~400 ha) is very patchy in radiocesium
distribution, and two individuals had no detectable radiocesium
concentrations above background. Overall, however,
mammals from the Red Forest Grassland averaged 2,400 Bq/
g, conveying a $\text{DR}_{\text{CE}}$ of 1.74 mGy/d. Glyboke Lake is situated
near the center of the Northern Trace, the first radioactive
plume released after the explosion (Fig. 1). Mammals from
Glyboke Lake were quite high in radiocesium concentrations,
averaging 1,500 Bq/g, yielding an estimated dose rate of 1.1
mGy/d. Chistogalovka was situated along the Western Trace
of radiation carried by winds primarily during the second day
after the explosion (Fig. 1). Although only about 4 km from
reactor number four, mammals from Chistogalovka were similar
to those from the remediated Red Forest Enclosure in
concentrations of radiocesium and dose rate estimates. The
Orchard is approximately the same distance from the reactor
complex as the Red Forest locations but is in the eastern di-
rection, opposite to the primary paths of wind-borne radiation
plumes (Fig. 1). Mammals from the Orchard had the lowest
radiocesium concentrations and $\text{DR}_{\text{CE}}$ estimates of any sam-
pling location within the 10-km zone, with values of 19 Bq/g
and 14 $\mu\text{Gy/d}$, respectively. As expected, mammals from six
combined locations about 30 to 45 km southeast of the reactor
had low values of 1.9 Bq/g and 1.4 $\mu\text{Gy/d}$.

Not only was there substantial variation in radiocesium
among localities, there were also considerable differences
among taxa (Table 1). The rank order of radiocesium concen-
trations across species differs for each of the locations col-
clected; it must be noted, however, that not all species occurred
at each site. Clethrionomys glareolus ($N = 77$) had the highest
overall average radiocesium concentration (5,100 Bq/g), fol-
lowed by Apodemus flavicolis ($N = 7$; 1,300 Bq/g). Both
of these species are herbivorous forest dwellers [9]. Insectivorous
species (Sorex araneus and Neomys foides) had markedly
lower concentrations of cesium than granivorous taxa at Gly-
boke Lake but had considerably greater concentrations than
some typical species found at the Red Forest Woodland and
Grassland locations. Three specimens of a carnivore, Mustela
nivalis, from the Red Forest Grassland (not shown in Table
1) showed great variation, ranging from 432 Bq/g (0.31 mGy/
d) to 36,000 Bq/g (26 mGy/d). Often, conspecific animals
captured within several meters of one another would differ by
an order of magnitude in their radiocesium concentrations and
dose rate estimates (Table 1).

Skeletal concentrations of $^{90}$Sr (Table 2) were much more
consistent among sites than were those for radiocesium.
Among taxa that had been analyzed for both radionuclides,
the variance of log-transformed $^{90}$Sr concentrations was
significantly lower than that for radiocesium ($F$ test, $p = 0.05$).
Average $^{90}$Sr concentrations were highest at Glyboke Lake
(497 Bq/g) but were not significantly greater than those for
the Red Forest Grassland (332 Bq/g) and Woodland (325 Bq/
g; $p > 0.10$). $^{90}$Sr levels were significantly lower at Chistog-
alovka than at the other locations sampled ($p < 0.05$). No
significant differences were observed between species when
averaged across locations ($p > 0.12$). Unfortunately, the spec-
imens analyzed for $^{90}$Sr concentrations were different from
those assessed for radiocesium, preventing examination of pos-
sible correlations between internal concentrations of the two
radionuclides. Estimated dose rates for $^{90}$Sr were higher than
for radiocesium in mammals from Glyboke Lake and Chis-
togalovka. Further, the rank order of mean $\text{DR}$ within sampling
locations was different for $^{90}$Sr and radiocesium.

Estimates of dose rates from external sources ($\text{DR}_{\text{ext}}$) ra-
diation were determined from the TLDs for the 13 Microtus oce-
onomus in the Red Forest Enclosure (Table 3). Comparison
of the two LiF TLDs in each collar demonstrated significant
conformity of their dose rate estimates for individuals ($r = 0.97$,
$p < 0.001$). Average $\text{DR}_{\text{ext}}$ was 0.735 mGy/d, over 30
times the mean estimate for the $\text{DR}_{\text{CE}}$ for the same individuals.
The $\text{DR}_{\text{ext}}$ estimates from TLDs conformed closely with esti-
mates obtained from a hand-held Thiac counter held at ground
level (3 mrem/h = 0.72 mGy/d). Samples from the Red Forest
Enclosure were not available for analysis of $^{90}$Sr concentra-
tions. However, if we assume that $^{90}$Sr levels are minimally
equal to those at Chistogalovka (the site most similar to the
Enclosure for radiocesium concentrations), then the dose rates
imparted by internal sources ($\text{DR}_{\text{CE}} + \text{DR}_{\text{ext}}$) would be about
43% of the $\text{DR}_{\text{ext}}$ estimated by the TLDs (0.32 mGy/d vs 0.74
mGy/d).

Estimates of dose rates from radiocesium were not signific-
antly correlated with those acquired by external TLDs ($r = -0.14$, $p > 0.15$). There was no significant correlation between
the whole-body counts per minute determined by the Thiac
and $\text{DR}_{\text{ext}}$ values from the TLDs ($r = 0.12$, $p > 0.2$). However,
the correlation between counts per minute and $\text{DR}_{\text{CE}}$ was highly
significant ($r = 0.88$, $p < 0.001$). Although not definitive,
these correlations suggest that estimates of external dose may
be largely independent of doses from internal radiocesium.
Because of the placement of the collars, the TLDs measured
surfacial dose, and doses to internal organs were likely lower
than measured by the TLDs. However, the primary radiations
Table 1. Radiocesium (134,137Cs) concentration (Becquerels per gram) in dry muscle samples for eight species of mammals from areas near the Chornobyl reactor and for regions outside the exclusion zones. Dose rate estimates were derived as a function of gamma and beta energies from radiocesium. Six individuals of three species are not shown in the table.

<table>
<thead>
<tr>
<th>Location/parameter</th>
<th>Apodemus agrarius</th>
<th>Apodemus flavicollis</th>
<th>Apodemus sylvaticus</th>
<th>Microtus arvalis</th>
<th>Microtus oeconomus</th>
<th>Microtus rossiaem.</th>
<th>Clethrionomys glareolus</th>
<th>Sorex arenaceus</th>
<th>Location summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Forest (grassland)</td>
<td>N = 1</td>
<td>N = 11</td>
<td>N = 6</td>
<td>N = 1</td>
<td>N = 7</td>
<td>N = 14</td>
<td>N = 3</td>
<td>N = 56 ≤</td>
<td>N = 3</td>
</tr>
<tr>
<td>Bq/g</td>
<td>2.424</td>
<td>927</td>
<td>249</td>
<td>60</td>
<td>822</td>
<td>2,902</td>
<td>3,382</td>
<td>2,396</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>10–6,966</td>
<td>141–3,659</td>
<td>8–918</td>
<td>—</td>
<td>5–2,390</td>
<td>417–8,909</td>
<td>336–5,501</td>
<td>5–36,188</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>1.76</td>
<td>0.67</td>
<td>0.18</td>
<td>0.043</td>
<td>0.60</td>
<td>2.10</td>
<td>2.45</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.007–5.06</td>
<td>0.10–2.66</td>
<td>0.006–0.66</td>
<td>—</td>
<td>0.004–1.73</td>
<td>0.30–6.47</td>
<td>0.24–3.99</td>
<td>0.004–26.26</td>
<td></td>
</tr>
<tr>
<td>Red Forest (enclosure)</td>
<td>N = 1</td>
<td>N = 3</td>
<td>N = 41</td>
<td>N = 1</td>
<td>N = 1</td>
<td>N = 47</td>
<td>N = 47</td>
<td>N = 26.0</td>
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<tr>
<td>Bq/g</td>
<td>67</td>
<td>67</td>
<td>21</td>
<td>22</td>
<td>66</td>
<td>—</td>
<td>2–166</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>—</td>
<td>13–166</td>
<td>2–98</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>N = 0.012</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.05</td>
<td>—</td>
<td>0.05</td>
<td>0.015</td>
<td>0.016</td>
<td>0.05</td>
<td>0.05</td>
<td>0.002–0.12</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>—</td>
<td>0.01–0.12</td>
<td>0.002–0.07</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.002–0.12</td>
<td></td>
</tr>
<tr>
<td>Red Forest (woodland)</td>
<td>N = 4</td>
<td>N = 2</td>
<td>N = 12</td>
<td>N = 1</td>
<td>N = 3</td>
<td>N = 30</td>
<td>N = 6</td>
<td>N = 58</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>806</td>
<td>649</td>
<td>1,847</td>
<td>4,249</td>
<td>513</td>
<td>24,720</td>
<td>2,592</td>
<td>13,615</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>239–1,354</td>
<td>87–1,210</td>
<td>322–8,267</td>
<td>—</td>
<td>101–1,209</td>
<td>606–82,078</td>
<td>96–8,118</td>
<td>87–82,078</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.59</td>
<td>0.47</td>
<td>1.34</td>
<td>3.11</td>
<td>0.37</td>
<td>17.94</td>
<td>1.88</td>
<td>9.88</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.17–0.98</td>
<td>0.06–0.88</td>
<td>0.23–6.00</td>
<td>0.07–0.88</td>
<td>0.44–5.97</td>
<td>0.07–5.89</td>
<td>0.06–5.97</td>
<td>0.06–5.97</td>
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</tr>
<tr>
<td>Glyboke Lake</td>
<td>N = 12</td>
<td>N = 4</td>
<td>N = 9</td>
<td>N = 22</td>
<td>N = 19</td>
<td>N = 2</td>
<td>N = 32</td>
<td>N = 11 ^a</td>
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</tr>
<tr>
<td>Bq/g</td>
<td>497</td>
<td>1,862</td>
<td>298</td>
<td>1,316</td>
<td>1,538</td>
<td>5,149</td>
<td>2,403</td>
<td>1,493</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>38–2,029</td>
<td>849–2,410</td>
<td>31–990</td>
<td>~0–7,223</td>
<td>51–4,563</td>
<td>2,950–7,347</td>
<td>119–25,941</td>
<td>46–269</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.36</td>
<td>1.35</td>
<td>0.22</td>
<td>0.95</td>
<td>1.11</td>
<td>3.73</td>
<td>1.74</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.03–1.5</td>
<td>0.62–1.75</td>
<td>0.02–0.72</td>
<td>~0–5.24</td>
<td>0.04–3.31</td>
<td>2.14–5.33</td>
<td>0.09–1.88</td>
<td>0.03–0.58</td>
<td></td>
</tr>
<tr>
<td>Orchard</td>
<td>N = 2</td>
<td>N = 13</td>
<td>N = 1</td>
<td>N = 15</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>~0–18.8</td>
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</tr>
<tr>
<td>Bq/g</td>
<td>29</td>
<td>28</td>
<td>25</td>
<td>60</td>
<td>29</td>
<td>—</td>
<td>—</td>
<td>19.0</td>
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</tr>
<tr>
<td>Range (Bq/g)</td>
<td>1–56</td>
<td>1–168</td>
<td>—</td>
<td>—</td>
<td>1–25</td>
<td>—</td>
<td>1–168</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.006</td>
<td>—</td>
<td>—</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.001–0.04</td>
<td>0.001–0.12</td>
<td>—</td>
<td>—</td>
<td>~0–0.025</td>
<td>—</td>
<td>—</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Chistogalivka</td>
<td>N = 17</td>
<td>N = 4</td>
<td>N = 17</td>
<td>N = 2</td>
<td>N = 25 ≤</td>
<td>N = 2</td>
<td>N = 25 ≤</td>
<td>N = 31</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>28</td>
<td>60</td>
<td>29</td>
<td>60</td>
<td>29</td>
<td>—</td>
<td>—</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>1–134</td>
<td>34–88</td>
<td>4–54</td>
<td>34–88</td>
<td>4–54</td>
<td>—</td>
<td>—</td>
<td>32.0</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>—</td>
<td>—</td>
<td>1–134</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>~0–0.1</td>
<td>0.02–0.06</td>
<td>0.003–0.04</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>Chornobyl Zone summary</td>
<td>N = 29</td>
<td>N = 7</td>
<td>N = 45</td>
<td>N = 50</td>
<td>N = 68</td>
<td>N = 27</td>
<td>N = 77</td>
<td>N = 19</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>372.3</td>
<td>1,259.1</td>
<td>555.2</td>
<td>695.0</td>
<td>469.4</td>
<td>602.3</td>
<td>5,062.2</td>
<td>632.3</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>1.5–2,029</td>
<td>67–2,410</td>
<td>1.35–3,659</td>
<td>~0–7,223</td>
<td>2.1–4,563</td>
<td>1.0–7,347</td>
<td>66.2–73,090</td>
<td>45.8–2,910</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>0.27</td>
<td>0.91</td>
<td>0.40</td>
<td>0.51</td>
<td>0.34</td>
<td>0.44</td>
<td>3.67</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.001–1.47</td>
<td>0.05–1.75</td>
<td>0.001–2.65</td>
<td>~0–5.24</td>
<td>0.002–3.31</td>
<td>~0–5.53</td>
<td>0.05–53.0</td>
<td>0.03–2.11</td>
<td></td>
</tr>
<tr>
<td>30–50 km southeast of Zone</td>
<td>N = 13</td>
<td>N = 20</td>
<td>N = 35</td>
<td>N = 14</td>
<td>N = 47</td>
<td>N = 2</td>
<td>N = 2</td>
<td>N = 133</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>0.33</td>
<td>7.5</td>
<td>0.78</td>
<td>1.0</td>
<td>1.1</td>
<td>1.8</td>
<td>0.8</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>0.0–8</td>
<td>0.2–85</td>
<td>0–6</td>
<td>0–6</td>
<td>0–19</td>
<td>1–3</td>
<td>0.3–1.4</td>
<td>0.8–85</td>
<td></td>
</tr>
<tr>
<td>Dose rate (mGy/d)</td>
<td>2.4 × 10^{-4}</td>
<td>0.006</td>
<td>5.7 × 10^{-4}</td>
<td>7.3 × 10^{-4}</td>
<td>8.1 × 10^{-4}</td>
<td>0.001</td>
<td>6.02 × 10^{-4}</td>
<td>0.0014</td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0–5.9 × 10^{-4}</td>
<td>0.0003–0.06</td>
<td>0–0.005</td>
<td>0–0.004</td>
<td>0–0.014</td>
<td>5 × 10^{-4}–0.002</td>
<td>2 × 10^{-4}–0.001</td>
<td>0–0.062</td>
<td></td>
</tr>
</tbody>
</table>

* Three specimens of Mustela nivalis not shown (values given in the text).

* One specimen of Neomys foides not shown (values given in the text).

* Two specimens of Siciota betulina not shown (values given in the text).
Table 2. Strontium-90 concentrations (Becquerels per gram) in skeletons and dose estimates (mGy/d) for mammals collected in areas near the Chernobyl Nuclear Power Plant

<table>
<thead>
<tr>
<th>Location/parameter</th>
<th>Apodemus agrarius</th>
<th>Apodemus flavicollis</th>
<th>Apodemus sylvaticus</th>
<th>Microtus arvalis*</th>
<th>Microtus oeconomus</th>
<th>Clethrionomys glareolus</th>
<th>Sorex arenaceus</th>
<th>Location summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Forest Grassland</td>
<td>N = 12</td>
<td>N = 21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N = 1</td>
<td>N = 34</td>
</tr>
<tr>
<td>Bq/g</td>
<td>389</td>
<td>314</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td>332</td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>79.4–871</td>
<td>21.1–1,374</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td>21.1–1,374</td>
</tr>
<tr>
<td>Dose (mGy/d)</td>
<td>1.3</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.3–3.0</td>
<td>0.1–4.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.1–4.8</td>
</tr>
<tr>
<td>Red Forest Woodland</td>
<td>N = 3</td>
<td>N = 4</td>
<td>N = 1</td>
<td></td>
<td></td>
<td></td>
<td>N = 8</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>330</td>
<td>370</td>
<td>131</td>
<td></td>
<td></td>
<td></td>
<td>325</td>
<td></td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>36.5–582</td>
<td>204–815</td>
<td>131</td>
<td></td>
<td></td>
<td></td>
<td>36.5–815</td>
<td></td>
</tr>
<tr>
<td>Dose (mGy/d)</td>
<td>1.1</td>
<td>1.3</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.1–2.0</td>
<td>0.7–2.8</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td>0.1–2.8</td>
<td></td>
</tr>
<tr>
<td>Glybokye Lake</td>
<td>N = 8</td>
<td>N = 1</td>
<td>N = 1</td>
<td>N = 10</td>
<td>N = 3</td>
<td>N = 13</td>
<td>N = 9</td>
<td>N = 45</td>
</tr>
<tr>
<td>Bq/g</td>
<td>262</td>
<td>167</td>
<td>171</td>
<td>752</td>
<td>1,068</td>
<td>271</td>
<td>630</td>
<td>497</td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>109–765</td>
<td>167</td>
<td>171</td>
<td>368–1,502</td>
<td>370–1,609</td>
<td>74–479</td>
<td>104–2,275</td>
<td>74–2,275</td>
</tr>
<tr>
<td>Dose (mGy/d)</td>
<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
<td>2.6</td>
<td>3.7</td>
<td>0.6</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.4–2.6</td>
<td>0.6</td>
<td>0.6</td>
<td>1.3–5.2</td>
<td>1.3–5.6</td>
<td>0.3–1.7</td>
<td>0.4–7.9</td>
<td>0.3–7.9</td>
</tr>
<tr>
<td>Chistogalivka</td>
<td>N = 2</td>
<td>N = 25</td>
<td>N = 9</td>
<td>N = 1</td>
<td>N = 10</td>
<td>N = 48</td>
<td>N = 48</td>
<td></td>
</tr>
<tr>
<td>Bq/g</td>
<td>30</td>
<td>76</td>
<td>23</td>
<td>89</td>
<td>76</td>
<td>23</td>
<td>89</td>
<td>79</td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>30–30.5</td>
<td>12–677</td>
<td>33.2–239</td>
<td>22.7</td>
<td>56.1–168</td>
<td>1.2–677</td>
<td>56.1–168</td>
<td>1.2–677</td>
</tr>
<tr>
<td>Dose (mGy/d)</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.1</td>
<td>0.4–2.3</td>
<td>0.1–0.8</td>
<td>0.1</td>
<td>0.2–0.6</td>
<td>0.2–0.6</td>
<td>0.004–2.3</td>
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</tr>
<tr>
<td>Chernobyl Zone summary</td>
<td>N = 10</td>
<td>N = 4</td>
<td>N = 17</td>
<td>N = 57</td>
<td>N = 12</td>
<td>N = 14</td>
<td>N = 20</td>
<td>N = 135</td>
</tr>
<tr>
<td>Bq/g</td>
<td>216</td>
<td>289</td>
<td>372</td>
<td>289</td>
<td>324</td>
<td>253</td>
<td>327</td>
<td>297</td>
</tr>
<tr>
<td>Range (Bq/g)</td>
<td>30.3–765</td>
<td>36.5–582</td>
<td>79.4–871</td>
<td>12–1,502</td>
<td>32.3–1,609</td>
<td>22.7–479</td>
<td>39–2,275</td>
<td>1.2–2,275</td>
</tr>
<tr>
<td>Dose (mGy/d)</td>
<td>0.7</td>
<td>1.0</td>
<td>1.3</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Range (dose)</td>
<td>0.1–2.6</td>
<td>0.1–2.0</td>
<td>0.3–3.0</td>
<td>0.04–5.2</td>
<td>0.1–5.6</td>
<td>0.1–1.7</td>
<td>0.1–7.9</td>
<td>0.004–7.9</td>
</tr>
</tbody>
</table>
* Karyotypes not examined. Specimens may be either *M. arvalis* or *M. rossiaemeridionalis*.

### DISCUSSION

Mean values of $^{134,137}$Cs and $^{90}$Sr concentrations for mammals in unremediated habitats in the Chernobyl region are among the highest ever recorded for free-ranging animals in otherwise natural environments. Animals from remediated areas were generally lower in radionuclide concentrations than their counterparts in adjacent unremediated habitats. However, it is clear that remediation has not had uniform effectiveness in reducing radionuclide availability to biota. Two remediated areas, the Red Forest Enclosure and Red Forest Grassland, showed marked differences in radionuclide concentrations in mammals. Mammals from the Red Forest Enclosure were among the lowest in radionuclide concentrations, whereas those from the Red Forest Grassland, just beyond the borders of the enclosure, often showed strikingly high values for radionuclide and for estimated dose rates. Animals from the Red Forest Woodland exhibited high concentrations of intramuscular cesium, ranging from 87 to an extraordinary 82,000 Bq/g (dry). The levels of residual radioactivity around the reactor

Table 3. Values of whole-body counts per minute, estimates of external dose rates from thermoluminescent dosimeters (TLDs) and estimates of internal dose rates from concentrations of radionuclides for 13 *Microtus oeconomus* fitted with collars in the Red Forest Enclosure near the Chernobyl reactor. Each collar carried two LiF TLDs, and values given are the average for each individual

<table>
<thead>
<tr>
<th>Animal number</th>
<th>Counts per minute</th>
<th>TLD dose rate (mGy/d)</th>
<th>Internal dose rate (mGy/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>4,000</td>
<td>0.480</td>
<td>0.071</td>
</tr>
<tr>
<td>205</td>
<td>3,600</td>
<td>1.058</td>
<td>0.058</td>
</tr>
<tr>
<td>115</td>
<td>2,300</td>
<td>0.754</td>
<td>0.034</td>
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<tr>
<td>221</td>
<td>1,700</td>
<td>0.816</td>
<td>0.003</td>
</tr>
<tr>
<td>197</td>
<td>2,700</td>
<td>0.875</td>
<td>0.017</td>
</tr>
<tr>
<td>111</td>
<td>1,000</td>
<td>0.676</td>
<td>0.009</td>
</tr>
<tr>
<td>169</td>
<td>800</td>
<td>0.741</td>
<td>0.004</td>
</tr>
<tr>
<td>183</td>
<td>1,200</td>
<td>0.646</td>
<td>0.007</td>
</tr>
<tr>
<td>179</td>
<td>2,700</td>
<td>0.598</td>
<td>0.010</td>
</tr>
<tr>
<td>117</td>
<td>3,600</td>
<td>0.975</td>
<td>0.026</td>
</tr>
<tr>
<td>171</td>
<td>1,300</td>
<td>0.905</td>
<td>0.005</td>
</tr>
<tr>
<td>73</td>
<td>3,600</td>
<td>0.480</td>
<td>0.043</td>
</tr>
<tr>
<td>187</td>
<td>1,500</td>
<td>0.546</td>
<td>—</td>
</tr>
<tr>
<td>Means</td>
<td>2,375</td>
<td>0.735</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Table 4. Concentrations of radioactive cesium and strontium in soils at sampling locations near the Chernobyl Nuclear Power Plant. Values are given for mean ± one standard deviation

<table>
<thead>
<tr>
<th></th>
<th>$^{134,137}$Cs (KBq/kg)</th>
<th>$^{90}$Sr (KBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Forest Grassland</td>
<td>22.1 ± 12.3</td>
<td>11.1 ± 6.4</td>
</tr>
<tr>
<td>Red Forest Enclosure</td>
<td>21.7 ± 12.9</td>
<td>11.3 ± 6.8</td>
</tr>
<tr>
<td>Red Forest Woodland</td>
<td>197.1 ± 77.7</td>
<td>98.9 ± 38.4</td>
</tr>
<tr>
<td>Glybokye Lake</td>
<td>124.2 ± 40.6</td>
<td>54.7 ± 28.2</td>
</tr>
<tr>
<td>Orchard</td>
<td>25.7 ± 12.8</td>
<td>13.8 ± 5.4</td>
</tr>
<tr>
<td>Chistogalivka</td>
<td>87.1 ± 47.8</td>
<td>46.8 ± 18.1</td>
</tr>
</tbody>
</table>
Dose rates at Chornobyl

were strongly influenced by climatic conditions extant at the time of the accident (Fig. 1). Thus, unremediuated areas to the south and east of the reactor (Orchard and Chistogalovka) exhibit relatively low accumulation of radiocesium.

There was no consistent rank order for species associations with radiocesium concentrations among the various contaminated habitats sampled. Apparently, high variation in radiocesium distributions in soil and vegetation has a profound influence on the concentrations found within and among species over the contaminated region. The range of values for radiocesium within a species may vary by an order of magnitude, even when specimens were collected less than 100 m apart. Clearly, accumulation of radiocesium within individual organisms is dependent on local availability in dietary components.

Concentrations of $^{90}$Sr within and among mammals from the sampling locations were much more consistent than for radiocesium. This consistency, however, was not evident when comparing variation in soil concentrations among the sites (Table 4). Variances of soil concentration within remediated sites were not significantly different from those in undisturbed locations. Thus, the relative homogeneity of $^{90}$Sr values within organisms is probably not due to differential effectiveness of cleanup activities in ameliorating the two radionuclides. It is more likely that the difference between the two variances is due to the slow turnover rate of $^{90}$Sr relative to that of $^{134,137}$Cs [19]. The biological half-life of $^{90}$Sr is about 130 times longer than that of $^{134,137}$Cs in a mammal the size of a mouse (233 d vs 7.2 d for a 20 g body weight) [19]. Therefore, radiocesium concentrations may fluctuate in accordance with recent changes in diet and/or movements of individuals, whereas $^{90}$Sr would be expected to remain relatively stable over short time periods.

Despite extraordinarily $^{134,137}$Cs and $^{90}$Sr concentrations in mammals in the 10-km Exclusion Zone, it is unlikely that dose rates are currently inflicting significant short-term morbidity in the mammal populations in the Chornobyl region. The LD50/30 for acute exposures in rodents are typically in the range of 8 to 12 Gy [22–27], and chronic dose rates greater than 100 mGy/d are required to induce significant mortality in small mammals [28]. If we assume a somewhat extreme scenario that dose rates from external and internal sources of radiation in the Chornobyl zone are approximately equal ($DR_{ex} = DR_{es}$), then the highest average dose ($DR_{es} + DR_{ca} + DR_{sr}$) would be about 30 mGy/d (Red Forest Woodland), or about one third that necessary to cause significant mortality. Interestingly, when this assumption is applied to individuals, it is found that 20% of $C. glareolus$ from the Red Forest Woodland would potentially exceed 100 mGy/d ($DR_{es} > 33.3$ mGy/d). Relative high radioresistance has been reported for this species [23], and data from other radioactively contaminated sites suggest that $C. glareolus$ may have evolved a greater tolerance to ionizing radiation [23,24]. In regions near the Red Forest shortly after the Chornobyl accident, $C. glareolus$ was found to have high embryonic mortality in the first year after the accident (34% vs 6% in controls; [10]).

Absorbed doses in excess of 10 mGy/d have been shown to impair reproduction in mammals [7,28–30]. Only 4.1% (19/461) of the animals collected were found to be experiencing dose rates from intramuscular cesium in excess of 10 mGy/d, while none exceeded that $DR$ for $^{90}$Sr. Fifty-five percent of $C. glareolus$ from the Red Forest Woodland were >10 mGy/d from radiocesium alone. The only other specimens with $DR_{ca}$ values >10 mGy/d were a $Mustela nivalis$ from the Red Forest Grassland and a $C. glareolus$ from Glyboke Lake.

Clearly, the potential for reproductive inhibition exists for some species within the Chornobyl region. Mammals from habitats such as the Red Forest Grassland, Red Forest Woodland, and Glyboke Lake are particularly vulnerable to doses exceeding the lower bound for reproductive failure. Despite the increase in many mammalian population numbers and diversity [9,10], reduction in fertility, increased mortality, and a variety of physiological disorders have been reported for mammals in the Chornobyl Zone [31,32]. The mosaic pattern of radioactive contamination probably provides sufficient sources of migrant individuals to replace those that fail to reproduce [10]. These data suggest that some regions of the Chornobyl zone may be reproductive sinks for mammal populations, and densities are maintained by immigration from nearby habitats with more benign levels of radiation [31].

Over the past decade, mammal populations in this region experienced substantially higher dose rates than at present. Undoubtedly, many populations near the reactor and at Glyboke Lake were eliminated in the months after the explosion. Doses along the trace of the initial plume of radiation released were estimated at 22 Gy/month for gamma and 860 Gy/month for beta irradiation [12]. Despite the legacy of radioactive contamination and present dose rates, recovery of mammal populations has taken place, with little data to suggest persistent impaired performance of the populations or communities.

Levels of contamination and dose rate estimates reported here would be expected to confer considerable insult to genetic material by ionizing radiation. Genetic damage and elevated rates of chromosomal aberrations has been reported for animals [9,33–39] and exposed humans [40–42] from the Chornobyl region. Elevated mutation rates were reported for a mitochondrial gene for rodents from Chornobyl [37]. A more thorough examination of the sequence data, however, could not discern an elevated mutation rate in the cytchrome b gene [43]. Thus, there is no evidence for marked change in coding segments of genes for organisms inhabiting these polluted environments. Suppression of reproduction at relatively low dose rates (e.g., 10 mGy/d) may prevent significant accumulation of mutations within populations because there may be little opportunity for parents to convey mutant gametes to progeny.

Guidelines recommended by the International Atomic Energy Agency [30] set maximum dose rates to plant and animal populations at 1 mGy/d. Mean dose rates for mammals in the Chornobyl zone were estimated at 1.0 and 2.4 mGy/d for $^{90}$Sr and $^{134,137}$Cs, respectively. The recommended maximum is exceeded by 20% of mammals collected in the Chornobyl Zone based on the dose rate for radiocesium alone and 15% based on the $DR_{sr}$. Our data suggest that the variation in dose rates may be more important than mean values when considering the overall impact to mammalian populations. Although substantial, the concentrations of radiocesium and $^{90}$Sr, combined with external doses, are nevertheless insufficient to impede continued survival and proliferation of mammal populations in the Chornobyl Exclusion Zone. Further studies are needed to address the complex relationships between radiation doses, subtle changes in biochemical and physiological measures, and the heterogeneity of contaminant distributions on population dynamics of fauna and flora. This paper provides important data against which these various biological endpoints may be measured.
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REFERENCES