Environmental Health and Toxicology
Open Access
Volume: 30, Article ID: e2015005, 8 pages
http://dx.doi.org/10.5620/eht.e2015005
• Original Article
eISSN: 2233-6567

Assessment of radiation exposure from cesium-137 contaminated roads for epidemiological studies in Seoul, Korea

Yun-Keun Lee[1], Young-Su Ju[2], Won Jin Lee[3], Seung Sik Hwang[4], Sang-Hyuk Yim[1], Sang-Chul Yoo[2*], Jieon Lee[5], Kyung-Hwa Choi[6+], Eunae Burm[6‡], Mina Ha[7]

[1]Wonjin Institute for Occupational and Environmental Health, Seoul; [2]Department of Occupational and Environmental Medicine, Hallym University Sacred Heart Hospital, Pyungchon; [3]Department of Preventive Medicine, Korea University College of Medicine, Seoul; [4]Department of Social Medicine, Inha University School of Medicine, Incheon; [5]Korea Federation for Environmental Movements, Seoul; [6]Department of Public Health, Graduate School of Dankook University, Cheonan; [7]Department of Preventive Medicine, Dankook University College of Medicine, Cheonan, Korea

Objectives We aimed to assess the radiation exposure for epidemiologic investigation in residents exposed to radiation from roads that were accidentally found to be contaminated with radioactive cesium-137 (^{137}Cs) in Seoul.

Methods Using information regarding the frequency and duration of passing via the ^{137}Cs contaminated roads or residing/working near the roads from the questionnaires that were obtained from 8875 residents and the measured radiation doses reported by the Nuclear Safety and Security Commission, we calculated the total cumulative dose of radiation exposure for each person.

Results Sixty-three percent of the residents who responded to the questionnaire were considered as ever-exposed and 1% of them had a total cumulative dose of more than 10 mSv. The mean (minimum, maximum) duration of radiation exposure was 4.75 years (0.08, 11.98) and the geometric mean (minimum, maximum) of the total cumulative dose was 0.049 mSv (<0.001, 35.35) in the exposed.

Conclusions An individual exposure assessment was performed for an epidemiological study to estimate the health risk among residents living in the vicinity of ^{137}Cs contaminated roads. The average exposure dose in the exposed people was less than 5% of the current guideline.

Keywords Accidental contamination, Cesium-137, Epidemiological studies, Radiation exposure assessment

Correspondence: Mina Ha
119 Dandae-ro, Dongnam-gu, Cheonan 330-714, Korea
Tel: +82-41-550-3854
Fax: +82-41-556-6461
E-mail: minahaoo@gmail.com

Current affiliation: *Department of Occupational and Environmental Medicine, Metro Hospital, Anyang, Korea; +Hallym Research Institute of Clinical Epidemiology, Hallym University, Chuncheon, Korea; ‡Department of Nursing, Munkyung College, Mungyeong and Department of Preventive Medicine, Dankook University College of Medicine, Cheonan, Korea

Received: April 11, 2015
Accepted: May 30, 2015
Published online: June 29, 2015

This article is available from: http://e-eht.org/

Introduction

Cesium-137 (^{137}Cs), which is an artificial radioactive substance, was found at concentrations more than 20 times higher than the recommended limit on two roads in a residential area in Nowon-gu, Seoul. This was discovered accidentally when a man carrying a radiation detector measured the radioactivity. The reported radiation level was 2.5 μSv/hr [1].

The two contaminated roads were later reported to the Nuclear Safety and Security Commission, and the Korean Institute of Nuclear Safety (KINS) measured the level of radiation on the two roads. On contaminated road 1, maximum radiation levels of 2.8 μSv/hr and 1.9 μSv/hr were measured on the road surface and 1 m above the road surface, respectively. A rigorous analysis of nuclides in an asphalt concrete sample extracted from the road demonstrated a radioactivity concentration of ^{137}Cs at 1.82

Copyright © 2015 The Korean Society of Environmental Health and Toxicology
This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

to 35.4 Bq/g. On contaminated road 2, the spatial rates of radiation on the road surface and 1 m above the road surface were 3.2 μSv/hr and 1.4 μSv/hr, respectively, and the concentration of radioactive ^{137}Cs was analyzed to be at 22.4 to 29.1 Bq/g. The concentration of radioactive ^{137}Cs in an asphalt concrete sample obtained from an uncontaminated referent area (comparative analysis) that was located far away from the contaminated area was 0.00235 Bq/g (Table 1) [1]. In the soil under the contaminated asphalt concrete, the radioactivity level of ^{137}Cs was similar to that in the uncontaminated referent area and no other type of radionuclide except for ^{137}Cs was found.

The 6 m wide and 200 m long contaminated road 1 and the 5 m wide and 90 m long contaminated road 2 are open to both cars and pedestrians. There is a high school nearby and commercial premises, i.e., shops, on both sides of contaminated road 1. A large number of people also travel to reach the subway station in the vicinity. Contaminated road 2 is located in a residential area that has an elementary school and three apartment complexes (approximately 1200 households) in the vicinity (Figure 1).

The sources of ^{137}Cs were supposed to be contamination of radioactive materials in the reclaimed asphalt pavement (RAP); however, the company responsible for the RAP delivery was shutdown several years ago and no clue was found as to how the contamination happened.

Similar accidents in other countries, including cases of ^{137}Cs leakage in Goiania, Brazil (1987) [2], asphalt contamination with thorium (Th) and uranium (U) in Taiwan [3], and cobalt-60 (^{60}Co) contamination in construction materials in Taiwan [4,5] have been reported.

Table 1. The cesium-137 (^{137}Cs) concentration and radiation dose rate of the contaminated roads in Seoul, Korea, reported by the Nuclear Safety and Security Commission, 2011 [1]

	Road 1	Road 2
^{137}Cs concentration in asphalt (Bq/g)	1.82-35.4	22.4-29.1
Maximum dose rate (μSv/hr)		
Road surface	2.8	3.2
1m height from road surface	1.9	1.4

This case received much media attention and a large scale epidemiological study supported by the Seoul Metropolitan Government was initiated to assess the possible health effects on pedestrians who walk on these roads and residents who live near the contaminated roads, which included an geo-ecological analysis of cancer in these areas compared to the adjacent areas and a questionnaire survey on past medical history, psychological stress, awareness of radiation-related health effects, and demand polls regarding the incident. This particular study was performed as a part of the epidemiologic study and aimed to assess the dose of radiation exposure in each individual over the period of potential radiation exposure since these roads were paved (2000 to 2011).

Materials and Methods

Study Population for Epidemiological Survey

The target area was Wolgye 2-dong in the northeastern part of Seoul where the two contaminated roads were located, wherein 'dong' is a smaller administrative unit with a 1.94 km^2 area, 12389 households, and 31053 residents [6], followed by 'gu' in the Seoul metropolitan city (Figure 2).

Two different methods were combined and adopted to select subjects for the survey conducted to assess the health effects of radiation exposure from the contaminated roads on residents living nearby. The survey was performed from February to June 2012. One method was a survey of all family members through the students enrolled in elementary, middle and high schools in the area by using self-administered questionnaires, and the other

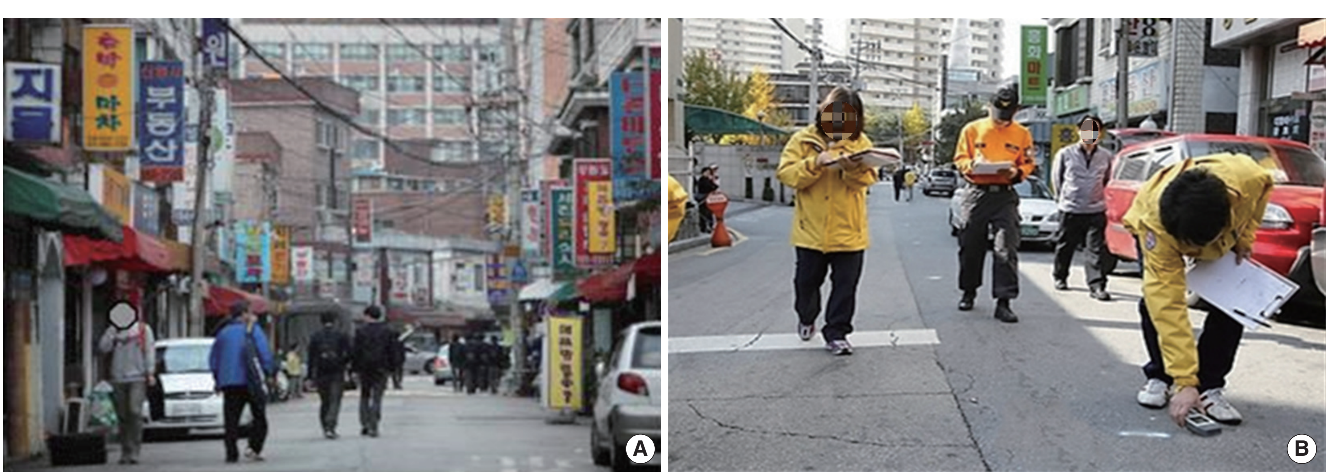

Figure 1. The two roads (A, road 1; B, road 2) paved with asphalt contaminated by radioactive cesium-137, photographed in December, 2011.

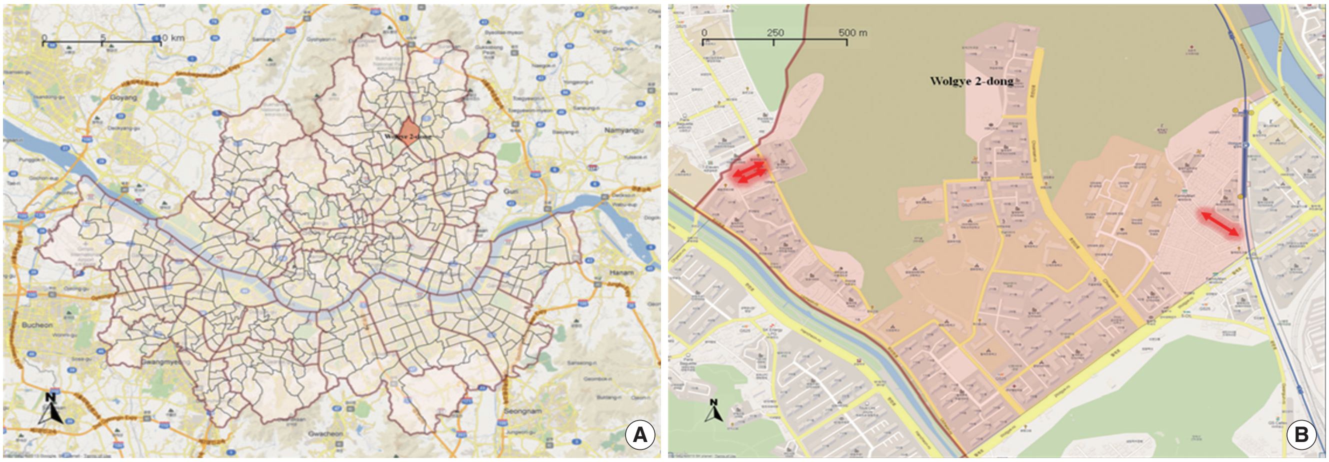

Figure 2. The study area where the radioactive cesium-137 contaminated roads were located in Seoul metropolitan city. (A) Seoul metropolitan city (outer brown line) and (B) Wolgye 2-dong and 2 contaminated roads (red lines).

method was a survey of one member of the family through a home visit and a face-to-face interview. One thousand two hundred households were sampled randomly based on the addresses in Wolgye 2-dong (estimated sampling error ±2.8%). The survey through home visit was conducted by five skilled interviewers who were carefully selected by the Korean Centers for Disease Control and Prevention for 'Community Health Survey 2013' [7]. A total of 10543 copies of survey questionnaires (from 34.2% of all residents) were collected. Nine thousand seventy-three copies of survey questionnaires were collected from schools and 1470 copies of survey questionnaires were collected through the home visit. The total number of subjects in the investigation was 8875 after excluding 215 subjects who did not respond completely to the survey questions; 1380 subjects who did not live in the Wolgye 2-dong area, were not enrolled in the schools of the area, and did not have jobs in the area; and 161 subjects who did not provide information on gender and age.

Assessment of Radiation Exposure

Assessment of the cumulative dose of radiation exposure from the roads contaminated by ^{137}Cs was carried out on pedestrians and those who either did business or lived in the commercial area close to these two roads. This assessment was limited to external radiation; internal exposure caused by inhaling dust contaminated with radioactive substances was not considered. This is because solid concrete materials that were used along with asphalt were contaminated by radioactive substances and the chances of these radioactive substances being present in the dust generated due to the wear and tear on these roads were quite low. Road construction or repair workers could have inhaled dust contaminated by radioactive substances while they were on duty, but there was no method to track road construction/repair records and workers. People who passed via these two contaminated roads by car and not on foot were also excluded from this assessment since the dose of radiation exposure was presumed to be extremely low.

The cumulative dose of radiation exposure of pedestrians was evaluated using the following method.

Cumulative dose of radiation exposure = Total exposure time (hour) × Dose/hour

Total exposure time (hour)

= Number of years during which the pedestrian passed via the contaminated road (×365 days) ×Frequency at which the pedestrian passed via the contaminated road per day x Hours for each instance of travelling via the contaminated road

Hours for each instance of travelling = Length of the road (km) / Walking speed (km/hr)

Survey on the Duration and Frequency of Passing Via the Contaminated Road

In the questionnaire, survey respondents were asked how many years they had passed via the contaminated roads (For how many years have you been passing via contaminated road 1 or 2?) and how frequently they had passed via the contaminated roads (How frequently have you been passing via contaminated road 1 or 2 per day?) from 2000 to 2011. The annual number of passages via the contaminated road was counted based on regular passages, i.e., commuting to schools (kindergarten, elementary, middle and high, and colleges) and workplaces. Irregular passages, i.e., the passing of housewives, was counted as an average number of passings per week.

Direct Observation of Walking Speed of Pedestrians

According to observations of human traffic using a video camera and timer, 154 and 130 pedestrians travelled via contaminated roads 1 and 2, respectively, per hour in the early morning hours (07:00 to 09:00 am), and 133 and 105 pedestrians travelled via contaminated roads 1 and 2, respectively, per hour in the afternoon hours (14:00 to 16:00 pm) (Figure 1). The walking speed of 56 respondents (21 persons at 07:00 to 09:00 am; 35 persons at 14:00 to 16:00 pm) who passed via the contaminated roads was measured, and the average walking speed of man and woman respondents was used to estimate their total exposure time (men mean [standard deviation; SD], 5.28 [0.51] km/hr; women mean [SD], 4.29 [0.78] km/hr).

Information on Measured Spatial Radiation Dose

The average spatial radiation dose measured 1 m above the asphalt surface by the KINS on November 8, 2011 [1] was used as the spatial dose of radiation exposure to pedestrians when they passed via the contaminated roads. KINS reported that they measured the spatial radiation rate on the road surface and 1 m vertically above the road surface at 26 and 42 spots separated by 5 m intervals on 100 m of road located in the residential area of roads 1 and 2, respectively, with portable radiation measurement instruments. Among the measured spots, the 10 highest spots, 5 each in road 1 and 2, were examined for types of radionuclides and radiation dose rate using the *in-situ* gamma nuclear analysis system (*in-situ* spectrometry) with a high-precision ionization chamber. Furthermore, at the same 10 spots, a 10 cm-diameter hole was carefully incised on the surface with a circle-cutting machine and a core with a depth of 5 to 7 cm, enough to include the paved asphalt, was removed to be analyzed for radionuclides and their concentrations using High Purity Germanium. For comparison with controls, at a referent region far from the contaminated area, spatial radiation was measured at 48 spots and 3 referent samples for radionuclide concentration analysis were obtained. In addition, soil samples under the asphalt concrete of the contaminated roads were also obtained and analyzed. In the samples from the referent region and soil under the asphalt concretes, the level of spatial radiation was similar and no radionuclides were found.

Retrospective Calculation of Spatial Radiation Dose Rate

The average spatial radiation dose rate measured by KINS at the time of discovery was 1.38 μSv/hr in contaminated road 1 and 1.01 μSv/hr in contaminated road 2. Annual radiation doses before 2011 based on the above mentioned doses were calculated using the following formula, in which the half-life of ^{137}Cs was taken into consideration (30.1 years) (Table 2).

$$A = A_o\, e^{-(0.693t/T1/2)}$$

Where A = final activity, Ao = initial activity, $T_{1/2}$ = half-life time, t = decay time

Calculation of Spatial Radiation Dose Rate Adjacent to the Sides of the Roads

People who were working in the shops located on both sides of the two contaminated roads could have been exposed to radi-

Table 2. Calculated radiation dose rates at 1 m vertical above the road surface and 2 m horizontally away from the road side border in the adjacent area due to cesium-137 contamination by year and distance in Seoul, Korea, 2000-2011

Year	Sites[a] at road 1		Sites[a] at road 2		Background[b]
	1 m vertical	2 m horizontal	1 m vertical	2 m horizontal	
2011	1.38[c]	0.35	1.01[c]	0.25	0.22 (0.27)
2010	1.41	0.35	1.03	0.26	
2009	1.45	0.36	1.06	0.27	
2008	1.48	0.37	1.08	0.27	
2007	1.51	0.38	1.11	0.28	
2006	1.55	0.39	1.13	0.28	
2005	1.59	0.40	1.16	0.29	
2004	1.62	0.41	1.19	0.30	
2003	1.66	0.42	1.21	0.30	
2002	1.70	0.43	1.24	0.31	
2001	1.74	0.44	1.27	0.32	
2000	1.78	0.45	1.30	0.33	

Unit: μSv/hr.
Estimated dose rates calculated based on the measured dose rate reported by the Nuclear Safety and Security Commission (NSSC) using the equations; $A=A_o\, e^{-(0.693t/T1/2)}$, (where A=final activity, A_0=initial activity, $T_{1/2}$=half-life time, t=decay time), and $I_1/I_2=D_2^2/D_1^2$, (where I_1=iIntensity 1 at D_1, I_2=iIntensity 2 at D_2, D_1=distance 1 from source, D_2=distance 2 from source).
[a]Sites at 1m vertically away from the road surface, sites at 2 m horizontally away from the road side border.
[b]Background dose rate reported by the NSSC, a measured value at a referent region far from the contaminated roads.
[c]The measured dose rate reported by the NSSC [6].

ation for a longer time, since neither road had a sidewalk and therefore the people were in direct contact with the contaminated road surface when they opened the doors of their shops. The cumulative dose of radiation exposure in people working in these shops was evaluated by surveying their total duration of stay inside the shops. The average radiation dose 2 m horizontally away from the contaminated road side border was used to measure the spatial radiation dose, as the distance between the main work area of shop workers and the contaminated roads' side border averaged 1 to 3 m (the spatial radiation dose 3 m or farther from the side border of the contaminated roads was near the normal level). This was applied only to shops in the basement and on the first floor; shops on the 2nd floor and higher were excluded from this calculation. The estimated cumulative dose included the background radiation dose.

The spatial radiation dose based on the distance from the contaminated road was calculated with the following formula:

$$I_1 / I_2 = D_2^2 / D_1^2$$

Where I_1 = intensity 1 at D_1, I_2 = intensity 2 at D_2, D_1 = distance 1 from source, D_2 = distance 2 from source

Statistical Analyses

We performed descriptive statistical analyses to show the distribution of radiation exposure and the mean value of the estimated dose of individual radiation exposure. ANOVA and *t*-test were used to test the difference in the mean dose of radiation exposure according to gender, age, and residential area. SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) was used with a statistical significance level of 0.05.

Results

Radiation Dose Rate According to the Year and Distance

The calculated spatial radiation dose on a yearly basis is presented in Table 2.

The radiation dose of contaminated road 1 was higher than that of contaminated road 2. The radiation dose of contaminated road 1 was 1.78 μSv/hr and that of contaminated road 2 was 1.30 μSv/hr when they were paved with asphalt (2000), which was 1.29 times higher than that at the time of discovery (2011). Compared to the background radiation dose (0.22 μSv/hr) 1 km away from the contaminated roads, the calculated radiation doses were 6.3 to 8.1 times higher in contaminated road 1 and 4.6 to 4.9 times higher in contaminated road 2.

Number of People Exposed to Radiation and Duration of Radiation Exposure

Among the 8875 subjects for analysis, 5598 (63.1%) subjects passed via the roads contaminated with ^{137}Cs; of which 3290 were women and 2308 were men. The percentage of the population exposed to radiation increased with age.

There were 866 men and women who lived within 30 m of the contaminated roads, which accounts for 15.5% of the total population exposed to radiation. These men and women would pass via the contaminated roads frequently for their daily routine activities or for business purposes.

There were 2860 men and women who lived within 30 to 500 m from the two contaminated roads, which represents 51.1% of the total population exposed to radiation. They mainly lived in houses or apartment complexes that were located slightly further away from the two contaminated roads and they would

Table 3. Estimated number of people exposed to radiation due to cesium-137 contaminated roads and duration of exposure by gender, age, and residential area among 8875 persons in Seoul, Korea, 2011

		Total No. of people	Exposed people[a]		Exposure duration among exposed people (yr)	
			n	%	Mean	Min, Max
Gender	Men	3764	2308	61.3	4.75	0.08, 11.91
	Women	5111	3290	64.4	5.10	0.01, 11.82
Age (yr)	≤6	49	34	69.4	1.67	0.67, 3.75
	7-12	1591	836	52.2	4.03	0.16, 8.98
	13-15	1668	969	58.1	4.43	0.25, 11.73
	16-18	2616	1644	62.8	4.50	0.24, 11.75
	≥19	2951	2115	71.6	5.97	0.01, 11.91
Residential area	A	354	331	93.5	6.06	0.08, 11.91
	B	590	535	90.5	5.60	0.33, 11.82
	C	4592	2860	62.3	5.16	0.01, 11.90
	D	3339	1872	56.1	4.26	0.25, 11.75
Total		8875	5598	63.1	4.96	0.01, 11.91

Min, minimum; Max, maximum; A, residents who lived within 30 meters from contaminated road 1; B, residents who lived within 30 meters from contaminated road 2; C, residents who lived within 30 to 500 meters from contaminated road 1 or 2; D, residents who lived more than 500 meters away from the contaminated road.
[a]Exposed defined as people who have ever passed the contaminated roads.

routinely pass via the contaminated roads while commuting to the school or workplace.

There were 1872 men and women who lived more than 500 m from the two contaminated roads, which represents 33.4% of the total population exposed to radiation. They lived in other administrative districts that were located far away from the contaminated roads. They are presumed to have passed via the contaminated roads while commuting to workplace or school or to have passed via the contaminated roads before moving to a new place.

The average duration of exposure of men and women to the contaminated roads was 4.96 years. The duration of radiation exposure was significantly longer in women (5.10 years) than in men (4.75 years) and it also increased significantly with age. The duration of exposure to contaminated road 1 was longer (6.06 years) than that to contaminated road 2 (5.60 years) (Table 3).

Estimated Cumulative Dose of Radiation Exposure

The average cumulative dose of radiation exposure in 5598 people was 0.393 mSv. There were no gender differences, but the cumulative dose of radiation exposure was statistically significantly higher in elderly subjects and residents living in the contaminated area. The cumulative dose of radiation exposure in subjects residing on contaminated road 1 was much higher, at 2.912 mSv, when compared to the cumulative dose of radiation exposure of 0.375 mSv in subjects residing on contaminated road 2. Sixty-one (1.1%) out of 5598 people who were exposed to radiation had a cumulative dose of radiation exceeding 10 mSv, and 102 (1.8%) people had a cumulative dose of radiation exceeding 5 mSv (Table 4).

Subjects exposed to a radiation dose of more than 5 mSv on a cumulative basis were exposed for more than five years, and those exposed to a radiation dose of more than 20 mSv were exposed for more than nine years (Figure 3).

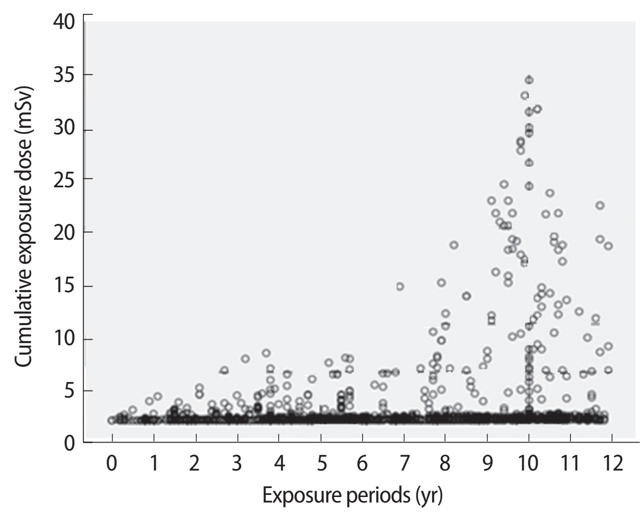

Figure 3. Distribution of cumulative exposure dose by exposure period among 5598 participants exposed to radiation due to the roads contaminated with radioactive cesium-137.

Table 4. Estimated cumulative radiation exposure dose and number of exposed people due to cesium-137 contaminated roads by gender, age, and residential area in Seoul, Korea, 2011

		Total No. of exposed people[a]	Cumulative radiation exposure dose[b]				No. of exposed people	
			AM	Median	GM	Min, Max	5 - <10 mSv (%)	≥10 mSv (%)
Gender	Men	2308	0.439	0.049	0.049	<0.001, 35.317	17 (0.74)	28 (1.21)
	Women	3290	0.360	0.049	0.048	<0.001, 32.297	24 (0.73)	33 (1.00)
				p=0.188[c]				
Age (yr)	≤6	34	0.059	0.032	0.029	0.002, 0.257	0 (0.0)	0 (0.0)
	7-12	836	0.085	0.049	0.038	<0.001, 1.029	0 (0.0)	0 (0.0)
	13-15	969	0.064	0.031	0.027	<0.001, 0.774	0 (0.0)	0 (0.0)
	16-18	1644	0.199	0.042	0.046	0.002, 12.850	3 (0.18)	3 (0.18)
	≥19	2115	0.820	0.064	0.073	<0.001, 35.317	38 (1.80)	58 (2.74)
				p<0.001[c]				
Residential area	A	331	2.912	0.226	0.264	0.003, 35.317	12 (3.63)	35 (10.57)
	B	535	0.375	0.070	0.070	0.001, 21.509	5 (0.93)	7 (1.31)
	C	2860	0.245	0.045	0.044	<0.001, 23.620	16 (0.56)	14 (0.49)
	D	1872	0.178	0.037	0.037	<0.001, 18.840	8 (0.43)	5 (0.27)
				p<0.001[c]				
Total		5598	0.393	0.049	0.048	<0.001, 35.317	41 (0.73)	61 (1.09)

Unit: mSv.

AM, arithmetic mean; GM, geometric mean; Min, minimum; Max, maximum; A, residents who lived within 30 meters from contaminated road 1; B, residents who lived within 30 meters from contaminated road 2. C, residents who lived within 30 to 500 meters from contaminated road 1 or 2; D, residents who lived more than 500 meters away from the contaminated road.

[a]Exposed people defined as people who have ever passed the contaminated roads.

[b]Cumulative radiation exposure dose including background radiation dose.

[c]Calculated by t-test or ANOVA.

Discussion

We aimed to calculate the total cumulative dose of radiation exposure in one third of the residents living in the surveyed area on an individual basis in order to perform an epidemiological investigation of the relationship between radiation exposure from roads contaminated with radioactive substances and its health effects. The findings indicate that approximately 63% of the surveyed residents living in the area were exposed to radiation since they had passed via the two contaminated roads at least once, and the estimated total cumulative dose of radiation exposure exceeded 10 mSv in approximately 1% of the surveyed residents. The total duration of radiation exposure was 4.75 years (minimum, 0.8; maximum, 11.98) and the geometric average of the total cumulative radiation exposure was 0.049 mSv (minimum, <0.001; maximum, 35.353), which is far below the current exposure guideline of 1 mSv a year for the general population [8].

^{137}Cs is an artificial radioactive substance that does not exist naturally. A byproduct of an artificial nuclear fission, ^{137}Cs is the major nuclide found in radioactive waste generated during the process of using or re-treating nuclear fuel [9]. Radioactive fallout from aerial weapons testing in the past caused soil contamination, and ^{137}Cs existed as a contaminant in nuclear fuel treatment facilities and nuclear reactor sites. ^{137}Cs has a half-life of approximately 30 years. It remains in nature for a long time and just a single leak could cause an adverse impact on the environment [10]. Once ^{137}Cs enters the human body, it spreads throughout the body and is then excreted from the body with an approximate half-life of 70 days. An experiment in a mouse model indicated a reduction in the number of sperm when ^{137}Cs was administered orally, and reports demonstrate that intravenous administration of ^{137}Cs in dogs caused a number of acute hematologic disorders and tumors in many organs in the longer term [10].

In 1987, Goiania, Brazil experienced exposure to ^{137}Cs when petty thieves stole discarded radioactive medical equipment [2]. ^{137}Cs leaked out when they were struggling to disassemble the equipment. The leak of ^{137}Cs caused contamination of the major roads in Goiania and triggered a serious catastrophe in the village. Four villagers who consumed the material or applied it on their skin without knowing that it was a radioactive substance died of acute radiation syndrome, and 13 other villagers had to be hospitalized for treatment.

In a case similar to this study, an asphalt road contaminated with Th and U was found in Taiwan [11]. A 150 m long and 6 m wide road was paved in 1992. It was then dug up after contamination was detected in 1998. Among the three radioactive substances of ^{232}Th, ^{238}U, and potassium-40 that were detected in the contaminated road, the measured level of ^{232}Th was the highest at 2596 to 4291 Bq/kg. The surface radiation dose of 1.01 to 1.38 μSv/hr in the two contaminated roads in Wolgye 2-dong was a little higher than that in the contaminated roads in Taiwan (0.2-1.3 μSv/hr).

In another case in Taiwan, construction materials (more than 20000 tonnes) such as structural steel (billet), pipeline, steel door and window frames that were made using steel contaminated with unidentified ^{60}Co in a steel plant in 1982 [4,5] were used in around 200 buildings and in more than 1000 apartment buildings and schools (built from 1982 to 1984), exposing more than 15000 people to ^{60}Co for 2 to 15 years. Thirteen percent of people surveyed were considered to have been exposed to more than 50 mSv [5]. The duration of radiation exposure and cumulative dose of radiation exposure in the present study were less than those in the buildings in Taiwan (47.8 - 150.7 mSv) [3].

This study has several limitations in estimating the cumulative dose of radiation exposure in the surveyed subjects. First, there is no physical measurement data on past radiation exposure of the surveyed residents. The individual dose of radiation exposure does not always match with the spatial dose measured at the site, and a relatively accurate dose of radiation exposure can be obtained by using a personal dosimeter. Second, there should be a statistical uncertainty when estimating the past environmental dose based on the present environmental dose (spatial dose) and when estimating the radiation dose 1 m above the road surface (for pedestrians) and 2 m away from the road-edge (for residents). We did not perform uncertainty analyses on these estimations. Third, there is a possibility of misclassification such as recall bias in the information gained via the retrospective survey. However, the sampling design of randomly selected households in the area might reduce the risk of bias, at least in the estimated representative value of total cumulative dose of radiation exposure. There was no evidence of a differential potential misclassification bias between the high-exposure group and the low-exposure group.

In summary, this is the first study to assess radiation exposure for an epidemiologic investigation from roads that were accidentally found to be contaminated by radioactive ^{137}Cs in Korea. The present study including future analytical results in the main epidemiologic investigation could provide an effective and scientific basis for risk communication with residents in the area. Although the level of radiation exposure assessed in people residing near the roads or passing via the roads was mostly very low, environmental management of radioactive materials including long-term observation of a small group of residents who were exposed to a relatively high dose in this area is needed.

Acknowledgements

This work was performed with the support of the Seoul Metropolitan Government. We would like to thank Professors Hae-Kwan Cheong, Yun-Chul Hong, Hojang Kwon, Myoungsoon You, and Dr. Sangil Chun for their invaluable scientific comments and advice, and the representatives of the residents and teachers of the participating schools for their enthusiastic cooperation in the questionnaire survey.

Conflict of Interest

The authors have no conflicts of interest with material presented in this paper.

References

1. Nuclear Safety and Security Commission. Report on radioactive materials analysis of contaminated roads and future recommendation for management, Nowon-gu, Seoul; 2011 [cited 2015 May 6]. Available from: http://www.nssc.go.kr/nssc/notice/report.jsp?mode=view&article_no=105&pager.offset=105&board_no=2 (Korean).
2. International Atomic Energy Agency. The radiological accident in Goiânia; 1988 [cited 2015 May 6]. Available from: http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.
3. Chang WP, Nabyvanets YB, Jen MH. Unusual 232Th and 238U contamination on some road surfaces in Taoyuan, Taiwan. Health Phys 2001;80(6):602-604.
4. Chang WP. Spread of Taiwan's radiation panic. Lancet 1993;342(8886-8887):1544.
5. Hwang SL, Guo HR, Hsieh WA, Hwang JS, Lee SD, Tang JL, et al. Cancer risks in a population with prolonged low dose-rate gamma-radiation exposure in radiocontaminated buildings, 1983-2002. Int J Radiat Biol 2006;82(12):849-858.
6. Nowon-gu. Number of population; 2012 [cited 2015 May 6]. Available from: http://www.nowon.kr/new/civil/civil.jsp?mid=510612 (Korean).
7. Korea Centers for Disease Control and Prevention. Community Health Survey; 2014 [cited 2015 May 6]. Available from: http://chs.cdc.go.kr/chs/sub01/sub01_02.jsp (Korean).
8. International Commissions of Radiological Protection. The 2007 recommendations of the international commissions on radiological protection [cited 2015 May 6]. Available from: http://www.icrp.org/docs/ICRP_Publication_103-Annals_of_the_ICRP_37(2-4)-Free_extract.pdf.
9. Agency for Toxic Substances and Disease Registry. Toxicological profile for ionizing radiation; 1999 [cited 2015 Feb 15]. Available from: http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=484&tid=86.
10. Agency for Toxic Substances and Disease Registry. Toxicological profile for cesium; 2004 [cited 2015 May 6]. Available from: http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=578&tid=107.
11. Chang TC, Chen WL, Chang WP, Chen CJ. Effect of prolonged radiation exposure on the thyroid gland of residents living in 60Co-contaminated rebar buildings. Int J Radiat Biol 2001;77(11):1117-1122.