AMERICAN JOURNAL OF HUMAN BIOLOGY 22:667–674 (2010)

Original Research Article

Chronic Radiation Exposure in the Rivne-Polissia Region of Ukraine: Implications for Birth Defects

KELSEY NEEDHAM DANCAUSE,[1] LYUBOV YEVTUSHOK,[2] SERHIY LAPCHENKO,[3] IHOR SHUMLYANSKY,[2] GENADIY SHEVCHENKO,[4] WLADIMIR WERTELECKI,[5] AND RALPH M. GARRUTO[1]*
[1]*Department of Anthropology, State University of New York, Binghamton, New York*
[2]*Rivne Oblast Medical Diagnostic Center and the OMNI-Net Center, Rivne, Ukraine*
[3]*Regional Children's Clinical Hospital and the OMNI-Net Center, Volyn, Ukraine*
[4]*Rivne Oblast Sanitary and Epidemiological Station, Rivne, Ukraine*
[5]*Department of Medical Genetics, University of South Alabama, Mobile, Alabama*

Objectives: The health effects of chronic low-dose radiation exposure remains a controversial question. Monitoring after the Chernobyl nuclear accident in Ukraine suggested that chronic low-dose radiation exposure was not linked to cancer mortality among the general population. However, elevated rates of birth defects in contaminated compared to uncontaminated regions suggest that exposure to radiation in utero might impact development and that chronic radiation exposure might represent an underestimated risk to human health.

Methods: We sought to determine current radiation exposure routes in Rivne-Polissia, a region of Ukraine contaminated by the Chernobyl accident. This represents a first step toward comprehensive studies of the effects of chronic radiation exposure on human health. We designed and administered a dietary and activity survey to 344 women in Polissia. We assessed types and sources of food consumed, types of outdoor activities, and alcohol intake.

Results: Alcohol intake was low and alone does not account for the observed high rates of birth defects. Wild foods, especially mushrooms and berries, and locally produced foods, especially milk related, were major radiation exposure routes. Additionally, women were exposed to radiation through inhalation while burning grasses and potato vines in fields, and wood for cooking and heating.

Conclusions: Twenty four years after the Chernobyl accident, women continue to be chronically exposed to low-dose radiation at levels exceeding current recommendations. This might contribute (especially synergistically with alcohol consumption and micronutrient deficiencies) to higher prevalence of birth defects in areas of Ukraine with high levels of radiation contamination compared to uncontaminated areas. Am. J. Hum. Biol. 22:667–674, 2010.

The health effects of chronic low-dose radiation exposure represent a continuing, controversial question in biology and medicine (see Parfitt, 2006). Contamination following nuclear accidents has raised public and scientific concern about pathways of exposure, the time frame of risk, and the contribution of radionuclides to population rates of developmental disorders and cancer (Cardis, 1996). Unfortunately, most estimates of the health risks of radiation exposure are derived from large, acute, external doses received by adult survivors of atomic bombs in Hiroshima and Nagasaki (Baverstock and Williams, 2006; Farilie, 2009) or during or immediately after the explosion of the Chernobyl nuclear reactor (Ivanov et al., 2001; Mück et al., 2002; Pröhl et al., 2002). These might not be applicable to low-dose, internal, chronic exposure or to potential health effects across the lifespan (especially in utero) (Fairlie, 2009). Furthermore, those studies that have examined health effects of chronic exposure have focused mostly on limited pathways, such as the transfer of radiation from dietary intake of milk (Lepicard and Dubreuil, 2001), mushrooms (Duff and Ramsey, 2008; Skuterud et al., 1997), meat (Åhman, 1999; Vilic et al., 2005), and fish (Travnikova et al., 2004). However, radiation exposure occurs through a number of internal and external pathways, and population exposure levels are expected to vary based on dietary and activity patterns. Human biologists and biomedical anthropologists can contribute to this body of knowledge by using the findings of studies with a single, specific focus, as a basis for designing more holistic studies that consider multiple pathways of exposure across the lifespan. Research among Chernobyl-impacted populations represents an opportunity to understand the health effects of an anthropogenic environmental insult on the health of human populations within the framework of a natural experimental model (Garruto et al., 1999; Little and Garruto, 2007).

The explosion of the Chernobyl nuclear reactor in April 1986 resulted in the release of radionuclides into the atmosphere over 10 days, with heavy contamination of parts of Belarus, Russia, and Ukraine and fallout spreading across parts of Europe (Chernobyl Forum, 2003–2005). Immediate concerns were focused on Iodine 131 (^{131}I), which has a half-life of 8 days and sequesters in the thyroid gland. Before evacuation of the most heavily contaminated areas (up to 11 days after the accident), residents were exposed to high levels of ^{131}I through inhalation and through continued consumption of milk and leafy vegetables with elevated ^{131}I levels. This acute exposure has been linked to a large fraction of the more than 4,000 cases of thyroid cancer recorded from 1986 to 2002 (Balanov, 2007).

Later concerns shifted to contamination with Cesium 134 (^{134}Cs), which has a half-life of 2 years; Strontium 90 (^{90}Sr), which has a half-life of 8 years; and particularly

*Correspondence to: Ralph M. Garruto, Graduate Program in Biomedical Anthropology, State University of New York, PO Box 6000, Binghamton, NY 13902-6000, USA. E-mail: rgarruto@binghamton.edu

Received 12 October 2009; Revision received 22 March 2010; Accepted 23 March 2010

DOI 10.1002/ajhb.21063

Published online 11 May 2010 in Wiley Online Library (wileyonlinelibrary.com).

Cesium 137 (^{137}Cs), which has a half-life of 30 years (Chernobyl Forum, 2006). Countermeasures implemented after the accident attempted to reduce the contamination levels of foods and to limit radionuclide exposure of populations in contaminated areas (Andersson et al., 2008; Fesenko et al., 2007; Howard et al., 2001). Today the majority of areas classified as "contaminated" are considered by the Chernobyl Forum, a group composed of eight United Nations organizations and scientific authorities, to have contamination levels little more than natural background radiation levels and to be safe living areas (Balanov, 2007). The lack of increased rates of solid cancers or leukemia due to radiation exposure among the general public tends to support conclusions that exposure to low whole-body doses of radiation holds little risk for increased total cancer mortality, and any increases that might have occurred would be at a magnitude too low to detect (Chernobyl Forum, 2003-2005; UNSCEAR, 2000).

The most agreed upon health effects of the accident include stress and psychosocial illnesses among individuals living in contaminated areas, as well as effects ultimately linked to a lack of economic opportunities and to economic instability in contaminated regions (Balanov, 2007; Baverstock and Williams, 2006; Bohannon, 2005). Teratogenic and physiological effects, however, remain debated. Some researchers suggest risk has been exaggerated and that governmental secrecy after the accident combined with years of inadequate communication between the scientific community and the public have exacerbated rumors fed by public fear of nuclear war and radiation (Rahu, 2003; Shields, 2004). Others have suggested that radionuclide release and exposure was many orders of magnitude higher than reported or assumed, accounting for a variety of observed health effects not expected at lower radiation levels, such as excess infant mortality in Germany, Poland, and the former Soviet Union immediately after the accident and increased prevalence of birth anomalies reported from Central Europe and Turkey (Nussbaum, 2007). These findings are supported by recent case-control studies of children living near nuclear power stations, who have increased risk of developing solid cancers and especially leukemia (Fairlie, 2009).

Unfortunately, there have been no systematic studies conducted in areas relatively proximal to the Chernobyl disaster site, and there remains a need for carefully designed comprehensive studies encompassing an array of exposure routes, population risk assessment measures, and health outcomes across the lifespan (Baverstock and Williams, 2006; Cardis, 1996). In 2000, population-based birth defects monitoring was initiated in three oblasts, or provinces, in Ukraine to systematically assess prevalence of a wide array of malformations in raions (counties) officially categorized as contaminated and others categorized as not impacted (Wertelecki, 2006). These surveys revealed an increased rate of Neural Tube Defects (NTDs) compared to data from Europe reported by the European Surveillance of Congenital Anomalies Organization (EUROCAT, 2009; Yuskiv et al., 2004) (Table 1), which was confirmed by ongoing monitoring from 2000 to 2006 of newborns in the Rivne Oblast (Wertelecki and Yevtushok, 2008).

The elevated prevalence of birth defects in Ukraine might be attributable to a number of factors, including alcohol consumption and micronutrient deficiency. For example, most flour is centrally produced in Ukraine and is not fortified with folic acid. This is expected to contribute greatly to prevalence of NTDs in the region (Yuskiv et al., 2004). However, comparisons of data from Ukrainian regions varying in level of radiation contamination suggest that chronic radiation also contributes to these figures. Prevalence of several birth defects is significantly higher in highly contaminated raions of Rivne compared to less contaminated raions (Wertelecki, 2010), despite reliance on the same dietary staples (which are not fortified with folic acid) in these regions. Table 2 presents a comparison of figures for three major birth defects with significantly elevated prevalence in areas with high levels of radiation contamination compared to areas with low levels of contamination. These figures exclude instances of likely mutations, chromosomal defects, or prenatal exposures to alcohol (Wertelecki, 2010) and might suggest that chronic exposure to low-dose radiation has greater effects on human health than commonly accepted.

Based on observations of rates of birth defects in the region, we initiated a survey to assess the multiple routes

TABLE 1. Selected birth defects[a] and prevalence (per 10,000 live births) in Europe (EUROCAT, 2009) and Ukraine[b] (Wertelecki, 2010) reported by full partners of the European Surveillance of Congenital Anomalies

Malformation	EUROCAT (2004–2007)	Ukraine (2005–2008)
Neural tube defects	10.2	18.5
Anencephaly and similar	3.8	8.1
Microcephaly	2.3	6.0
Anophthalmia-Microphthalmia	1.4	2.3
Congenital cataract	1.0	2.2
Tetralogy of fallot	3.0	2.7
Cleft lip w/without palate	9.6	10.6
Cleft palate	6.1	5.0
Limb reduction	5.7	5.6

[a]Data include fetal demise and interruptions of pregnancies.
[b]Combined data from Rivne and Khmelnytsky Oblasts.

TABLE 2. Rates of selected birth anomalies (per 10,000 live births) with significantly elevated prevalence in contaminated compared to uncontaminated regions of Rivne, Ukraine, 2000–2006 (Wertelecki, 2010)

Anomaly	Contaminated Raions (Polissia)	Uncontaminated Raions (not Polissia)	*P*-value[a]	OR[b]	CI[c]
Births (*n*)	43,392	53,046			
NTDs	27.0	18.3	0.003	1.46	1.13–1.93
Microcephaly	3.7	1.3	0.02	2.8	1.15–6.79
Microphthalmia	1.8	0.4	0.03	4.89	1.04–23.03

[a]Fisher's Exact Test.
[b]Odds Ratio.
[c]95% Confidence interval.

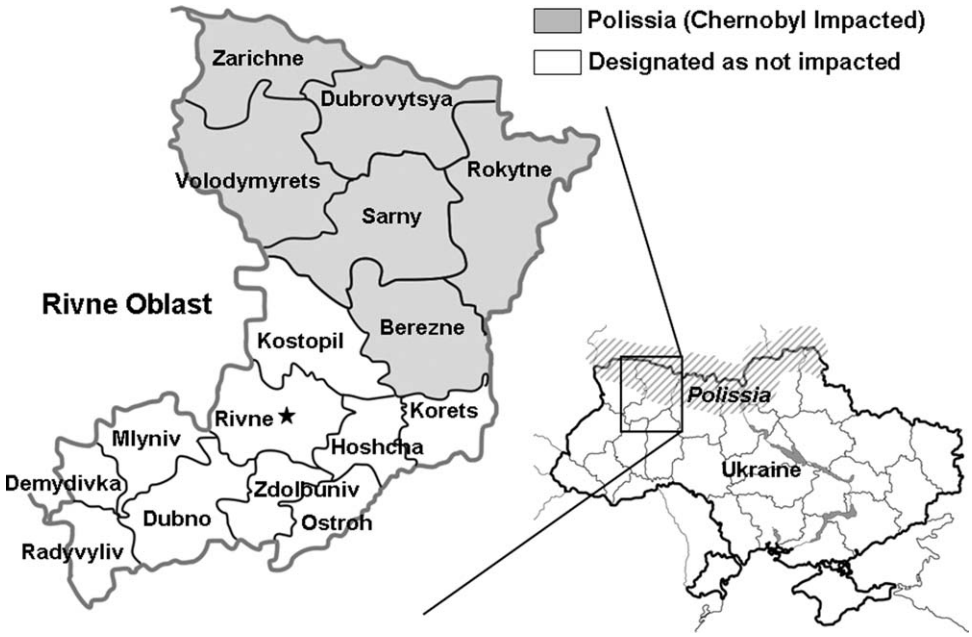

Fig. 1. Map of Rivne-Polissia with raions (counties). Modified from: OMNI-Net Ukraine, Univ. South Alabama, 2009.

of exposure to ^{137}Cs among families from the Polissia region of Rivne oblast participating in the birth defects monitoring program, as well as other factors contributing to high rates of birth anomalies, such as alcohol consumption. These assessments form the first component of our efforts to assess the role of long-term low-dose chronic radiation exposure on human health outcomes.

METHODS

Study area

Polissia is a region of wooded, boggy lowlands stretching from north central Ukraine westward toward Poland and northward toward Belarus, which includes the site of the Chernobyl nuclear reactors. The population of the north half of the Rivne oblast (Rivne-Polissia) has an agricultural and subsistence-based economy producing local foodstuffs for local consumption in an ecosystem contaminated by ^{137}Cs. ^{137}Cs levels vary widely in Rivne-Polissia. The region has scattered "hot spots" of significantly higher radiation levels than surrounding areas, and the boggy, potassium poor soils contribute to enhanced absorption of ^{137}Cs to all living systems. Many residents of Rivne-Polissia remain highly concerned about the effects of radiation exposure, and particularly about consumption of potentially contaminated food and its risks to their children's health.

Exposure survey

A survey was designed and administered in Ukrainian to 344 women in six officially categorized contaminated raions (Berezne, Dubrovytsya, Roktyne, Sarny, Volodymyrets, and Zarichne) (see Fig. 1) to assess exposure to potentially contaminated foods and environmental products. The questionnaire asked the source of a wide variety of meats, vegetables, fruits, dairy products, grain products, eggs, and local wild foods such as mushrooms, berries, and nuts. Sources included from the participant's "own" animals or garden, from "local" sources, wild products (where applicable), and "imported" sources. The survey also addressed the types of activities likely to expose individuals to water or soil in areas with potentially high levels of contamination and asked the time spent weekly in activities such as hunting, fishing, working in gardens and fields, collecting wild foods, and collecting firewood. Survey results were analyzed from a deidentified database in accordance with Institutional Review Board regulations at the State University of New York in Binghamton.

The survey was also used to assess alcohol consumption among women participating in the birth defects monitoring program. Questions addressed the number of alcohol units and the frequency of consumption in the month before and throughout pregnancy, and behaviors associated with problem drinking based on questions developed for the Michigan Alcoholism Screening Test (MAST) (Selzer, 1971).

Radiation dose estimates

Based on the types of foods consumed and their source, we estimated the mean annual radiation dose associated with food consumption among our sample. Dietary exposure was estimated using dietary intake patterns for adults outlined by the Ministry of Health Care of Ukraine (MHCU, 1997). Daily intake of each food in kg or l was multiplied by estimated ^{137}Cs levels to estimate daily ^{137}Cs exposure from food. For milk, potatoes, and vegetables, ^{137}Cs levels were measured by the research team in 2004 and in 2007. Estimates for mushrooms and berries are based on reports from Karachov (2006); our figures include a reduction in radiation levels since the time of measurement, based on the half-life of mushrooms and berries (Zamostian et al., 2002). Other major foods consumed by women in the survey for which we do not have

TABLE 3. Water and fuel sources: Percentage of respondents using each source

	Well	Spring	Bottled	Piped water supply	Rain	River	Lake
Water Source	85.4	9.4	50.0	5.3	0	0	0
	Wood	Gas	Central Heating	Peat	Coal	Other	
Home Heating Fuel Source	76.7	17.5	9.0	1.8	0.4	2.0	
	Wood	Gas	Electricity	Other			
Cooking Fuel Source	52.3	48.9	11.5	11.5			

Participants used multiple water and fuel sources; thus, percentages for each category total more than 100%.

^{137}Cs contamination values include locally produced meat, primarily pork, and locally grown fruit, primarily apples. Estimates for ^{137}Cs levels in pork and apples were estimated based on soil levels measured by the research team in 2007 multiplied by transfer factors for these foods reported by Travnikova et al. (2001) for the Klintsy district of the Bryansk region of Russia. Polissia and Klintsy both have very high transfer factors of radiation contamination from soil to food because of their soil characteristics. Our estimates of radiation exposure through the diet are acknowledged to be rough because there is great regional variation in local soil contamination levels, transfer coefficients, and responses to countermeasures, but we include them for illustrative and comparative purposes.

RESULTS

Rivne contamination levels

We recorded soil levels averaging 301.6 Bq/m^2 in 2007, ranging from 24.6 to 907 Bq/m^2. In 2007, levels of up to 361 Bq/kg were recorded in milk, 60 in carrots, 165 in potatoes, 433 in potato stems, and 1,440 in ashes from potato stems which residents burn yearly. The maximum dietary exposure allowance approved by the Ministry of Health Care of Ukraine in 1997 was 210 Bq/day, and residents whose foods are contaminated above accepted limits are encouraged not to ingest contaminated foods and to import foods from uncontaminated regions (MHCU, 1997).

Sample characteristics

We administered a dietary and activity survey to 344 women. Participants averaged 26.5 years old and had, on average, 12.3 years of education; all participants had at least 9 years of education. Most women (94.5%) were married and lived with their husbands. Participants reported living in their raion 21.6 years, on average, and 72.2% had lived in their raion 20 years or more. Brick and wood were the most common building materials: 35.7% of participants lived in brick houses, 53.7% in wood, 4.3% in stone, and 6.0% in "other."

Living, water, and fuel

Of the participants, 93.3% obtained water from either a well or spring; half also used bottled water and 5.3% used a piped water supply. No respondents used rain, river, or lake water (Table 3). Of the participants who answered questions about their home and cooking fuel source, 76.7% heated their house with wood. The most common cooking fuel sources included wood (52.3% of respondents) and gas (48.9% of respondents).

TABLE 4. Food and beverage sources (percentage of respondents)

Food or Beverage	Own	Local	Imported
Pork	91.3	9.9	0
Chicken	77.3	16.0	2.0
Goose	37.5	0.6	0
Duck	35.5	0.9	0
Beef	13.4	6.4	0.3
Rabbit	13.4	0.9	0
Lamb/Sheep	0	0	0.3
Milk	71.8	15.1	0
Cheese	68.3	8.4	0
Hard Cheese	6.4	45.6	5.5
Yogurt	0	21.8	3.5
Butter	36.0	55.5	6.4
Sour Cream	74.7	23.5	0.9
Kefir	61.3	10.4	0.6
Vegetables[a]	98.0	6.4	1.2
Apples	91.6	17.2	3.2
Cherries	70.3	7.3	0
Grapes	34.9	8.7	4.9
Pears	68.3	8.4	0
Plums	64.8	6.1	0
Cranberries (wild)	N/A	33.4	N/A
Blueberries (wild)	N/A	79.4	N/A
Nuts	30.5	12.7	0.3
Honey	13.7	26.5	1.2
Herbs	77.9	37.2	2.0
Flour[b]	2.9	96.5	10.5
Noodles[c]	0	96.2	3.2
Grain	0	95.9	9.3
Eggs	84.6	30.8	0.3
Mushrooms (wild)	N/A	74.7	0
Beer	0.3	22.7	6.4
Kvass	2.9	6.1	0.3
Wine[d]	4.9	17.7	25.0
Moonshine	5.8	0	0
"Horilka"[e]	0	4.1	3.2
Apple Juice	74.4	38.4	8.1
Tea[f]	0.6	1.2	85.2
Coffee	0	0	32.8

[a]There was little variation by type of vegetable, so all vegetables consumed are reported together.
[b]Own flour is produced from participants' own wheat and ground at local mills. Local flour is produced in Rivne mills using wheat from Rivne. Imported flour is purchased and produced outside Rivne.
[c]Local noodles are produced from local flour (made from wheat grown and ground in Rivne). Imported noodles are purchased and produced outside Rivne.
[d]Own and local wine is made from apples; imported wine is made from grapes.
[e]"Vodka" in Russian.
[f]Own tea is herbal tea; imported tea is black.

Food and beverage sources

Most of the food consumed in Polissia was from participants' own or local sources, and very little imported food was consumed (Table 4). All but one participant ate "own" or "local" meat, mostly pork, chicken, goose, and duck. Only eight individuals reported eating "imported" meat. All participants consumed either own or local milk and milk products, and of the 84.9% of participants who reported drinking milk, all drank own or local milk. Only 10.8% of respondents consumed imported milk and milk products, such as cheese, yogurt, and butter. All partici-

pants ate own and local vegetables, including potatoes, onions, beets, cabbage, carrots, cucumbers, beans, marrows, and tomatoes. The only imported vegetables, reported by four respondents (1.2%), were onions. Similarly, all respondents ate either own or local fruit, whereas only 29 respondents (8.4%) reported eating imported fruit, including grapes and apples.

Most participants also consumed local wild berries and mushrooms, which represent a major source of radiation exposure. Of the participants, 85.5% collected and ate wild berries and 74.7% collected and ate wild mushrooms. No participants consumed imported berries or mushrooms.

Most other reported foods, such as nuts, herbs, eggs, flour, and noodles, were either own or local. Most nonalcoholic beverages were also from own or local sources. Ninety percent of participants consumed imported drinks, including herbal tea (85.2%), coffee (32.8%), and apple juice (8.1%). Notably, the main imported beverages were made with water, which is mostly from local sources.

Alcohol use

Women were asked about smoking, alcohol, and drug use before and during pregnancy. Of the 286 who responded, only one woman (0.3%) reported smoking during the last 3 months. Reported alcohol consumption before pregnancy was low: 37.4% of women did not drink at all during the month before their pregnancy, and of those who did, most drank only one or two units on one or two occasions. During pregnancy, 66.4% reported drinking no alcohol. Of those who did drink during pregnancy, 83.0% drank one or two units on one or two occasions (Table 5). Notable exceptions include one woman who reported drinking one or two units on 10 occasions during pregnancy, one woman who drank three to four units once during pregnancy, and one woman who reported drinking daily in small amounts during pregnancy. None of the women reported using alcohol to calm down or cure headaches, feeling guilty about drinking, forgetting what they had done after drinking, or being criticized by family and friends for drinking. Most women (67.0%) reported being able to drink no more than two drinks without feeling nauseated or to still feel good.

The alcohol consumed was primarily local, including beer, apple wine, vodka, and kvass (mildly alcoholic beer made from bread). The most common imported alcohol was grape wine, reported by 25.0% of respondents. Imported beer, kvass, and vodka were consumed by a small percentage of participants. Those participants who drank imported vodka often added sugar and local wild berries to it to make liqueurs.

TABLE 5. Alcohol consumption before and during pregnancy

Units consumed (percentage of respondents and mean number of times)						
		1–2 units		3–4 units		Small amounts daily
	None %	%	# Times (Range)	%	# Times (Range)	%
One month before pregnancy	37.4	61.9	1.9 (1–7)	2.1	2.8 (1–6)	0.3
During pregnancy	66.4	32.9	1.7 (1–10)	0.3	1	0.3
Maximum drinks consumed without feeling nauseated						
(# drinks)	≤2	3	4	5	No response	
(% of participants)	67.0	11.0	4.8	2.1	15.1	

Activities

Participants answered questions about activities they performed both now and in the past that might expose them to potentially contaminated areas. The main occupations reported included housekeeping (30.7% of participants), sales (10.0%), bookkeeping (9.3%), and teaching (7.0%). Participants worked outside on average 26 h per week, mostly in fields (mean 13 h per week) and gardens (mean 3.9 h per week). Women also spent considerable time gathering wild products when in season, with 66.0% of women spending between 5 and 20 days per year gathering wild mushrooms and 75.4% spending between 5 and 20 days per year gathering wild berries. Hunting was uncommon, but 23.8% of participants reported fishing as a household activity.

Radiation dose estimates

Our estimates of radiation dose through the diet, based on average consumption levels of meat, milk and milk products, potatoes, vegetables, mushrooms, fruits, and berries, and average contamination levels of these products in Rivne-Polissia as discussed above, was 268.25 Bq ^{137}Cs per day (Table 6). In Rokitnovsky raion of Rivne Oblast, milk has been estimated to account for 70–75% of daily ^{137}Cs intake (Zamostian et al., 2002; see also Likhtarev et al., 2000), berries and mushrooms from 10 to 15%, and potatoes and vegetables from 10 to 15% (Zamostian et al., 2002). These foods alone were estimated to result in exposure levels averaging 250.34 Bq/day among women in

TABLE 6. Estimated ^{137}Cs exposure through diet

Food Type	Mean ^{137}Cs Level in Polissia (Bq/kg)	Daily Intake (kg)	Mean Daily ^{137}Cs intake in Polissia (Bq)	MOH 1997 Accepted ^{137}Cs Levels (Bq)
Milk and Milk products	113.88	1.02	116.38	100.00
Meat[a]	84.45	0.19	15.71	200.00
Potatoes	31.76	0.36	11.40	60.00
Vegetables	15.71	0.28	4.38	40.00
Fruits[b]	5.73	0.13	2.21	70.00
Mushrooms[c]	13875.00	0.01	87.37	2.30
Berries[c]	2200.00	0.01	30.80	500.00
Estimated Dietary Intake			268.25	
Accepted MOH 1997 Levels			210.0	

[a]Mean ^{137}Cs level is based on estimates for pork, which was the main meat consumed. Beef is estimated to have a much higher ^{137}Cs level (301.6 Bq/kg).
[b]Mean ^{137}Cs level is based on estimates for apples, which was the main fruit consumed.
[c]Mean ^{137}Cs levels based on estimates from Karachov, 2006, corrected for half-life reduction since 1999.

our sample. Contamination levels of berries and mushrooms vary widely among contaminated regions; mushroom ^{137}Cs levels recorded in 1999 in Polissia ranged from 5,000 to 32,000 Bq/kg and berry ^{137}Cs levels ranged from 800 to 8,000 Bq/kg (Karachov, 2006). These forest products thus represent a major source of variation in intake, as observed by Handl (2003). Assuming lower and upper contamination levels for both berries and mushrooms, estimated ^{137}Cs intake for our survey participants ranges from 184.4 to 362.4 Bq/day.

DISCUSSION

Radiation exposure

The results of our survey indicate that women in Rivne-Polissia are exposed to radiation through a number of pathways. Internal exposure through food has been the key exposure route of concern to international authorities in Polissia since the Chernobyl accident. Initial contamination levels in Rivne-Polissia were low compared to other regions, but beginning in 1987, researchers noted unusually high levels of ^{137}Cs transferring from soil to plants. The soil in Polissia is associated with high soil-to-milk transfer coefficients (Zamostian et al., 2002), and the continued dependence of the population on locally grown food and forest products as demonstrated in this report contributes to high internal exposure to ^{137}Cs through the diet and by inhalation.

The Ministry of Health Care of Ukraine set recommendations for maximum daily ^{137}Cs intake from food at 210 Bq/day (MHCU, 1997). These recommendations were based on the food types and amounts consumed by Ukrainian adults, and contamination levels of foods measured in various regions, to maintain total yearly body levels below 1 mSv. Assuming an average Ukrainian adult diet with a heavy reliance on forest products typical in Polissia, women in our survey had an average exposure of 268 Bq/day, exceeding the recommended intake of 210 Bq/day even without including other reported foods such as nuts, honey, and locally produced flour and grain products. Although intake may vary greatly throughout the year, especially during peak mushroom consumption from mid-July to mid-October, women also dry and pickle mushrooms to use throughout the year, so exposure through mushroom consumption occurs year-round. Furthermore, the reduced mushroom and berry consumption observed immediately after the accident has since reversed and many Polissia adults rely even more heavily on mushrooms than before the accident due to economic stress (Karachov, 2006). As noted above, these estimates are rough because of the wide variation in contamination levels throughout the region, but they suggest that women continue to be exposed to levels of radiation exceeding recommendations, and we expect that our exposure estimates in fact underestimate the levels of radiation exposure through diet in Rivne-Polissia.

Although the greatest doses of radiation were the initial exposure to deposited radionuclides on the soil and internal doses from ingesting contaminated food, absorption and inhalation of resuspended materials also contribute to radiation dose (Chernobyl Forum, 2006). Women in our survey are exposed to radiation through activities such as collecting firewood and working in fields, where radionuclides in tilled soil and cow manure (used as fertilizer) might be absorbed. Perhaps the greatest contribution to radiation exposure, aside from dietary factors, is through inhalation of smoke from the burning of contaminated wood and vegetative debris. Whereas skin limits the amount of radiation absorbed, inhalation is a particularly malignant form of exposure and women in our study were exposed to smoke both inside and outside their homes. About half of our participants reported using wood as cooking fuel, and 65% use wood to heat their homes, which contributes to exposure through smoke inhalation inside the home. Dried potato stems, leaves, and grasses left in fields and gardens are traditionally burned annually, further contributing to inhalation exposure (see Fig. 2).

In our study, the mean ^{137}Cs activity in potato stems was recorded in 2007 at about 96 Bq/kg, and ashes remaining from these burned stems had mean ^{137}Cs levels of 490 Bq/kg (range 5–1,440 Bq/kg). Experiments from heather burning show that between 12 and 39% of ^{137}Cs in the plant material is lost as smoke (Horrill et al., 1995) and up to 4% is lost during burning of wood and forest litter (Yoschenko et al., 2006a,b). Temperature greatly influences the amount of radionuclides lost to smoke, and experiments assessing the fate of radionuclides during the burning of wood, straw, and radish plants at temperatures typical of field fires found that between 40 and 70% of ^{137}Cs were lost to the atmosphere (Amiro et al., 1996).

We suspect that inhalation contributes dramatically to overall radiation exposure in Polissia. For example, assuming that about 40% of the ^{137}Cs in potato stems is sequestered in smoke, burning 20 kg of potato stems with the current contamination levels of this plant material in Polissia could result in the release of about 770 Bq ^{137}Cs. Women burn potato stems for long hours over several days during the burning period and are thus exposed to heavy doses of resuspended ^{137}Cs. Furthermore, the contaminated smoke drifts over a wide area, and because many individuals traditionally burn plant materials at the same time, this activity produces widespread exposure of humans as well as cyclic re-exposure of soil, forests, and animals to radiation. Redistributing the remaining ash over gardens and fields along with manure further results in re-exposure through absorption. Little attention has been paid to the consequences of smoke inhalation as a route of radiation exposure nor to its impact on internal exposure estimates.

Implications for birth defects in Rivne-Polissia

In 1998, the Ukrainian American Birth Defects Program (UABDP) was created, with the goal of training a team to create and sustain birth defects surveillance centers around the country. These centers provide international analyses of birth defects prevalence, early intervention and prevention programs, and the distribution of educational information to physicians and to the public. The privately sustained UABDP initiative later received USAID funding and, following the completion of the USAID phase, became incorporated in 2004 as OMNI-Net Ukraine, a not-for-profit international Ukrainian organization dedicated to monitoring and preventing birth defects. Currently, there are three OMNI-Net Birth Defects Teams in the oblasts of Khmelnytsky, Rivne, and Volyn, which include partners working in medical centers in Kherson, Autonomous Republic of Crimea and Zakarpattia province (Wertelecki, 2006).

Fig. 2. Fall is potato harvest time in Ukraine. (a) Potato plants (tops) die when the tuber is ready to be harvested and the plant tops are winrowed or raked into piles for burning; (b) actual burning of the potato plants (tops); and (c) burning causes the radioactive isotope 137Cs, which is taken up by the plant and tubers from the contaminated soil, to be particalized and airborne over a wide area and thus re-exposure occurs through inhalation. Note the potato tubers at the feet of the person overseeing the burning.

The observations from this birth defects monitoring, as outlined in Tables 1 and 2, suggest that prevalence of some major birth anomalies is higher in Ukraine than in other parts of Europe. Furthermore, in Ukraine, prevalence of many birth defects is significantly elevated in areas with high levels of contamination compared to areas with low levels of contamination even more than two decades after the Chernobyl accident. While its seeming lack of involvement in cancer prevalence and mortality have led many to devalue the health risks of chronic low-dose radiation exposure, the sensitivity of the developing fetus to environmental assaults (Fairlie, 2009) and the multiple routes through which women are exposed to radiation throughout the lifespan warrant careful studies of if and to what extent this exposure impacts human health. Sensitivity to ionizing radiation is particularly high during embryogenesis (De Santis et al., 2007), and constant radiation exposure of the unborn through maternal ingestion and inhalation may interfere with embryonic development, holding consequences more severe than for mature individuals (Fairlie, 2009). This may be particularly true if alcohol consumption, micronutrient deficiencies (especially folic acid; see Courtemanche et al., 2004; Endoh et al., 2007), and chronic radiation exposure are additive or synergistic. The potential effects of low-dose chronic radiation exposure on healthy birth outcomes indicate that health risks of chronic radiation exposure might be greater than previously believed. This necessitates follow up of individuals who continue to be exposed to low-dose radiation, especially pregnant and lactating mothers, and their children throughout the lifespan.

ACKNOWLEDGMENTS

The authors wish to thank Oleksandr Komov, Head of Epidemiological Assessment, Rivne Oblast Sanitary and Epidemiological Station, and Volodymyr Kuznetsov, Head of the Radiology Department, Rivne Oblast Sanitary and Epidemiological Station, for their assistance in data analysis and discussion regarding radiation contamination in the study area. The authors also thank Justin R. Garcia, SUNY Binghamton, for helpful discussion and research assistance.

LITERATURE CITED

Åhman B. 1999. Transfer of radiocaesium via reindeer meat to man—effects of countermeasures applied in Sweden following the Chernobyl accident. J Environ Radioact 46:113–120.

Amiro BD, Sheppard SC, Johnston FL, Evenden WG, Harris DR. 1996. Burning radionuclide question: what happens to iodine, cesium and chlorine in biomass fires? Sci Total Environ 187:93–103.

Andersson KG, Brown J, Mortimer K, Jones JA, Charnock T, Thykier-Nielsen S, Kaiser JC, Proehl G, Nielsen SP. 2008. New developments to support decision-making in contaminated inhabited areas following incidents involving a release of radioactivity to the environment. J Environ Radioact 99:439–454.

Balonov MI. 2007. The Chernobyl Forum: major findings and recommendations. J Environ Radioact 96:6–12.

Baverstock K, Williams D. 2006. The Chernobyl accident 20 years on: an assessment of the health consequences and the international response. Environ Health Perspect 114:1312–1317.

Bohannon J. 2005. Panel puts eventual Chornobyl death toll in thousands. Science 309:1663.

Cardis E. 1996. Epidemiology of accidental radiation exposures. Environ Health Perspect 104 (Suppl 3):643–649.

Chernobyl Forum. 2003–2005. Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine. Vienna: International

Atomic Energy Agency. Available at: http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf. Accessed 7 Sept., 2009.
Chernobyl Forum. 2006. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. Report of the Chernobyl Forum Expert Group 'Environment.' Vienna: International Atomic Energy Agency. Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf. Accessed 7 Sept., 2009
Courtemanche C, Huang AC, Elson-Schwab I, Kerry N, Ng BY, Ames BN. 2004. Folate deficiency and ionizing radiation cause DNA breaks in primary human lymphocytes: a comparison. FASEB J 18:209–211.
De Santis M, Cesari E, Nobili E, Straface G, Cavaliere AF, Caruso A. 2007. Radiation effects on development. Birth Defects Res C Embryo Today 81:177–182.
Duff MC, Ramsey ML. 2008. Accumulation of radiocesium by mushrooms in the environment: a literature review. J Environ Radioact 99:912–932.
Endoh K, Murakami M, Umegaki K. 2007. Vulnerability of folate in plasma and bone marrow to total body irradiation in mice. Int J Radiat Biol 83:65–71.
EUROCAT (European Surveillance of Congenital Anomalies). 2009. Prevalence Tables, 2004-2007.Available at: http://www.eurocat-network.eu/. Accessed 3 June, 2009
Fairlie I. 2009. Commentary: childhood cancer near nuclear power stations. Environ Health 8:43.
Fesenko SV, Alexakhin RM, Balonov MI, Bogdevitch IM, Howard BJ, Kashparov VA, Sanzharova NI, Panov AV, Voigt G, Zhuchenka YM. 2007. An extended critical review of twenty years of countermeasures used in agriculture after the Chernobyl accident. Sci Total Environ 383:1–24.
Garruto RM, Little MA, James GD, Brown DE. 1999. Natural experimental models: the global search for biomedical paradigms among traditional, modernizing, and modern populations. Proc Natl Acad Sci USA 96:10536–10543.
Handl J, Beltz D, Botsch W, Harb S, Jakob D, Michel R, Romantschuk LD. 2003. Evaluation of radioactive exposure from 137Cs in contaminated areas of Northern Ukraine. Health Phys 84:502–517.
Horrill AD, Kennedy VH, Paterson IS, McGowan GM. 1995. The effect of heather burning on the transfer of radiocaesium to smoke and the solubility of radiocaesium associated with different types of heather ash. J Environ Radioact 29:1–10.
Howard BJ, Beresford NA, Voigt G. 2001. Countermeasures for animal products: a review of effectiveness and potential usefulness after an accident. J Environ Radioact 56:115–137.
Ivanov VK, Gorski AI, Maksioutov MA, Tsyb AF, Souchkevitch GN. 2001. Mortality among the Chernobyl emergency workers: estimation of radiation risks (preliminary analysis). Health Phys 81:514–521.
Karachov II. 2006. Problems of radioactive pollution of forest food products and internal irradiation of population (translated from Ukrainian). Probl Nutr 1:8–16.
Lepicard S, Dubreuil GH. 2001. Practical improvement of the radiological quality of milk produced by peasant farmers in the territories of Belarus contaminated by the Chernobyl accident. The ETHOS project. J Environ Radioact 56:241–253.
Likhtarev IA, Kovgan LN, Vavilov SE, Perevoznikov ON, Litvinets LN, Anspaugh LR, Jacob P, Prohl G. 2000. Internal exposure from the ingestion of foods contaminated by 137Cs after the Chernobyl accident—report 2. Ingestion doses of the rural population of Ukraine up to 12 y after the accident (1986-1997). Health Phys 79:341–357.
Little MA, Garruto RM. 2007. Global impacts of anthropogenic climate change on human health and adaptability. In Bahasin V, Bhasin MK, editors. The anthropologist—anthropology today: trends, scopes and applications. Delhi, India: Kaml'a-Raj Enterprises (KRE). p 335–351.
MHCU (Ministry of Health Care of Ukraine). 1997. Order #255 Regarding Approval of Acceptable Levels of Cs-137 and Sr-90 in Food and Drinking Water (DR-97). (In Ukrainian.).
Mück K, Pröhl G, Likhtarev I, Kovgan L, Golikov V, Zeger J. 2002. Reconstruction of the inhalation dose in the 30-km zone after the Chernobyl accident. Health Phys 82:157–172.
Nussbaum RH. 2007. The Chernobyl nuclear catastrophe: unacknowledged health detriment. Environ Health Perspect 115:A238–A239; author reply A239-A240.
Parfitt T. 2006. Opinion remains divided over Chernobyl's true toll. Lancet 367:1305–1306.
Pröhl G, Mück K, Likhtarev I, Kovgan L, Golikov V. 2002. Reconstruction of the ingestion doses received by the population evacuated from the settlements in the 30-km zone around the Chernobyl reactor. Health Phys 82:173–181.
Rahu M. 2003. Health effects of the Chernobyl accident: fears, rumours and the truth. Eur J Cancer 39:295–299.
Selzer ML. 1971. The Michigan alcoholism screening test: the quest for a new diagnostic instrument. Am J Psychiatry 127:1653–1658.
Shields RA. 2004. Radiation and risk: putting things into perspective. Nucl Med Commun 25:985–986.
Skuterud L, Travnikova IG, Balonov MI, Strand P, Howard BJ. 1997. Contribution of fungi to radiocaesium intake by rural populations in Russia. Sci Total Environ 193:237–242.
Travnikova IG, Bazjukin AN, Bruk GJ, Shutov VN, Balonov MI, Skuterud L, Mehli H, Strand P. 2004. Lake fish as the main contributor of internal dose to lakeshore residents in the Chernobyl contaminated area. J Environ Radioact 77:63–75.
Travnikova IG, Bruk GJ, Shutov VN, Bazjukin AB, Balonov MI, Rahola T, Tillander M. 2001. Contribution of different foodstuffs to the internal exposure of rural inhabitants in Russia after the Chernobyl accident. Radiat Prot Dosim 93:331–339.
UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). 2000. Report to the general assembly, with annexes: sources and effects of ionizing radiation, Vol. 1/2. New York: United Nations. Available at: http://www.unscear.org/unscear/en/publications.html#Pubimages. Accessed 7 Sept., 2009.
Vilic M, Barisic D, Kraljevic P, Lulic S. 2005. 137Cs concentration in meat of wild boars (Sus scrofa) in Croatia a decade and half after the Chernobyl accident. J Environ Radioact 81:55–62.
Wertelecki W. 2006. Birth defects surveillance in Ukraine: a process. J Appl Genet 47:143–149.
Wertelecki W. 2010. Malformations in a Chornobyl-Impacted Region. Pediatrics 125:e836–e843
Wertelecki W, Yevtushok L. 2008. Elevated Neural Tube Defects (NTD) Rates in Ukraine: Highest in Polissia. Abstract presented at the 1st Central and Eastern European Summit on Preconception Health and Prevention of Birth Defects. Budapest, Hungary, August. Program and Abstract Book: 67.
Yoschenko VI, Kashparov VA, Levchuk SE, Glukhovskiy AS, Khomutinin YV, Protsak VP, Lundin SM, Tschiersch J. 2006a. Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part II. Modeling the transport process. J Environ Radioact 87:260–278.
Yoschenko VI, Kashparov VA, Protsak VP, Lundin SM, Levchuk SE, Kadygrib AM, Zvarich SI, Khomutinin YV, Maloshtan IM, Lanshin VP, Kovtun MV, Tschiersch J. 2006b. Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part I. Fire experiments. J Environ Radioact 86:143–163.
Yuskiv N, Andelin CO, Polischuk S, Shevchuk O, Sosynyuk Z, Vihovska T, Yevtushok L, Oakley GP Jr, Wertelecki W. 2004. High rates of neural tube defects in Ukraine. Birth Defects Res A Clin Mol Teratol 70:400–402.
Zamostian P, Moysich KB, Mahoney MC, McCarthy P, Bondar A, Noschenko AG, Michalek AM. 2002. Influence of various factors in individual radiation exposure from the Chernobyl disaster. Environ Health 1:4.