Additional Thyroid Dose Factor from Transportation Sources in Russia after the Chernobyl Disaster

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Beginning approximately 4 years after the Chernobyl nuclear accident a steady increase in the incidence of thyroid cancer was observed in children and adolescents of the Bryansk Oblast, which received the highest level of radionuclide contaminants in Russia. We examined the spatial relationship between the residence location of patients with identified thyroid cancer (0–18 years old at the time of the accident) and a number of geographic parameters to better account for the etiology of thyroid cancer spatial distribution. Geographic parameters analyzed included spatial distribution of ^{137}Cs and ^{131}I in soil, population demographics, measurements and reconstructions of absorbed thyroid ^{131}I doses in the population, and maps of major transportation arteries. An interesting finding is the lack of a consistent correlation between the spatial distribution of radionuclides in the soil and thyroid cancer incidence. Instead, most of the thyroid cancer cases were diagnosed in settlements situated on major railways and roads. Correlating population with thyroid cancer cases and transportation arteries reveals a much higher cancer rate on or near major roads and railways than at a distance from them, again independent of radionuclide soil concentration. There are other important factors, of course, that must be considered in future evaluations of this phenomenon. These include the influence of iodine endemic zones, genetic predisposition to thyroid cancer, and duration of residence time in contaminated areas. The feasibility of radionuclide transport on railways and roads is discussed, together with the vectors for transfer of the contaminants to the human population. Developing a model to reconstruct the radiation dose to the thyroid over time in this geographic region is proposed in light of the impact of transportation arteries. Specific studies are outlined to provide the data necessary to develop this model as well as to better characterize the feasibility and scientific validity of the contribution to human health effects of this transport factor. Transport factor refers to the transport of radionuclides on transportation arteries and the transfer of these agents to the human population residing in the vicinity of these arteries. If the impact on thyroid cancer of the transport of radionuclides on major railways and roads is indeed significant, a major reappraisal of the risk of large-scale radioactive release into the environment is necessary. — *Environ Health Perspect* 105(Suppl 6):1491–1496 (1997)

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Introduction

Thyroid cancer is one of the more definitive health consequences of the Chernobyl nuclear accident and its relation to radiation exposure has been firmly established. After the accident, a steady increase in the incidence of childhood thyroid cancer was observed in the most heavily contaminated territories in Belarus and Ukraine (*1,2*). Since 1990 a significant increase was observed in Chernobyl-contaminated regions of the Russian Federation (*3*). In spite of mass examination of the population in the contaminated territories of Bryansk Oblast from 1986 to 1989, only one case of the disease with a morphologically verified diagnosis was reported (1987). In the following years the number of cases increased: 4 in 1990, 4 in 1991, 8 in 1992, 11 in 1993, 20 in 1994, 21 in 1995, and 7 cases up to September 1996. All patients ranged in age from newborn to 18 years at the time of the accident.

A serious challenge in assessment and prognosis of the health consequences of the Chernobyl accident was in establishing a relationship between specific diseases and the external and internal absorbed doses of radiation. Major factors contributing to the dose received from the accident were contamination of the environment with radioactive iodine during the first 2 months and contamination of territories with long-lived radionuclides, mainly ^{137}Cs. Detailed maps of Chernobyl-related contamination were generated using direct measurements and simulation modeling (*4,5*). In these studies various health disorders detected in the course of routine medical examination of patients in the monitored areas were collated with the mean contamination level for those in corresponding administrative units—an oblast (region), a rayon (district), or a settlement.

Using a geographic correlation approach, however, the incidence of thyroid cancer in children and adolescents does not appear correlated with the Chernobyl-related contamination level of the Bryansk Oblast area. More than 50% of the thyroid cancer patients reside in areas with relatively low densities of ^{137}Cs soil contamination (0.1–5 Ci/km^2). Such levels are much lower than those in the strictly monitored territories (^{137}Cs concentrations of 5–15 Ci/km^2 and higher, I concentrations of more than 15 Ci/km^2), where the other 50% of cases were detected. A similar lack of correlation is apparent between thyroid cancer incidence and ^{131}I soil contamination and various determinations of absorbed ^{131}I thyroid dose.

In searching for a feasible explanation for the pattern of thyroid cancer occurrence in Bryansk Oblast, the potential impact of an additional dose-forming factor attributable to transportation arteries was considered. Relationships between the various geographic parameters that could affect geographic distribution of Chernobyl-related thyroid cancer were examined. Evidence supporting the hypothesis that thyroid cancer incidence in Bryansk Oblast is related to the location of

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transportation arteries was evaluated and the information needed to address this question was outlined.

Materials and Methods

The association between potential transportation-mediated dispersal of radionuclides from the Chernobyl accident and the incidence of thyroid cancer in Bryansk Oblast was investigated by reevaluation and interpretation of certain available data sets from the region. An analysis of potential associations was made among the following: distribution of the thyroid cancer incidence over the settlements of the Bryansk Oblast; geographic maps with detailed landscape features, transportation arteries, and waterways; maps of ^{137}Cs- and ^{131}I-contaminated areas and settlements (*4,5*); demographic data on the population of Bryansk Oblast; and available data about measured and reconstructed absorbed thyroid doses (*6–8*).

From 1986 to the present annual obligatory (compulsory) medical examinations of children and adolescents have been carried out in seven highly contaminated (≥5 Ci/km^2) districts of Bryansk Oblast. These examinations, performed by specialists of Russian federal research centers and by local physicians, include pediatric and endocrinologist exams, sonography, blood and urine analysis, and assessment of the thyroid gland function (thyroid-stimulating hormone, T4, antithyroid autoantibodies). Annual examination coverage included 90 to 92% of children and adolescents of the seven contaminated districts in Bryansk Oblast.

The thyroid cancer incidence study involved patients between the ages of 0 and 18 at the time of the Chernobyl accident. This age range was selected for several reasons. First, it is generally acknowledged to be the age range most sensitive to thyroid damage through the absorption of radioiodine. Second, this cohort was a primary target for evaluation in Russian and various international studies on the health consequences of the Chernobyl accident, and other data sets for association analysis thus were more likely to be available. Another factor considered in using this group for the study was that persons from this cohort were less likely to migrate; it was essential to establish continuity in residence location so as to have more confidence in making geographic associations between location of the patient and the source of exposure. Of the 76 patients cited in this study, 71 had firmly established continuities of residence.

Main transportation arteries were evaluated with regard to location of thyroid cancer incidence. These associations were analyzed for both railroads and main highways. Of particular interest, of course, were the main transportation arteries connecting Bryansk Oblast with the Chernobyl power complex in Ukraine. Other landscape features such as elevated areas, hills, waterways, and highly populated areas as well as the population demographics of rural areas were also considered when making associations with cancer incidence.

Extensive measurements of soil disposition of radionuclides dispersed (^{137}Cs and ^{131}I) from the Chernobyl accident have been made and published for Bryansk Oblast (*4,5*). The ^{137}Cs was used in the association because it is the highest constituent environmental radionuclide by magnitude for the Chernobyl accident and its gamma-emitting character has made its measurement easier and more reliable so widespread dispersion maps are more available for it than for other radionuclides. Because ^{131}I is known to concentrate in an individual's thyroid after exposure and because of its potential association with thyroid cancer, it was also used in the study.

The internal dose calculated to have been absorbed by the thyroids of the population of Bryansk Oblast was also used in the analysis (*6–8*). Doses absorbed in the thyroids of some inhabitants were obtained using direct radiometry of the thyroid between May and June 1986. Using these data and a model for estimating absorbed doses, calculations of thyroid doses on a geographic basis were made based on the time dependency between the volume concentration of ^{131}I in the surface air layer and the density of ^{131}I fallout on soil obtained by modeling atmospheric transport of ^{131}I (*6*). Comparisons were then made between the distribution of these calculated thyroid doses and thyroid cancer incidence on a geographic basis.

The association analysis was then conducted for individual settlements, examples of which are provided in Table 1 for the Novozybkov, Klintsy, Zlynka, Gordeevka, and Krasnaja Gora settlements. A width of 1 km for the corridor along the road and railway was used to determine the impact of intense exposure to radionuclides by the transport factor. The population of the individuals in the appropriate age range is compared to the thyroid cancer incidence to give an incidence rate for that age group in that geographic unit. The incidence rate is calculated as:

Incidence rate = {Number of cases}/ {(Number of residents 0–18 years of age) × 6 years of follow-up (1991–1996)} × 100,000

The mean levels of contamination of the two radionuclides of interest, ^{137}Cs and ^{131}I, were averaged for that geographic unit when there was sufficient homogeneity of the values for that area. If there was a wide range of values, which was often the case, the range of values was given in Ci/km^2. Locations of major roads or railways were noted as present or absent. These transportation arteries were those known to have carried heavy traffic from the Chernobyl reactor complex in the period immediately following the accident. Minor roads were not considered in the analysis.

Results and Discussion

Since the Chernobyl accident, 76 thyroid cancers have been reported in children and adolescents born from 1968 to 1986 in Bryansk Oblast. In all these cases patients' places of residence at the time of the accident and during the following years

Table 1. Association of thyroid cancer incidence rates with radionuclide disposition and transportation arteries.

	Settlements		
	Novozybkov	Klintsy	Zlynka, Gordeevka, and Krasnaja Gora
Number of residents 0 to 18 years of age at time of the Chernobyl accident (thousands)	18.9	31.5	15.4
Number of thyroid cancer cases among residents 0 to 18 years of age at time of the Chernobyl accident	10	14	2
Incidence rate in this age group	8.8	7.4	2.2
Mean level of contamination of settlements			
^{131}I (Ci/km^2)	50	20	60–80
^{137}Cs (Ci/km^2)	15–30	5–10	15–40
Do major railways and/or roadways pass through settlement(s)?	Yes	Yes	No

were noted. There was no significant change in places of residence among the patients from the time of the accident until the time of disease registration. One exception was three thyroid cancer patients in Trubchevsk, of whom two actually resided in Klintsy.

A map of the Bryansk Oblast depicts thyroid cancer incidence and its distribution over the settlements under study (Figure 1). Many of these settlements are concentrated near major railways and highways. Some are in areas of high radioactive contamination, especially those near the western border such as Novozybkov with ^{137}Cs concentrations ranging from 9 to 20 Ci/km^2 and ^{131}I concentrations from 36 to 60 Ci/km^2 soon after the accident. Some of the settlements on the major transportation arteries are in territories with intermediate levels of contamination; these include Klintsy, Klimovo, Starodub, and Unecha, with ^{137}Cs concentrations from 1 to 4 Ci/km^2 and ^{131}I concentrations from 2 to 12 Ci/km^2. Some populated areas on the main transportation lines—Bryansk, for example—may be characterized as almost clean points ($^{137}Cs < 0.4$ Ci/km^2, $^{131}I < 1$ Ci/km^2).

In the settlements situated far from major transport arteries only individual cases of thyroid cancer were registered. A comparison of the locations of the settlements with these cases does not correlate with the mean ^{137}Cs or ^{131}I contamination levels for corresponding settlements or rayons. For example, several settlements of Zlynkovski, Klintsovsky, Novozybkovsky, and Krasnogorski rayons are situated in territories with high levels of contamination (^{137}Cs from 3–100 Ci/km^2 and ^{131}I from 20–280 Ci/km^2). A considerable incidence of thyroid cancer might be anticipated in these territories, yet only two cancer cases were found. It is worth notice that these settlements are a considerable distance from the major transportation arteries. These data suggest that some unspecified dose-forming components may be present and that a transportation-related factor in radionuclide dispersion should be considered among them.

The lack of association between the ^{131}I soil concentrations and thyroid cancer incidence is illustrated for the most contaminated areas of the Bryansk Oblast (Figure 2). The isopleth bars for the ^{131}I concentrations steadily decrease in concentration with increasing distance from the western border between Ukraine and Belarus. Highly contaminated areas in the northern regions around Makarichi and Krasnaja Gora have hardly any incidence of thyroid

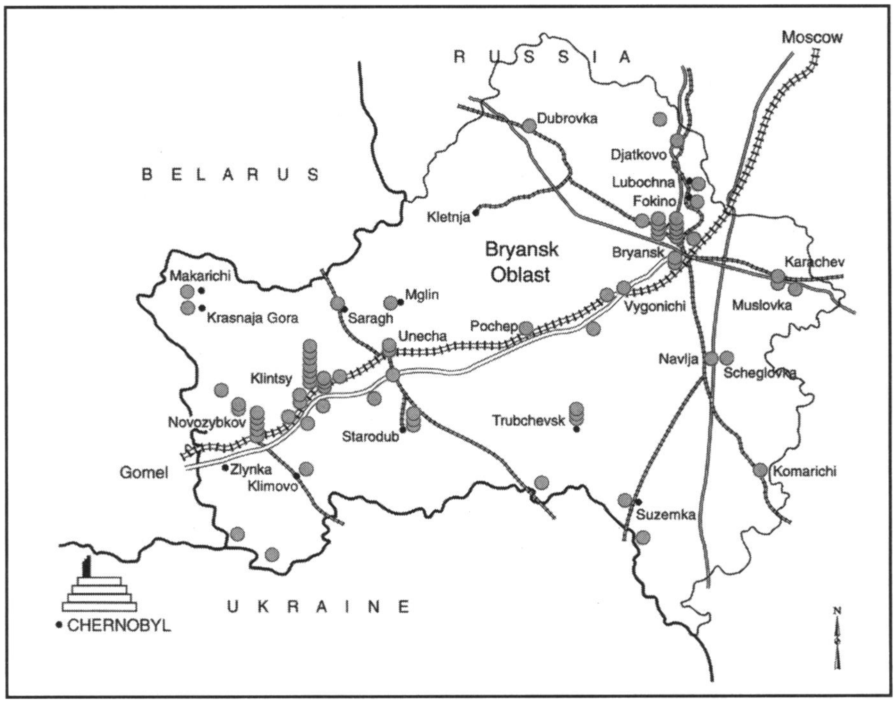

Figure 1. Map of Bryansk Oblast showing major railways and highways and the distribution of thyroid cancers in children and adolescents (shaded circles).

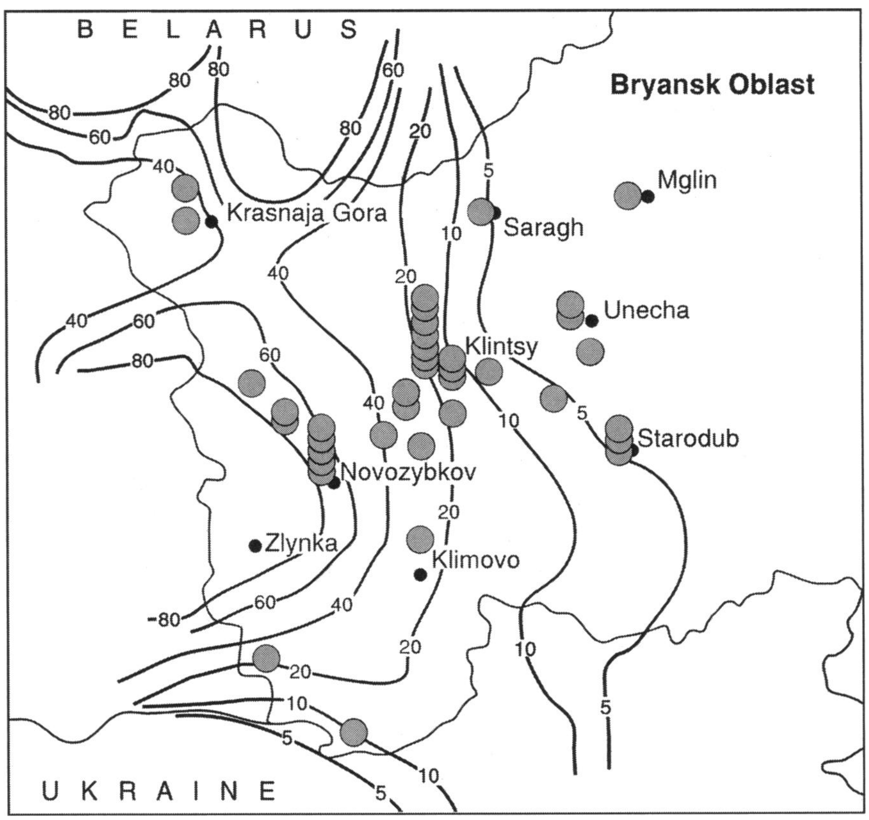

Figure 2. Map of the most highly contaminated region of Bryansk Oblast, showing isopleths of specific surface deposition densities of ^{131}I and the incidence of thyroid cancer by location (shaded circles). Modified from Pitkevich et al. (*4*).

cancer; these areas are located far from the heavily traveled main roads that connect with the Chernobyl reactor complex. Even settlements on the main roads do not follow patterns of cancer incidence proportionately commensurate with the distribution of ^{131}I. Novozybkov has more than twice the concentration of ^{131}I in the soil as Klintsy, which is farther to the east; yet Novosybkov has fewer cases.

Adjusting the comparison in this region for population, Table 1 shows the incidence rates for Novosybkov and Klintsy on the major transportation arteries and for several settlements that are distant from the main roads. Klintsy is a population center of approximately 76,000 people, including 18,000 adolescents. Adjusted for population, the thyroid cancer incidence rates in Klintsy and Novosybkov are relatively high and fairly close. The incidence rates for settlements such as Krasnaja Gora, which are far from the main roads, are much lower. This is interesting in light of the fact that the ^{131}I concentration in Krasnaja Gora is twice as high as that in Novosybkov and three to four times higher than that in Klintsy.

Comparison of population density, cancer incidence, and proximity to main transportation arteries is expanded to all of Bryansk Oblast in Table 2. The table shows population (children and adolescents born from 1968 to 1986) in settlements near the main roads (within 10 km), the number of cancer cases, and corresponding incidence rates (per 100,000). There is more than a 6-fold difference in thyroid cancer incidence rates of settlements situated near major transport arteries and those located some distance from them. The population characterized as being near main roads is separate from that of Bryansk in Table 2. This is a very crude measurement and requires a much higher degree of analysis on a geographic basis. The last general census of the population in Russia was in 1989. To get up-to-date information on the population of cities, villages, and other settlements we used data from the Health Care Department of the Administration of Bryansk Oblast. It monitors population characteristics (sex, age, etc.) each year, although the data are not published in an official publication.

It should be pointed out that in April to June 1986, i.e., in the period of the heaviest fallout of iodine and other radionuclides from destroyed Unit 4 of the Chernobyl nuclear power plant, railway and motor traffic continued in Ukraine and Belarus, even originating from the 30-km zone around Chernobyl. Trains and motorcars leaving this highly contaminated area traveled on the main roads in Bryansk Oblast, the area in Russia located nearest the reactor. These vehicles had the potential to transport radioactivity over great distances and could have deposited significant radiation doses along railways and main roads as well as in settlements situated in the vicinity of these transport arteries.

During the time under study, food supplies from state and private sectors were transported along these same routes. Central and local representatives of the State Sanitary and Epidemiological Inspection of the Russian Federation monitored and eliminated from circulation a considerable amount of meat, milk products, vegetables, and other foodstuffs, the radioactive content of which exceeded maximum admissible levels. However, many of these products were purchased directly along the railroad tracks and on the highways by the public. Therefore, consumption of contaminated food products not removed from public access would have led to higher exposure of residents, particularly in the populated areas near roads and railways.

The abovementioned scheme neither rejects nor replaces, but significantly supplements other factors having an impact on the distribution of radiation-induced effects after Chernobyl. Such factors as the influence of iodine deficiency zones, mean levels of soil contamination with radionuclides, and genetic predisposition for thyroid cancer merit further investigation. Also, the duration of stay in the contaminated territory needs to be considered in further analysis of the relative role of the transport factor. Prolonged exposure to low doses of ^{137}Cs damages immune, endocrine, and hematopoetic systems (*9*) and this may provoke the development of thyroid pathology, including thyroid cancer. Our preliminary results demonstrate that thyroid cancer incidence among persons evacuated from contaminated to clear areas does not exceed the spontaneous incidence level.

Another important factor to consider is the issue of equal access to medical care in areas far from main roads relative to those areas close to main roads. It is reasonable to consider areas distant from main roads rural in nearly all cases, whereas areas close to main transportation arteries would be considered urban areas. However, the fact that the program for evaluating Bryansk Oblast for Chernobyl-related effects was designed to include the entire population of children and adolescents of Bryansk Oblast and not just those in a specific geographic area or subpopulation, led to an all-inclusive medical surveillance design. The degree of participation by all local physicians was mandated by the government and helped to ensure an unbiased estimate of thyroid cancer incidence across the oblast.

The general scheme of the dose-forming transport factor and its relationship to other dose-forming factors is presented in Figure 3. As can be seen, one of the most important sequences of the involvement of vehicles in radionuclide migration would be the relatively rapid transfer of short-lived iodine isotopes. These isotopes are considered dangerously radioactive and accumulate in the body mainly through inhalation. To retrospectively reconstruct radiation doses to the thyroid due to radionuclides and particularly to short-lived iodine isotopes, a special model should be developed. The model should include the following factors: *a*) the distance from Chernobyl to the patients' place of residence along the roads; *b*) multiple resuspension of particles by traffic, which could result in high levels of absorbed doses through inhalation; *c*) the increasing contamination of soil and grass in the vicinity of the roads during the early period after the Chernobyl accident and, as a result, concentrations of radioactivity in products open to the atmosphere such as milk and leafy vegetables.

The hypothesis that significant radionuclide dissemination may occur through transportation arteries has some precedence in the literature in the definitive geographic relationship observed between lead deposition and roadways. Lead concentrations in edible crops increase with increased traffic volume and decrease with increasing distance of the crops from highways (*10*). Lead concentration in soil

Table 2. Number of thyroid cancers in children and adolescents in the Bryansk region according to place of residence.

Settlements	Number of residents	Number of cases	Per 100,000
Near main roads	155,912	55	35
Far from main roads	85,748	6	7
Bryansk	159,897	15	9

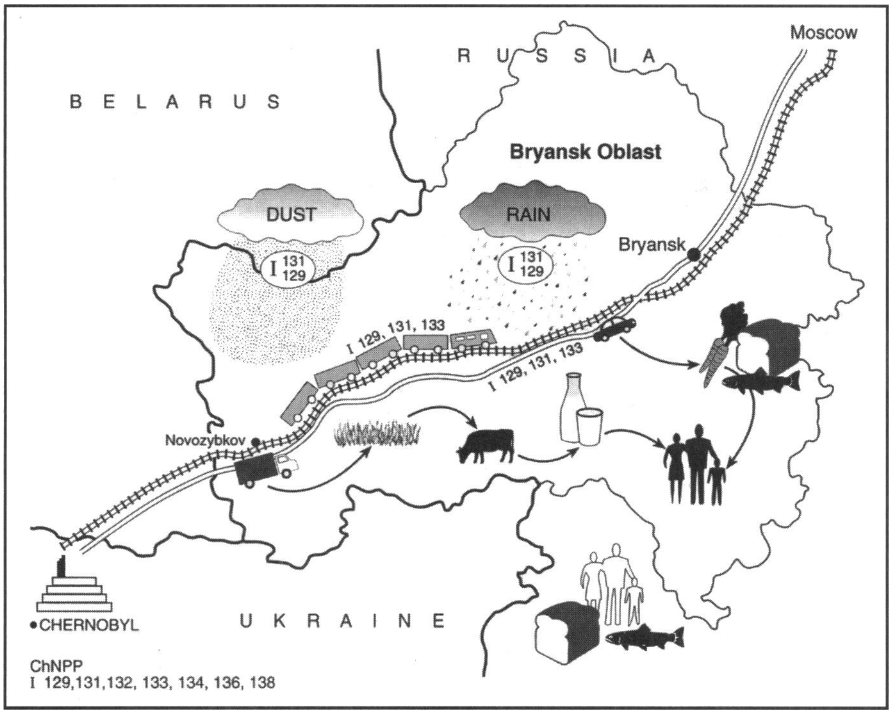

Figure 3. Scheme of the various dose-forming factors for thyroid in Bryansk Oblast following the Chernobyl accident in May to June 1986. ChNPP, Chernobyl nuclear power plant. I 129, I 131, I 133, etc. are iodine isotopes released.

varies with the soil's proximity to highways (*11*). Indeed, some soils known to be contaminated primarily by car emissions have been found next to highways and exceed U.S. Environmental Protection Agency hazardous waste guidelines (*12*). It is therefore reasonable to assume that radionuclide dispersion may have resulted from cars or trains and also may have resulted in contamination of crops grown near transportation arteries or on food being sold near or on these arteries.

The fact that road dust containing environmental pollutants results in significant particulate deposition in humans has been well established. Using lung measurements for the components of tires, it was established that road dust generated by cars is retained in human lungs, especially of those who work near roads (*13*). Approximately 4% of the total mass of typical road dust is less than 2 µm in aerodynamic diameter and therefore in the highly respirable range of particulates (*14*). Unless inhaled particles are in a respirable range, the impact of the dust particles on human health will be negligible, regardless of the contaminant load (*15*). Because road dusts are in the respirable range and also directly result in deposition in the lungs, it is likely that road-generated dusts that contained Chernobyl-related radionuclides resulted in impacts on the health of individuals in their proximity.

In establishing that significant long-term exposure of populations to potentially toxic dusts disseminated from roads occurs, it is important to note the high levels of road-generated environmental contaminants that also end up in house dusts. Dusts in homes even some distance away from roads had similar levels of lead as the dusts on roads outside the homes, which demonstrated that road-generated contaminants were getting inside homes (*16*). That this phenomenon seems to be peculiar to environmental contaminants has been shown by elemental studies of house dusts. The studies show a remarkable uniformity in elemental composition of dusts (except for pollutant metals) throughout metropolitan areas (*17*). Contamination of household dusts by road-generated pollutants therefore significantly increases the risk of the general population because people are exposed to the contaminants for much longer periods than if they were exposed only to atmospheric pollutants.

Indeed, it has been reported that only 1 to 2% of settled household dust is from atmospherically transported particles (*18*). In contrast, approximately 40 to 50% of household dust has been estimated to result from soil- and road-generated dust (*17*). Therefore, exposure to environmental contaminants from the Chernobyl disaster in household dust is related more to soil contamination or road transport than to exposure to airborne particles. This is particularly important when one considers that most of the risk from exposure to Chernobyl-related radioiodine was originally believed to be because of atmospheric dispersion and inhalation by the thyroid cancer victims immediately following the accident.

There also apparently is increased risk for younger people to the potential dispersion of radionuclides by road dust. Because the age range of thyroid cancer patients examined in the current study was 0 to 18 years at the time of the accident, the age-related factor is important to consider. Street dusts represent a significant source of lead uptake in children and significantly increase their risk for thyroid cancer (*19*). Fine particulates containing environmental contaminants adhered preferentially to childrens' hands (*20*). The high degree of hand-to-mouth activity of young children resulted in a high level of inadvertent ingestion of environmental contaminants in dust, which included road-generated toxins (*21*). Therefore, the age range of the thyroid cancer patients considered in this study could also have been a factor contributing to the increased impact of road-generated dust contaminants on subsequent health outcomes.

Another important factor to consider is the time of year in which the accident occurred, i.e., late April, just as winter was ending in Eastern Europe. Road dust levels in March are 13 times higher than those in the middle or late summer (*14*) and are exacerbated by snow and ice conditions, which are major considerations in Russia. It appears that the early spring conditions in the Soviet Union at the time of the Chernobyl accident may also have been a factor in providing more opportunities (at least relative to later in the year) for generation of road dusts that would ultimately be involved in additional radionuclide dispersion.

The role of the transport factor after the Chernobyl accident has been discussed in previous studies. One major area involving consideration of this factor was dust-control measurements in the 30-km zone and in various territories affected by the accident (*22*). Several papers on traffic resuspension of fallout material following the Chernobyl accident were reviewed in (*23*). In measurements of ^{137}Cs in air in Denmark, a pronounced weekly cycle was noted in atmospheric concentrations of ^{137}Cs in July and August 1986. Highest concentrations were on weekdays and the lowest on weekends. This weekly periodicity has been attributed to resuspension of Chernobyl-derived radionuclides by traffic; e.g., roads are normally busier during the week than on weekends. However, these papers did not estimate individual doses. We concur with Boice and Linet (*24*), who suggest that "The studies published thus far, however, have not resolved several important issues. For example, because ecological study designs have been used, no relation between individual doses and risk of cancer has been shown."

In general, the results obtained to date on the relationship between thyroid cancer incidence and residence near transport arteries strongly point to the necessity for reevaluation of risks based on radioecological parameters.

Additional studies regarding the transport factor should include:

- Careful dosimetric studies of the vicinity of railways and roadways, mainly within settlements.
- Determination of individual absorbed doses based on modeling as well as on biodosimetry (i.e., analysis of chromosomal aberrations, reciprocal translocations) and electron spin resonance dosimetry of tooth enamel.
- Targeted medical examination of persons living near main transport arteries in Bryansk Oblast to detect thyroid irregularities. The age range of the cohort examined should include persons up to 30 years of age, as those 0 to 20 years of age at the time of accident (especially women) are the most sensitive to radiation exposure of the thyroid tissue.
- Development of two-vector models of thyroid irradiation attributable to the transport factor; one vector is distance of the settlement from Chernobyl and the second vector is distance of residence to the nearest railway or highway, or both.
- Introduction of a new cohort group composed of those inhabitants in settlements near main transport arteries who were hypothesized to be at higher risk as well as the staff of transport companies.

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