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A Nation-Wide Survey on Indoor Radon from 2007 to 2010 in Japan

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^{222}Rn/Building type/Structural materials/Building age/Population-weighted mean.

In two previous nation-wide surveys in the late 1980s and early 1990s, Japanese indoor radon concentrations increased in homes built after the mid 1970s. In order to ascertain whether this trend continued, a nation-wide survey was conducted from 2007 to 2010. In total 3,900 houses were allocated to 47 prefectures by the Neyman allocation method and 3,461 radon measurements were performed (88.7% success). The fraction of reinforced concrete / concrete block buildings was 32.4%, similar to the value from national statistics. Arithmetic mean (standard deviation, SD) and geometric mean (geometric SD) of radon concentration after adjusting for seasonal fluctuation were 14.3 (14.7) and 10.8 (2.1) Bq/m^3. The corresponding population-weighted values were 13.7 (12.3) and 10.4 (2.0) Bq/m^3, respectively. It was estimated that only 0.1% of dwellings exceed 100 Bq/m^3, a new WHO reference level for indoor radon. Radon concentrations were highest in houses constructed in the mid 1980s and decreased thereafter. In conclusion, arithmetic mean indoor radon in the present survey was slightly lower than in previous surveys and significant reductions in indoor radon concentrations in both wooden and concrete houses can be attributed to alterations in Japanese housing styles in recent decades.

INTRODUCTION

Indoor radon is the primary source of radiation exposure among the general population throughout the world.[1)] Although radon has been known to be a risk factor for lung cancer in miners, its impact on public health was not directly estimated in the 20th century.[2)] Recently, pooled analyses of lung cancer case-control studies conducted in North America,[3)] Europe,[4)] and China[5)] have demonstrated that radon in dwellings is indeed a risk factor for lung cancer. These new data prompted the World Health Organization (WHO) to issue a new guideline for indoor radon in 2009 and revise the reference level.[6)]

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In Japan, nation-wide radon surveys were conducted in the late 1980s and early 1990s.[7,8)] In the former survey radon concentrations were measured in about 5,700 dwellings using a passive radon detector that could not discriminate radon (^{222}Rn) from thoron (^{220}Rn),[9,10)] while in the latter survey a total of 899 dwellings, about 20 in each prefecture, were measured using a passive radon-thoron discriminating device.[8)] According to those studies, radon concentrations in Japanese dwellings were considered to be low, so the Japanese government did not regulate indoor radon levels. However, there was concern that radon levels in Japanese dwellings might increase because of changes in housing styles and construction materials in recent years; these changed dramatically from the traditional Japanese wood-and-paper house to modern wooden homes or reinforced concrete buildings. Such modern homes are generally characterized by improved air-tightness and decreased natural ventilation. Fujimoto and Sanada reported that average indoor radon concentrations in concrete houses increased with year of construction.[11)] In Japan, the average life of wooden houses was about 30 years. If Fujimoto and Sanada's observation was valid in newly constructed homes in the 1990s and 2000s, it was hypothesized that the alteration in Japanese housing styles and construction materials might be associated with an increase in radon concentrations in dwellings in Japan. If this assumption was correct, it was critical for Japanese government to know the fraction of homes where indoor radon levels exceeded a new reference level of 100 Bq/m^3. In the present study, we utilized passive radon-thoron discriminating devices for measuring ^{222}Rn in 3,900 homes across the country and conducted a questionnaire survey to determine housing style, construction materials, ventilation status, and other pertinent factors.

MATERIALS AND METHODS

Sampling and allocation

Volunteers willing to have radon measured in their homes were recruited through public health offices and academic associations. A total of 3,900 homes were selected and the number of homes in each prefecture was allocated by the Neyman allocation method[12)] utilizing the SD of radon concentrations in each prefecture that had been obtained in a former survey by Fujimoto *et al.*[7)] Neyman allocation was utilized to reduce the variance in population-weighted radon concentration. Then, the fraction of selected concrete buildings in each prefecture was adjusted to be proportional to national statistics as of 2003 that was the latest statistics.

In the Neyman allocation method, the number of volunteers in each prefecture (n_j) is calculated by a formula,

$$\frac{n_j}{n} \fallingdotseq \frac{N_j S_j}{\sum_{m=1}^{m=k} N_m S_m}$$

where n is a total size of samples, *i.e.*, 3900, N_j and S_j are the population of prefecture j, and prefecture-specific SD of radon measurements, respectively, and k is a total number of prefectures. In the Fujimoto's study, a radon detector utilized could not discriminate radon from thoron. Thus prefecture-specific SD reflected not only variance in radon measurements but also variance in thoron measurements. It was plausible that allocated numbers of volunteers in some prefectures were larger because of the larger thoron influence. Since the major source of thoron in Japanese houses was soil-plaster and because Japanese houses with soil-plaster were relatively enriched in local prefectures where population size was small, using SD in the first survey would not bias prefecture-specific mean of indoor radon concentrations. An increment in the allocated numbers in such prefectures would result in a decrease in variance in radon measurements.

Radon measurement

Radon-thoron discriminating devices were purchased from RadoSys Ltd. (Budapest, Hungary), which were recognized as a suitable detector for a large scale survey.[13)] Devices were set for 6 months from March to August or from September to February and placed either in a living room or bedroom. The present nation-wide survey began in September 2007 and ended in February 2010. After measurement, the devices were sealed and sent to our institute by mail. Films in recovered devices were etched and counted by an automated track counting microscope (RadoMeter 2000, RadoSys Ltd.) according to the manufacturer's instructions at the Japan Chemical Analysis Center, Chiba, Japan. The radon-thoron discriminating devices used in each cycle were calibrated in the ^{222}Rn reference chamber of the National Institute of Radiological Sciences (NIRS), Chiba, Japan.[14)]

Coefficients for adjusting seasonal fluctuation

Supposing the shape of log-normal distribution of indoor radon measurements in the March-August period was similar to the corresponding shape in the September-February period after parallel translation, seasonal coefficients were calculated so as to make the mean of logarithmic transformed radon concentrations equal in both periods. Let x_i and y_i be logarithmic transformed indoor radon measurement in an individual home from March to August and from September to February, respectively, and x_m and y_m be the mean of logarithmic transformed indoor radon measurements in the March to August period and the September to February period, respectively, individual logarithmic transformed indoor radon concentration after adjusting seasonal fluctuation were calculated as follows: $(x_i + (y_m - x_m)/2)$ for the March to August period and $(y_i - (y_m - x_m)/2)$ for the September to February period. Seasonal coefficients in linear term were expressed as $e^{(ym-xm)/2}$ and $e^{-(ym-xm)/2}$ for measurements in the March to August period and the September to February period, respectively.

Questionnaire

A self-administered questionnaire with 26 items was administered to obtain information about the room where the device was set, building materials and styles, construction year, frequency of natural ventilation, and type of mechanical ventilation. Respondents to questionnaire were either master or housewife.

Ethical consideration

This research protocol was reviewed and approved by the Ethical Committee for Epidemiological Research in the National Institute of Public Health (NIPH-IBRA#07009).

Statistical analyses

Statistical significance was assessed according to the indicated tests using SPSS version 15 (SPSS Japan Inc. Tokyo, Japan). A p value less than 0.05 was considered to be statistically significant.

RESULTS

Houses

A total of 3,900 volunteers was selected across Japan according to the allocation strategy mentioned above and

3,461 radon measurements (88.7%) were successfully performed. There were 1,781 wooden houses, 213 two-by-four wooden houses, 266 prefabricated wooden houses (either steel-framed or wood-framed), 1,086 reinforced concrete buildings, 35 concrete block houses, 51 other types of houses, and 29 houses of unknown type (Table 1). The fraction of reinforced concrete buildings and concrete block houses in the present study was 32.4%, nearly equal to the fraction of reinforced concrete buildings in the national statistics "Dwellings by construction materials (5 groups)" in 2003 (31.9%). These features ensure that the present results are representative of radon concentrations in Japanese dwellings. In the following analyses, wooden houses, two-by-four wooden houses, and prefabricated houses were treated as a single category "wooden houses" and reinforced concrete buildings and concrete block houses as the category "concrete houses" for simplicity.

Table 1. The distribution of main characteristics

		March-August period	September -February period	Total
Building materials	Wooden / prefabricated houses	1063	1197	2260
	Reinforced concrete buildings / concrete block houses	515	606	1121
	Others	31	20	51
	Unknown types	15	14	29
	Subtotal	1624	1837	3461
Year of measurements	2007	0	810	810
	2008	826	472	826
	2009	798	555	472
	Subtotal	1624	1837	3461

Distribution of radon concentrations in dwellings

As shown in Fig. 1, the distribution of logarithmic transformed radon concentrations in concrete houses was compatible with a normal distribution (one-sample Kolmogorov-Smirnov test z = 0.675, p = 0.752), while in wooden houses it was marginally compatible with a normal distribution (one-sample Kolmogorov-Smirnov test z = 1.355, p = 0.051). Departure from linearity (lack of correspondence between the observed distribution and a normal distribution) in the latter was observed primarily in areas with less than 3 Bq/m^3, the lower detection limit of the passive radon-thoron discriminating device. Thus, the distribution of radon in Japanese houses closely follows a log- normal distribution if very low values are ignored.

Seasonal fluctuation

In the present study, radon detectors were set from March to August or from September to February. As shown in Table 2 (upper part), indoor radon concentrations were lower in the March-August period than in the September-February period. It is well known that outdoor and indoor radon concentrations are relatively higher in winter and lower in summer.[15,16] Distributions of possible radon modifying factors such as construction years and building materials were not statistically different between the March to August period and the September to February period by a multinomial logistic regression model (data not shown). To adjust for seasonal fluctuation, seasonal coefficients were calculated separately for wooden houses and concrete houses as mentioned in the Material and Methods, because the levels of indoor radon were significantly higher in concrete houses than in

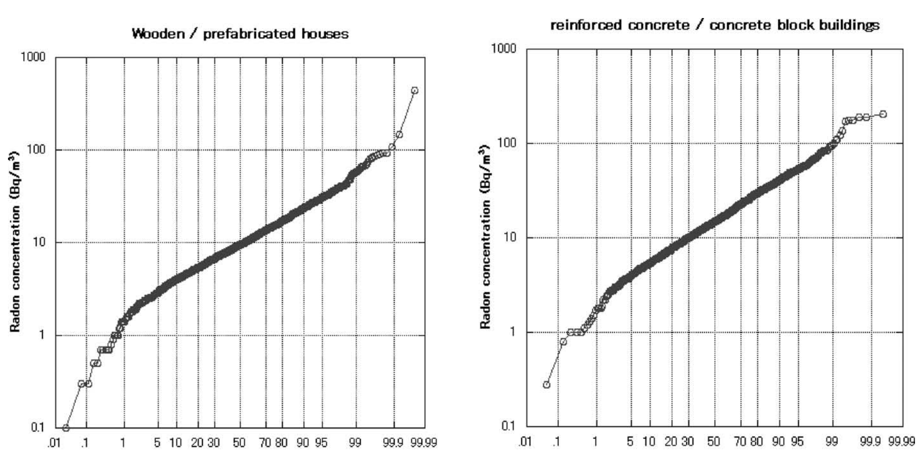

Fig. 1. Cumulative frequency distribution of ^{222}Rn concentrations in dwellings versus that of a standard normal distribution. (Left) Wooden / prefabricated wooden houses (one-sample Kolmogorov-Smirnov test, z = 1.355, p = 0.051); (Right) reinforced concrete buildings and concrete block houses (one-sample Kolmogorov-Smirnov test, z = 0.675, p = 0.752).

Table 2. Seasonal fluctuation of indoor radon concentrations

		ln radon concentration (Bq/m^3)§	
		March-August	September-February
Before adjustment	All dwellings	2.07 ± 0.73 (n = 1624)	2.69 ± 0.72 (n = 1837)
	Wooden / prefabricated houses	1.91 ± 0.66 (n = 1063)	2.56 ± 0.647 (n = 1197)
	Reinforced concrete buildings / concrete block houses	2.40 ± 0.77 (n = 515)	2.95 ± 0.77 (n = 606)
	Others	1.87 ± 0.50 (n = 31)	2.48 ± 0.59 (n = 20)
	Unknown types	2.16 ± 0.55 (n = 15)	3.16 ± 0.96 (n = 14)
After adjustment	All dwellings	2.38 ± 0.72 (n = 1624)	2.38 ± 0.72 (n = 1837)
	Wooden / prefabricated houses	2.24 ± 0.66 (n = 1063)	2.23 ± 0.65 (n = 1197)
	Reinforced concrete buildings / concrete block houses	2.67 ± 0.77 (n = 515)	2.67 ± 0.77 (n = 606)
	Others	2.20 ± 0.50 (n = 31)	2.15 ± 0.59 (n = 20)
	Unknown types	2.49 ± 0.55 (n = 15)	2.82 ± 0.96 (n = 14)

§ Logarithmic-transformed indoor radon concentrations are shown with (lower panel) or without (upper panel) adjustment for seasonal fluctuation.

wooden houses ($p < 0.001$ by a two-tailed Student t-test). For other (n = 51) and unknown (n = 29) types of houses, the seasonal adjustment for wooden houses was applied. As shown in Table 1 (lower part), these adjustments performed well.

Table 3. Indoor radon concentrations in Japan

	Radon concentration (Bq/m^3)§			
	Arithmetic mean	SD	Geometric mean	GSD
Raw data	15.2	17.0	11.0	2.2
After adjusting seasonal fluctuation	14.3	14.7	10.8	2.1
Population-weighted values†	13.7	12.3	10.4	2.0

§ Indoor radon concentrations are shown as raw data, i.e., before adjusting seasonal fluctuation, or processed data after adjusting seasonal fluctuation with or without weighting by population density.

† Population-weighted values were calculated using the arithmetic means or geometric means of prefectures and their populations in 2003.

Indoor radon concentrations in Japan

Table 3 shows a summary of radon concentrations. Arithmetic mean (SD) and geometric mean (GSD) of indoor radon concentrations after adjusting for seasonal fluctuation were 14.3 (14.7) and 10.8 (2.1) Bq/m^3, respectively, and the arithmetic mean was slightly lower than the value 15.5 (13.5) Bq/m^3 reported by Sanada.[8)] The population-weighted arithmetic mean (SD) and geometric mean (GSD) were 13.7 (12.3) and 10.4 (2.0) Bq/m^3, respectively. Population-weighted mean was calculated on the basis of prefecture-specific values averaged over all prefectures with weights of number of populations in each prefecture. The number of populations in each prefecture was from population statistics in 2003. The present study is the first to report population-weighted mean indoor radon concentrations in Japan obtained by nation-wide survey.

Figure 2 depicts box-and-whisker plots of indoor radon concentrations after adjusting for seasonal fluctuation in each prefecture. The top five prefectures in terms of arith-

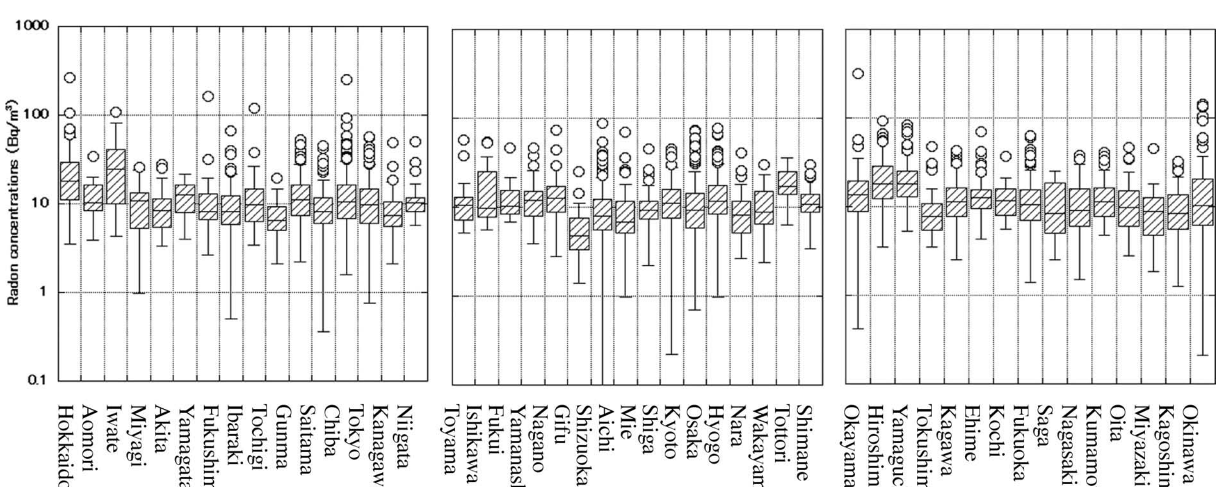

Fig. 2. Box-and-whisker plots of indoor radon concentrations within prefectures. Indoor radon concentrations in each prefecture are depicted after adjusting for seasonal fluctuation.

metic mean (SD) were Iwate (29.8 (25.5) Bq/m^3), Hokkaido (24.7 (28.7) Bq/m^3), Yamaguchi (22.8 (16.2) Bq/m^3), Okinawa (22.8 (33.4) Bq/m^3), and Hiroshima (21.9 (13.3) Bq/m^3). The top five prefectures in terms of geometric mean (GSD) were Iwate (21.0 (2.4) Bq/m^3), Yamaguchi (19.0 (1.8) Bq/m^3), Hiroshima (18.6 (1.8) Bq/m^3), Hokkaido (18.4 (2.1) Bq/m^3) and Tottori (17.5 (1.6) Bq/m^3).

Supposing indoor radon concentrations follow a log-normal distribution, the fraction of dwellings in which indoor radon levels would exceed the WHO reference level of 100 Bq/m^3 was estimated; only 0.1% of homes in Japan were estimated to have indoor radon levels that exceed the reference level. The fractions exceeding the reference were estimated to be 3.8, 3.3, and 0.9% in Iwate, Okinawa, and Hokkaido, respectively.

Table 4. Effects of construction years on indoor radon concentrations

		ln radon concentration (Bq/m^3)		
Type of house	Construction-year category	N	mean	SD
All combined	2003 and after	505	2.16	0.75
	1999–2002	393	2.3*	0.75
	1995–1998	510	2.36***	0.77
	1992–1994	316	2.32*	0.65
	1988–1991	440	2.43***	0.75
	1982–1987	394	2.54***	0.69
	1974–1981	451	2.47***	0.66
	1973 and before	394	2.46***	0.64
Wooden / prefabricated wooden houses	2003 and after	270	1.92	0.67
	1999–2002	248	2.12***	0.63
	1995–1998	318	2.15***	0.71
	1992–1994	224	2.18***	0.56
	1988–1991	285	2.25***	0.67
	1982–1987	278	2.4***	0.6
	1974–1981	299	2.37***	0.59
	1973 and before	313	2.43***	0.61
Reinforced concrete / concrete block buildings	2003 and after	218	2.46	0.71
	1999–2002	139	2.62	0.85
	1995–1998	186	2.74**	0.75
	1992–1994	81	2.72	0.7
	1988–1991	137	2.78**	0.79
	1982–1987	110	2.92***	0.77
	1974–1981	144	2.68	0.75
	1973 and before	78	2.56	0.77

Data were analyzed by one-way ANOVA; if there was significant heterogeneity, construction-year category 2003 and after was compared with each of the others using a 2-sided Dunnett-t test. *p < 0.05, **p < 0.005, ***p < 0.001.

Alteration of indoor radon by year of construction

Because indoor radon concentrations in the present study were lower than those in the former surveys,[7,8] radon levels were analyzed by broadly categorizing homes into either wooden or concrete structures and by number of years since they were built. The building code in Japan was revised in 2003 to prevent so called “sick building” or “sick house” syndromes associated with volatile chemicals released from building materials. Thus we defined the latest year category to be from 2003, which represents about the 12.5th percentile of samples. As shown in Table 4, indoor radon concentrations in eight construction-year categories, if treated as continuous variables, were positively associated with number of years since construction (Pearson correlation = 0.14, $p < 0.001$ for all samples). The correlation was more pronounced in wooden houses (Pearson correlation = 0.239, $p < 0.001$) than in concrete houses (Pearson correlation = 0.093, $p < 0.001$). Treating construction-year category as a categorical variable, we analyzed whether indoor radon concentrations differed among categories. Indoor radon concentrations in all dwellings, in wooden houses, and in concrete houses showed significant heterogeneity with construction-year category ($p < 0.001$ by a one-way ANOVA test) and there was a small peak in radon levels during the 1982 to 1987 category. Indoor radon concentrations in the category beginning 2003 in wooden houses were significantly lower than those in all other construction-year categories ($p < 0.001$, by a 2-sided Dunnett t test), while in concrete houses it was also lower but less significant (Table 4). These results demonstrate that modern Japanese wooden houses are more resistant to radon than older wooden houses and this was a major force in reducing indoor radon concentrations in Japan.

DISCUSSION

A nation-wide indoor radon survey was conducted from 2007 to 2010 using a passive radon-thoron discriminating device. After adjusting for seasonal fluctuations, arithmetic mean ± SD of radon concentration was 14.3 ± 14.7 Bq/m^3, slightly lower than the value 15.5 ± 13.5 Bq/m^3 previously reported by the NIRS.[8] This difference did not seem to be due to random error but rather was caused—at least in part—by an incremental increase in radon resistance of Japanese houses. The population-weighted mean concentration in Japan was also calculated for the first time. Japanese mean indoor radon concentration was third from the bottom among 29 OECD countries for which radon levels have been published.[6]

In the present study, we calculated seasonal coefficients under the supposition that the shape of log-normal distribution of indoor radon concentrations in the March-August period was similar to the corresponding shape in the September-February period after parallel translation. More sophisticated mathematical methods were proposed based on measurements in UK[17] or Austria.[18] However, it was not clear whether mathematical methods using country-specific coefficients were usable for Japanese homes. Thus, we utilized empirical seasonal coefficients in the present study.

Epidemiologic studies on miners have established radon gas as a human carcinogen.[2,19] However, it is debatable whether radon risk can be extrapolated from the very high radon environments in mines to the low to moderate radon levels in homes.[20–22] Recently, pooled analyses of case-control studies on radon and lung cancer were conducted in North America, Europe, and China.[3–5] Those studies definitively demonstrated that indoor radon is a risk factor for lung cancer. The WHO issued indoor radon concentration guidelines in 2009 and a new reference level of 100 Bq/m^3 was set for minimizing indoor radon risk.[6] Supposing logarithmic transformed radon concentrations follow a normal distribution in Japanese homes, we estimated the fraction of houses for which radon concentrations would exceed the WHO reference level of 100 Bq/m^3. Overall, only 0.1% of houses in Japan were estimated to exceed this reference level. In Iwate and Okinawa prefectures the estimates were more than 3%, but we interpret these values with caution because our survey was not intended to make a precise radon map and thus it is difficult to clearly demonstrate "radon-prone" areas in those prefectures. Further studies are needed to clarify this issue.

Indoor radon may be affected by many factors, including long-term climate change, seasonal climate changes, type of housing, construction materials, air-tightness, ventilation rate, type of ventilation, and year of construction. In the past two or three decades, Japanese housing styles changed from traditional wood-and-paper construction with high natural ventilation to modern wooden homes equipped with aluminum sashes, large plywood and other panels, and low natural ventilation in the crawl space under the floor. These new features were associated with increased air-tightness and reduced energy consumption for heating and cooling. In addition, the fraction of reinforced concrete buildings increased since the 1970s and was around 30% since 1993. Because the Japanese government has not regulated indoor radon, these new features might be thought to favor higher accumulation of radon in dwellings as predicted by Fujimoto.[11] However, as shown in Table 4, the more recent the construction year, the lower the radon concentration.

There was a small peak in radon levels in both wooden houses and concrete houses during the construction-year period 1982–1987. This increase in indoor radon in the mid 1980s, though the reason is not known, is compatible with an observation by Fujimoto.[11] Ito and Asano reported that the usage of phosphor-gypsum plaster boards as a fire-resistant building material seemed to be decreasing in the mid 1970s and gypsum plaster boards in the 1980s contained little ^{226}Ra-radioactivity[23] (phosphor-gypsum plasters contain ^{226}Ra and emit ^{222}Rn). Thus, the increase in indoor radon in the mid 1980s could not be due to phosphor-gypsum plaster boards. Indoor radon is influenced by natural and artificial ventilations. The frequency of natural ventilation was higher in the March to August period than in the September to February period, which was at least in part a reason for seasonal fluctuation (data not shown). Whether the frequency of natural ventilation altered during last two decades was not known. On the contrary, the fraction of homes equipped with any kinds of artificial ventilations increased steadily from 23.6% in the construction-year category 1982–1987 to 35.1% in the construction-year category 1999–2002 and finally to 60.3% in the construction-year category 2003 and after in the present study. The rate of reduction in radon concentrations occurred mostly in the final construction-year category, 2003 and after. It is interesting that a new building code was implemented in Japan in 2003 to prevent the so called "sick house syndrome" associated with the release of volatile chemicals from building materials. As a result of this code, contractors must design houses or buildings with the required ventilation rate to reduce levels of formaldehyde. We believe that this regulation was also effective in reducing indoor radon concentrations. It may be argued that aged houses might have more cracks in the floor through which radon gas could infiltrate from soil. However, this may not be the sole reason because radon levels in houses built before 1982 were lower than those built in the mid 1980s. In the future we will report an analysis of factors associated with logarithmic transformed indoor radon concentrations by multivariate regression analyses, such as season, building material, building style, ventilation frequency and type of ventilation system (Yamaguchi *et al*., manuscript in preparation).

In the present study, about 11% of samples could not be measured. Major reason for "unsuccessful measurements" was volunteers' refusal in measuring indoor radon because other family members were reluctant to do so. Other minor reasons were the accidental destruction of radon-thoron discriminating device, forgetting to unpack device, movement, and failure in returning a device before deadline. Since indoor radon was not a public concern in Japan, refusal rate may not be altered by the levels of indoor radon. Thus, about 11% of "unsuccessful measurements" would not cause serious bias.

Finally, we considered whether the method of selecting homes imposed any limitations on our assessment of mean indoor radon concentration in Japan. Because radon risk has not been recognized as a public health threat in Japan, and thus radon mitigation has not been conducted, the method of selecting homes should not cause a large bias in estimating indoor radon concentration due to concerns about radon prompting subjects to volunteer. However, volunteers identified through public health offices and academic associations might have higher incomes and live in newer homes than the average Japanese. This might bias mean indoor radon concentration towards lower levels. Such bias would not be peculiar to the present study since previous nationwide studies also recruited volunteers from public health offices and academic or educational societies.

In conclusion, it is clear that indoor radon concentrations in Japan have not increased in recent years.

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