Original Contribution

Radio-Frequency Radiation Exposure from AM Radio Transmitters and Childhood Leukemia and Brain Cancer

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Leukemia and brain cancer patients under age 15 years, along with controls with respiratory illnesses who were matched to cases on age, sex, and year of diagnosis (1993–1999), were selected from 14 South Korean hospitals using the South Korean Medical Insurance Data System. Diagnoses were confirmed through the South Korean National Cancer Registry. Residential addresses were obtained from medical records. A newly developed prediction program incorporating a geographic information system that was modified by the results of actual measurements was used to estimate radio-frequency radiation (RFR) exposure from 31 amplitude modulation (AM) radio transmitters with a power of 20 kW or more. A total of 1,928 leukemia patients, 956 brain cancer patients, and 3,082 controls were analyzed. Cancer risks were estimated using conditional logistic regression adjusted for residential area, socioeconomic status, and community population density. The odds ratio for all types of leukemia was 2.15 (95% confidence interval (CI): 1.00, 4.67) among children who resided within 2 km of the nearest AM radio transmitter as compared with those resided more than 20 km from it. For total RFR exposure from all transmitters, odds ratios for lymphocytic leukemia were 1.39 (95% CI: 1.04, 1.86) and 1.59 (95% CI: 1.19, 2.11) for children in the second and third quartiles, respectively, versus the lowest quartile. Brain cancer and infantile cancer were not associated with AM RFR.

brain neoplasms; child; environmental exposure; leukemia; radiation; radio

The increasing use of hand-held mobile telephones and personal communication service phones has necessitated an increase in the number of transmitters needed to support these devices. These transmitters have created public concern regarding the health effects of radio-frequency radiation (RFR). In urban areas in the United States, most RFR in the environment is produced by local radio and television stations, with smaller contributions from cellular telephone communications and emergency-services mobile radios (1). Radio and television transmission towers might be one of the major sources of RFR exposure in most industrialized countries. Although most are not located in populated areas, radio

and television transmitters have large coverage areas and operate at relatively high power levels, which can result in a high level of population exposure, particularly in densely populated countries such as South Korea.

There is a long history of public concern about radio and television antennas and resistance to the placement of such antennas, for numerous reasons related to aesthetics, property values, and health (1). Studies investigating the association between radio and television transmission towers and cancer have usually been performed in response to such concerns, but the results have not been consistent (2–13). Inconclusive results might have arisen from several deficiencies in each study, such as diverse sources of exposure, poor estimation of population exposure, small numbers of cases, and selective investigation in response to clusters (1).

Amplitude modulation (AM) radio frequency is relatively low in the RFR range, ranging from 300 kHz to 3,000 MHz. In South Korea, there are 109 AM radio transmission towers with 144 antennas, with a power of 1–1,500 kW and frequencies ranging from 540 kHz to 90,500 kHz. AM radio antennas are the oldest types of RFR transmitters in South Korea. They were established between 1927 and 1995 and have been operating 24 hours a day since then.

Previously, Ha et al. (5) and Park et al. (13) reported on cancer incidence and mortality among persons residing near AM radio towers and demonstrated the need for a study with an analytical design and improved exposure assessment. In this study, we investigated the association between childhood leukemia and brain cancer and residential exposure to AM radio-transmission radiation using a case-control design and thorough exposure assessment. We employed a software program we developed that incorporated a geographic information system.

MATERIALS AND METHODS

Study population

Case and control selection. In South Korea, medical insurance is provided to all people under the South Korean National Health Insurance System. Eligible cases and controls under the age of 15 years were selected from the South Korean Medical Insurance Data System using *International Classification of Diseases*, Ninth (ICD-9) or Tenth (ICD-10) Revision, codes for leukemia (ICD-9: 204–208; ICD-10: C91–C95) and brain cancer (ICD-9: 191–192; ICD-10: C70–C72). Each case was matched by age and sex to a control child with the same year of first diagnosis who visited a clinic with a respiratory disease, such as acute or chronic bronchitis, emphysema, laryngitis, or asthma (ICD-9 codes 469–519; ICD-10 codes J20 and J40–J46). Controls predominantly comprised asthma patients (30.1 percent). The subjects were restricted to children diagnosed at one of 14 large hospitals which were either cancer hospitals or tertiary-care hospitals in the national medical referral system.

Through the National Cancer Registry, cases' cancer diagnoses were confirmed and controls were checked for a history of cancer diagnosis. The medical records of all eligible subjects were reviewed at the hospitals at which their illnesses had been diagnosed. Case diagnoses that had not been confirmed by the National Cancer Registry (the registry's completeness was 80 percent in 1998 (14)) were confirmed through the medical record review. The patients' residential addresses were obtained from their medical records at the time of diagnosis. Among the 3,369 cases and 3,369 matched controls who were diagnosed from 1993 to 1999 at one of the 14 large hospitals, persons whose cancer diagnosis was not confirmed (156 cases), persons who had previously been diagnosed with cancer (25 controls), persons with cancers other than leukemia or brain cancer (98 cases), and persons with incomplete addresses (231 cases and 262 controls) were excluded. Therefore, 2,884 cases (1,928 leukemia and 956 brain cancer) and 3,082 controls were included in the study.

Exposure assessment. Among the 109 AM radio transmitters and 144 radio antennas in South Korea, 31 transmitters and 49 antennas were included in the study (figure 1). The transmitters all had a power of 20 kW or more (20 kW for six transmitters, 50 kW for nine, 100 kW for eight, 250 kW for three, 1,000 kW for four, and 1,500 kW for one).

For assessment of individual RFR exposure from all AM radio transmitters, we developed a prediction program incorporating a geographic information system, through the statistical prediction models of "flat-earth attenuation" (15), "smooth-earth attenuation" (16), "asymptote modeling" (17), and "irregular-earth attenuation" (18). This program considered five conditions at the receiving point, such as distance, altitude, the electrical characteristics of the area (conductivity and permittivity), and the characteristics of the propagating pathway (low-salinity seawater, average-salinity seawater, fresh water, very wet land, wet ground, land, medium-dry ground, dry ground, very dry ground, freshwater ice −1°C, freshwater ice −10°C). We used the ground-type classifications of the International Telecommunication Union's Radiocommunication Sector (19).

In order to validate the prediction program, we performed actual measurements of electric and magnetic field strength at sites around 11 AM radio transmitters. The sites were chosen through stratification by the electrical conductivity of the land (five sites from "land," four sites from "wet ground," and two sites from "medium-dry ground"), according to the International Telecommunication Union classification (20). A passive monopole antenna was used for the electric field measurement, and a passive loop antenna and isotropic probe were used for the magnetic field measurement, with automatic data inquiry and processing software incorporating a spectrum analyzer and global positioning system.

The measurements were done in two ways. One method involved measuring at fixed points. The measurements were carried out at different angles at several fixed points the same distance away from the target transmitter, and measurements were repeated after changing the distance. All measurement was done for 6 minutes at each point. The other method involved using a vehicle loaded with the measurement devices. At several hundred points within 3 km of the target transmitters, measurement was carried out while

FIGURE 1.   Locations of the 31 AM radio transmitters with a power of 20 kW or more in South Korea, 1995.

the vehicle was moving from point to point. The results of the prediction program and the actual measurement were compared, and correction coefficients were obtained through the functions of the two results and the distance from the transmitter. The prediction program was modified with these correction coefficients. Because the exposure values estimated by means of each statistical prediction model were similar and the risks estimated from these values did not differ, we performed the analyses based on the ''flat-earth attenuation'' model (15).

We calculated the maximum adjusted RFR exposure estimate (E') for each transmitter by means of functions for the unadjusted estimate E and the distance d, using the following equations: for $d < 7$ km, $E + 4 \log_{10} (d) - 4.5$; for 7 km $\leq d \leq 20$ km, $E - (25 \log_{10} (d)) + 107$; and for $d > 20$ km, E. We defined peak RFR exposure as the highest exposure estimate among all of the individual exposure estimates obtained from each transmitter established before

the subjects' year of diagnosis. The total RFR exposure from all transmitters was calculated by $\sqrt{\sum (E_i'^2)}$.

Confounder information

In order to adjust for the possible confounding effect of socioeconomic status (SES) on childhood cancer, we reconstructed a categorical indicator using 1998 national statistical data for the number of cars owned per 100 persons in the regions where the study subjects resided. SES was classified into three categories: 20 or more cars per 100 persons was defined as high SES, 10–19 cars per 100 was defined as medium SES, and less than 10 cars per 100 was defined as low SES (21). We also categorized the population density of these regions in order to take into account the level of industrialization and environmental pollution: 5,000 or more persons per km^2 was defined as high density, 500–4,999 was

TABLE 1. Selected characteristics of leukemia and brain cancer patients and matched controls under age 15 years, South Korea, 1993–1999

	Controls* (n = 3,082)		Leukemia cases								Brain cancer cases					
			Lymphocytic (n = 1,300)		Myelocytic (n = 510)		Other (n = 118)		All (n = 1,928)		Neuroepithelial (n = 851)		Nonneuroepithelial (n = 105)		All (n = 956)	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Age (years) at diagnosis																
0–4	1,085	35.2	460	35.4	187	36.7	45	38.1	692	35.9	270	31.7	23	21.9	293	30.7
5–9	1,031	33.5	480	36.9	152	29.8	37	31.4	669	34.7	276	32.4	34	32.4	310	32.4
10–14	966	31.3	360	27.7	171	33.5	36	30.5	567	29.4	305	35.8	48	45.7	353	36.9
Sex																
Male	1,847	59.9	769	59.2	314	61.6	68	57.6	1,151	59.7	524	61.6	64	61.0	588	61.5
Female	1,235	40.1	531	40.9	196	38.4	50	42.4	777	40.3	327	38.4	41	39.1	368	38.5
Residential location																
Seoul	1,238	40.2	261	20.1	134	26.3	29	24.6	424	22.0	288	33.8	32	30.5	320	33.5
Busan	298	9.7	152	11.7	44	8.6	5	4.2	201	10.4	68	8.0	13	12.4	81	8.5
Daegu	408	13.2	54	4.2	91	17.8	21	17.8	166	8.6	49	5.8	8	7.6	57	6.0
Incheon	85	2.8	46	3.5	12	2.4	3	2.5	61	3.2	41	4.8	6	5.7	47	4.9
Gwangju	44	1.4	27	2.1	15	2.9	7	5.9	49	2.5	15	1.8	0	0.0	15	1.6
Daejun	202	6.6	26	2.0	13	2.6	1	0.9	40	2.1	28	3.3	4	3.8	32	3.3
Ulsan	29	0.9	33	2.5	7	1.4	4	3.4	44	2.3	19	2.2	2	1.9	21	2.2
Gyeonggi-do	361	11.7	293	22.5	74	14.5	15	12.7	382	19.8	156	18.3	14	13.3	170	17.8
Gangwon-do	25	0.8	66	5.1	17	3.3	2	1.7	85	4.4	34	4.0	3	2.9	37	3.9
Chungcheongbuk-do	34	1.1	38	2.9	11	2.2	1	0.9	50	2.6	19	2.2	6	5.7	25	2.6
Chungcheongnam-do	94	3.0	41	3.2	12	2.4	3	2.5	56	2.9	27	3.2	4	3.8	31	3.2
Jeollabuk-do	17	0.6	25	1.9	7	1.4	1	0.9	33	1.7	15	1.8	0	0.0	15	1.6
Jeollanam-do	23	0.7	69	5.3	16	3.1	4	3.4	89	4.6	12	1.4	2	1.9	14	1.5
Gyeongsangbuk-do	118	3.8	94	7.2	34	6.7	7	5.9	135	7.0	37	4.3	2	1.9	39	4.1
Gyeongsangnam-do	83	2.7	62	4.8	21	4.1	15	12.7	98	5.1	37	4.3	7	6.7	44	4.6
Jeju-do	17	0.6	13	1.0	2	0.4	0	0.0	15	0.8	5	0.6	2	1.9	7	0.7
Unknown	6	0.2	0	0.0	0	0.0	0	0.0	0	0.0	1	0.1	0	0.0	1	0.1
Population density of residential community†																
High	1,937	62.8	528	40.6	271	53.1	52	44.1	851	44.1	441	51.8	59	56.2	500	52.3
Medium	553	17.9	275	21.2	83	16.3	35	29.7	393	20.4	174	20.4	19	18.1	193	20.2
Low	586	19.0	497	38.2	156	30.6	31	26.3	684	35.5	235	27.6	27	25.7	262	27.3
Unknown	6	0.2	0	0.0	0	0.0	0	0.0	0	0.0	1	0.1	0	0.0	1	0.1
Socioeconomic status of residential community‡																
High	387	12.6	118	9.1	47	9.2	14	11.9	181	9.4	100	11.8	17	16.2	117	12.2
Medium	2,373	77.0	916	70.5	389	76.3	88	74.6	1,393	72.3	625	73.4	76	72.4	701	73.3
Low	316	10.3	266	20.5	74	14.5	16	13.6	354	18.4	125	14.7	12	11.4	137	14.3
Unknown	6	0.2	0	0.0	0	0.0	0	0.0	0	0.0	1	0.1	0	0.0	1	0.1

* Matched to cases on age, sex, and year of diagnosis.

† Classified according to mean population density (number of persons per km^2) of the regions where the study subjects resided during 1994–1998 (large city: ≥5,000 persons; medium city: 500–4,999 persons; rural area: <500 persons).

‡ Classified according to the number of cars owned per 100 persons in the regions where the study subjects resided in 1998 (high: ≥20; medium: 10–19; low: <10).
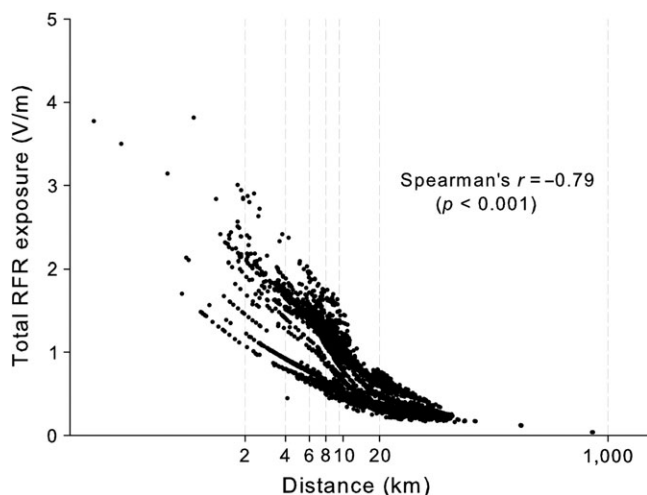
FIGURE 2. Correlation between total radio-frequency radiation (RFR) exposure and residential distance from the nearest AM radio transmitter, South Korea, 1993–1999. Total RFR exposure was calculated using the maximum adjusted RFR exposure estimate (E') for each radio transmitter (indexed by i) established before the subjects' year of diagnosis ($i = 1{\sim}{\leq}31$), using the equation $\sqrt{\sum(E_i{}^2)}$.

defined as medium density, and less than 500 was defined as low density (21).

Statistical analysis

We used conditional logistic regression to estimate odds ratios, calculate 95 percent confidence intervals, and perform likelihood ratio tests (two-sided test with a significance level of $\alpha = 0.05$). The matching variables (age at diagnosis, sex, and year of diagnosis) and confounders (categorized SES and population density of the residential community) were included in all analyses. SAS for Windows, version 9.1 (SAS Institute Inc., Cary, North Carolina), was used.

The study was approved by the institutional review board of Dankook University Hospital (Cheonan, South Korea).

RESULTS

Table 1 shows selected characteristics of the cases ($n = 1,928$ for leukemia, $n = 956$ for brain cancer) and controls ($n = 3,082$). A major proportion of the leukemia cases were of the lymphocytic type ($n = 1,300$; 67.4 percent). A total

TABLE 2. Conditional odds ratios for childhood leukemia according to radio-frequency radiation exposure from AM radio transmitters among children under age 15 years, South Korea, 1993–1999

	No. of controls	Lymphocytic leukemia			Myelocytic leukemia			All leukemia		
		No. of cases	OR*,†	95% CI*	No. of cases	OR†	95% CI	No. of cases	OR†	95% CI
Distance (km)‡										
≤2	12	27	1.60	0.69, 3.72	8	—§		36	2.15	1.00, 4.67
>2–4	90	54	0.95	0.56, 1.61	12	0.31	0.13, 0.71	73	0.66	0.44, 0.99
>4–6	120	91	1.32	0.87, 1.99	24	0.59	0.30, 1.17	120	1.07	0.77, 1.49
>6–8	211	140	1.28	0.91, 1.81	58	1.15	0.68, 1.96	218	1.26	0.96, 1.65
>8–10	329	170	0.99	0.72, 1.36	91	1.41	0.86, 2.29	276	1.10	0.85, 1.41
>10–20	629	258	0.71	0.54, 0.93	139	1.24	0.81, 1.89	428	0.80	0.65, 0.99
>20	664	556	1.00	Referent	177	1.00	Referent	772	1.00	Referent
Unknown	9	4	0.42	0.07, 2.40	1	0.26	0.02, 3.56	5.00	0.48	0.12, 1.95
p (trend)¶				0.10			0.22			0.10
Total radio-frequency radiation exposure (mV/m)#										
Q1*	513	514	1.00	Referent	177	1.00	Referent	737	1.00	Referent
Q2	514	241	1.39	1.04, 1.86	110	1.22	0.84, 1.78	362	0.75	0.58, 0.97
Q3	515	188	1.59	1.19, 2.11	122	1.01	0.70, 1.45	330	0.70	0.55, 0.90
Q4	513	353	1.08	0.80, 1.45	100	1.53	0.99, 2.35	494	0.83	0.63, 1.10
Unknown	9	4	2.66	0.58, 12.18	1	2.24	0.35, 14.21	5	0.39	0.10, 1.54
p (trend)¶				0.06			0.18			0.44

* OR, odds ratio; CI, confidence interval; Q, quartile.

† Odds ratios were based on conditional logistic regression models and were adjusted for residential location, population density, and socioeconomic status of the community of residence.

‡ Distance from the nearest AM radio transmitter established before the subjects' year of diagnosis.

§ Because of the small number of cases, the odds ratio was infinite and the confidence interval was not calculable.

¶ Test for trend based on the corresponding continuous variable, excluding the "unknown" exposure category.

Calculated using the maximum adjusted radio-frequency radiation exposure estimate (E') for each radio transmitter (indexed by i) established before the subjects' year of diagnosis ($i = 1{\sim}{\leq}31$), using the equation $\sqrt{\sum(E_i{}^2)}$. Q1: <518.41 mV/m; Q2: 518.41–<624.35 mV/m; Q3: 624.35–<916.96 mV/m; Q4: ≥916.96 mV/m.

of 1,274 patients (66.1 percent) had acute lymphocytic leukemia, 362 (18.8 percent) had acute myelocytic leukemia, 70 (3.6 percent) had chronic myelocytic leukemia, and 118 (6.1 percent) had nonlymphocytic/nonmyelocytic leukemia. There were 26 and 78 patients with other types of lymphocytic and myelocytic leukemia, respectively. Childhood leukemia risks were higher in the communities with a low population density or a lower SES than in those with a medium/high density or a higher SES, but the differences were not statistically significant in the multivariate conditional logistic regression models including variables for residential location, population density, and community SES.

The brain cancers comprised astrocytoma (558 cases; 58.4 percent), embryonal tumor (209 cases; 21.9 percent), ependymoma (51 cases; 5.3 percent), oligodendroglioma (32 cases; 3.3 percent), and choroid plexus papilloma (one case; 0.1 percent) as neuroepithelial tumors and germ-cell tumor (49 cases; 5.1 percent) and other types of tumor (56 cases; 5.9 percent) as nonneuroepithelial tumors. Childhood brain cancer risks were similar in the different residential locations, regardless of population density or SES.

Total RFR exposure was highly correlated with peak RFR exposure (Spearman correlation coefficient: $r = 0.88$, $p < 0.001$); therefore, we only evaluated the association of total RFR exposure with leukemia or brain cancer. Total RFR exposure was also correlated with physical distance from the individual's residence to the nearest transmitter ($r = -0.79$, $p < 0.001$), and much of the agreement between the two metrics came from close correlation at the lower RFR level (figure 2).

A significantly higher risk of all types of leukemia was apparent among children residing within 2 km of the nearest AM radio transmitter established before the subjects' year of diagnosis, as compared with children who resided more than 20 km from it (odds ratio = 2.15, 95 percent confidence interval (CI): 1.00, 4.67) (table 2). However, there was no trend of increasing leukemia risk with decreasing distance from residential location to the nearest transmitter, regardless of pathologic type (p trend = 0.10). Total RFR exposure showed a borderline-significant positive trend with lymphocytic leukemia (table 2; p trend = 0.06) but not a linear dose-response relation (figure 3). The odds ratios for lymphocytic leukemia among children with total RFR exposure in the second and third quartiles were 1.39 (95 percent CI: 1.04, 1.86) and 1.59 (95 percent CI: 1.19, 2.11), respectively, in comparison with children in the first (lowest) quartile.

The risk of myelocytic leukemia showed no association with total RFR exposure or with distance from the nearest transmitter (table 2).

Childhood brain cancer risk was not related to decreasing distance or increasing total RFR exposure from all transmitters established before the subjects' year of diagnosis, regardless of pathologic type (table 3).

Cancer among infants (diagnosed at age less than 1 year) did not show any association with decreasing distance or increasing total RFR exposure, for both leukemia and brain cancer (table 4).

The risks of lymphocytic leukemia according to physical distance and total RFR exposure are illustrated in figure 3.
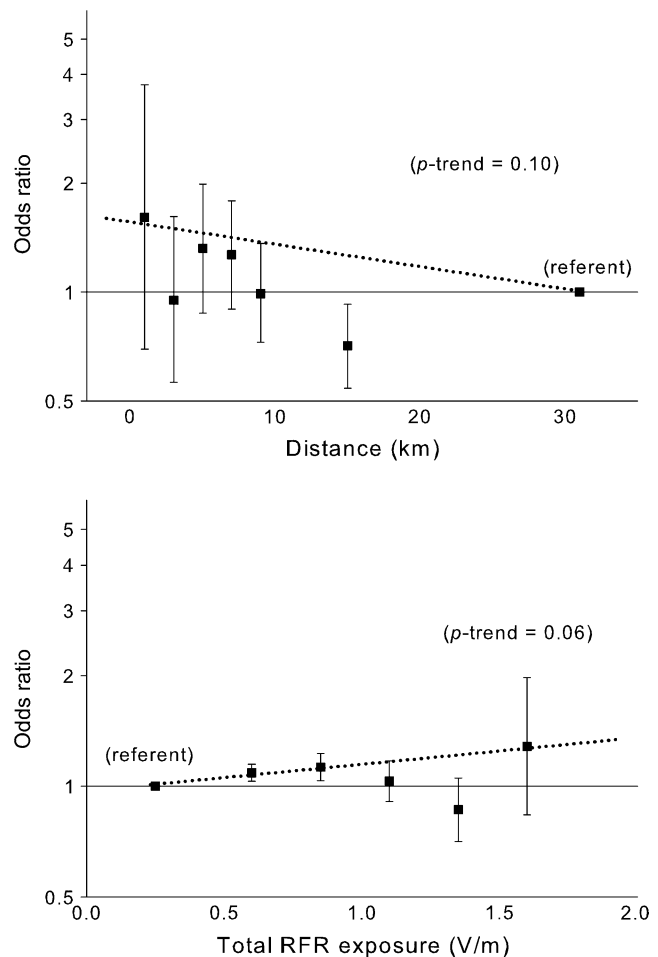
FIGURE 3. Conditional odds ratios for childhood lymphocytic leukemia according to residential distance from the nearest AM radio transmitter (top) and total radio-frequency radiation (RFR) exposure (bottom), South Korea, 1993–1999. Results were adjusted for residential location, population density, and socioeconomic status of the community of residence. Bars, 95% confidence interval.

DISCUSSION

In this study, there was an increased risk of lymphocytic leukemia among children with higher levels of exposure to RFR from AM radio broadcasting than among children with lower levels of exposure. The risk of childhood brain cancer did not appear to be associated with distance from the nearest AM radio transmitter or level of RFR exposure from AM transmitters. For cancer in infants (both leukemia and brain cancer), which might reflect a potential effect of RFR exposure incurred during gestation, there did not appear to be an association with physical distance or level of RFR exposure.

One of the strengths of this study was that individual RFR exposure was assessed using a newly developed prediction program designed for this study. This program covered RFR exposure from 31 AM broadcasting transmitters with a power of 20 kW or more that were established and operating before the subjects' birth. The program for predicting

TABLE 3.   Conditional odds ratios for childhood brain cancer according to radio-frequency radiation exposure from AM radio transmitters among children under age 15 years, South Korea, 1993–1999

	No. of controls	Neuroepithelial cancer			Nonneuroepithelial cancer			All brain cancer		
		No. of cases	OR*,†	95% CI*	No. of cases	OR†	95% CI	No. of cases	OR†	95% CI
Distance (km)‡										
≤2	4	8	1.17	0.30, 4.63	2	—§		10	1.42	0.38, 5.28
>2–4	27	28	1.29	0.68, 2.45	4	1.62	0.09, 28.02	32	1.40	0.77, 2.56
>4–6	89	52	1.00	0.63, 1.57	7	2.32	0.36, 15.01	59	1.02	0.66, 1.57
>6–8	100	80	1.00	0.67, 1.50	10	4.79	0.75, 30.71	90	1.08	0.73, 1.59
>8–10	160	105	0.96	0.67, 1.38	9	0.55	0.14, 2.17	114	0.94	0.67, 1.33
>10–20	282	215	1.02	0.76, 1.37	29	0.78	0.23, 2.58	244	1.01	0.77, 1.34
>20	354	356	1.00	Referent	44	1.00	Referent	400	1.00	Referent
Unknown	2	7	4.46	0.52, 38.26	0	—		7	4.30	0.50, 36.73
p (trend)¶				0.65			0.37			0.76
Total radio-frequency radiation exposure (mV/m)#										
Q1*	256	288	1.00	Referent	41	1.00	Referent	329	1.00	Referent
Q2	254	163	0.62	0.44, 0.89	22	0.74	0.17, 3.30	185	0.66	0.47, 0.92
Q3	254	164	0.74	0.52, 1.06	17	0.54	0.12, 2.43	181	0.72	0.51, 1.01
Q4	254	229	0.71	0.48, 1.03	25	1.60	0.37, 6.85	254	0.77	0.54, 1.10
Unknown	2	7	3.67	0.43, 31.13	0	—		7	3.56	0.42, 30.17
p (trend)¶				0.79			0.13			0.73

* OR, odds ratio; CI, confidence interval; Q, quartile.

† Odds ratios were based on conditional logistic regression models and were adjusted for residential location, population density, and socioeconomic status of the community of residence.

‡ Distance from the nearest AM radio transmitter established before the subjects' year of diagnosis.

§ Because of small numbers of cases, odds ratios were infinite and confidence intervals were not calculable.

¶ Test for trend based on the corresponding continuous variable, excluding the "unknown" exposure category.

Calculated using the maximum adjusted radio-frequency radiation exposure estimate (E') for each radio transmitter (indexed by i) established before the subjects' year of diagnosis ($i = 1–\leq31$), using the equation $\sqrt{\sum(E_i'^2)}$. Q1: <532.55 mV/m; Q2: 532.55–<622.91 mV/m; Q3: 622.91–<881.07 mV/m; Q4: ≥881.07 mV/m.

the level of RFR exposure from AM broadcasting transmitters was based on the "flat-earth attenuation" model (15) and was validated and corrected by actual measurements. Most previous epidemiologic studies on the effect of exposure from television or frequency modulation broadcasting antennas used only distance as a proxy measure of RFR exposure (3–13).

Furthermore, two types of RFR exposure from AM radio transmitters were estimated: peak RFR exposure and total RFR exposure. Since there has not been an established plausible biologic mechanism for interpreting the association between RFR exposure and childhood cancer, the use of different metrics for RFR exposure could provide different findings regarding a potential mechanism. In this study, total RFR exposure seemed more likely to be associated with childhood leukemia than peak RFR exposure, possibly suggesting that RFR exposure acts as a promoter rather than an initiator of the carcinogenic process.

The number of childhood cancer patients in this study was large enough to produce moderate statistical power for detecting an effect of RFR exposure from AM transmitters. The number of cases in previous studies was small, ranging from 1 to 123 (1). To our knowledge, the present study is the largest study related to this topic to date.

Besides the matching variables (age at diagnosis, sex, and year of diagnosis), all risk estimates were adjusted for potential confounders of childhood cancer, such as residential location, SES, and population density of the community of residence.

Twenty-nine of the 31 target radio towers were established and initiated between 1925 and 1980; the rest were established in 1991 and 1995. Therefore, the children in this study—who were born in 1988, on average (range, 1978–1999)—should have had a sufficient latency period for any cancer due to AM RFR exposure to develop.

Although two reanalyses of previous studies could not confirm their findings of a positive association (3, 10), most epidemiologic studies on television and radio transmitters have found an increased risk of lymphocytic leukemia in adults (4, 22) and children (8, 9, 11, 23) residing near these towers, a decreasing risk in both adults (3) and children (11, 24), or no association in children (3) with increasing distance from the towers. The sizes of the reported odds ratios for childhood leukemia were 2.0 (95 percent CI: 0.1, 8.3) for children living within 2.6 miles (4.2 km) of a radio tower (9) and 2.2 (95 percent CI: 1.0, 4.1) for children living within 6 km of a radio tower (11). In another study, Hocking et al. (8) reported odds ratios of 1.6 (95 percent CI: 1.1, 2.3) for all

TABLE 4. Conditional odds ratios for leukemia and brain cancer in infants according to radio-frequency radiation exposure from AM radio transmitters, South Korea, 1993–1999

	Leukemia cases						Brain cancer cases						
	No. of controls	Lymphocytic			All			No. of controls	Neuroepithelial			All		
		No.	OR*,†	95% CI*	No.	OR†	95% CI		No.	OR†	95% CI	No.	OR†	95% CI
Distance (km)‡														
≤10	25	12	1.06	0.28, 3.99	20	1.29	0.47, 3.56	20	8	0.28	0.03, 2.99	10	0.41	0.05, 3.10
>10–20	20	11	1.36	0.21, 8.74	19	1.47	0.51, 4.24	11	7	0.72	0.07, 7.20	10	0.49	0.06, 3.80
>20	18	15	1.00	Referent	20	1.00	Referent	13	11	1.00	Referent	12	1.00	Referent
p (trend)§				0.99			1.00				0.46			0.78
Total radio-frequency radiation exposure (mV/m)¶														
Q1*	15	19	1.00	Referent	24	1.00	Referent	11	6	1.00	Referent	9	1.00	Referent
Q2	16	6	0.33	0.05, 2.30	10	0.47	0.14, 1.59	11	5	2.85	0.22, 37.32	7	3.56	0.49, 25.95
Q3	16	4	0.94	0.19, 4.72	10	0.62	0.17, 2.24	11	6	0.87	0.03, 27.22	7	1.41	0.12, 17.11
Q4	16	9	0.75	0.19, 2.95	15	0.83	0.27, 2.53	11	9	8.51	0.32, 224.36	9	5.13	0.44, 60.26
p (trend)§				0.98			0.65				0.20			0.27

* OR, odds ratio; CI, confidence interval; Q, quartile.

† Odds ratios were based on conditional logistic regression models and were adjusted for residential location, population density, and socioeconomic status of the community of residence.

‡ Distance from the nearest AM radio transmitter established before the subjects' year of diagnosis.

§ Test for trend based on the corresponding continuous variable.

¶ Calculated using the maximum adjusted radio-frequency radiation exposure estimate (E') for each radio transmitter (indexed by i) established before the subjects' year of diagnosis ($i = 1–\leq31$), using the equation $\sqrt{\sum(E_i'^2)}$. Quartile cutpoints for leukemia—Q1: <528.67 mV/m; Q2: 528.67–<646.43 mV/m; Q3: 646.43–<1,002.83 mV/m; Q4: ≥1,002.83 mV/m. Quartile cutpoints for brain cancer—Q1: <485.85 mV/m; Q2: 485.85–<632.96 mV/m; Q3: 632.96–<810.81 mV/m; Q4: ≥810.81 mV/m.

leukemia, 1.6 (95 percent CI: 1.0, 2.4) for lymphatic leukemia, and 1.7 (95 percent CI: 0.6, 4.8) for myeloid leukemia among children living within 4 km of a transmitter. Within 2 km of a transmitter, odds ratios for childhood leukemia were found to be 1.1 (95 percent CI: 0.6, 2.0) (3) and 1.1 (95 percent CI: 0.0, 6.3) (23). McKenzie et al. (10) used a continuous exposure unit of $\mu W/cm^2$ and reported an odds ratio for childhood leukemia of 0.9 (95 percent CI: 0.6, 1.4). Although it is difficult to directly compare risk magnitudes between studies because of the heterogeneity of referent groups among the studies, we found that odds ratios among children who lived within 2 km of the nearest tower were 1.60 (95 percent CI: 0.69, 3.72) and 2.15 (95 percent CI: 1.00, 4.67) for lymphocytic leukemia and all types of leukemia, respectively (table 2). A decreasing risk of lymphocytic leukemia with increasing inverted quadratic distance, which was suggested by a study recently performed in Italy (11), was not replicated in this study. As figure 2 shows, the correlation between physical distance and estimated RFR exposure obtained using the prediction program was mainly due to agreement at lower levels of RFR exposure. Therefore, the estimated risk for physical distance might be more sensitive to misclassification of exposure at smaller distances.

To our knowledge, there has been no previously published study on the association between infant cancer and prenatal RFR exposure or the association between childhood brain tumors and RFR exposure from television or radio transmitters. This study could not provide evidence for an association between RFR exposure during pregnancy and cancer in infants, possibly because of the lack of power.

Limitations of previous studies included limited sample sizes, lack of information on exposure, short follow-up periods, and limited ability to deal with potential confounders (24). Although there is concern regarding a possible carcinogenic effect of RFR below the levels that cause detectably harmful heating of tissues, experimental studies on a possible biologic mechanism to support a tumorigenic effect from RFR have not provided any convincing evidence (25–27).

This study had some limitations. The exposure estimates calculated by our prediction program mainly depended on the function of distance, as well as the ground characteristics and characteristics of the transmitting antennas, such as radiation frequency, power, radiation pattern, gain, and height. However, it did not consider the existence of buildings or irregular geographic features (e.g., mountains), which could block the radiation and reflect it. Therefore, our exposure estimates might have differed from the actual levels of exposure. Furthermore, because there was no detailed information on residential history, cumulative historical RFR exposure from AM transmitters was not taken into account. The setting of this study did not allow any speculation regarding RFR exposure during pregnancy. Finally, this study did not consider other sources of RFR exposure, particularly mobile telephones or their base stations. However, mobile telephones have only been widely used in South Korea since the late 1990s. Therefore, this source might not have made a significant contribution to overall RFR exposure among children in this study.

The results of this study suggest a possible carcinogenic effect of AM RFR exposure on children, particularly with regard to lymphocytic leukemia. More studies will be needed to confirm this finding using a validated RFR exposure metric, as well as to elucidate possible biologic mechanisms. Furthermore, prospective studies with long-term birth cohorts will be needed to investigate the effect of fetal exposure to RFR.

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