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Indoor Radon Concentrations in Homes of Sichuan Residents and the Dose to the Population Exposed to Radon and its Daughters

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Abstract

This paper presents the results of indoor radon surveys in the Sichuan province of China. The indoor radon concentrations found using scintillation or the two-filter method, ranged from 1.0 Bqm^{-3} to 170.2 Bqm^{-3}. The arithmetic mean concentrations of indoor radon and its progeny were 17.8 Bqm^{-3} and 10.8 Bqm^{-3} EER (2.9 mWL), respectively. A seasonal pattern of the maximum in winter and the minimum in summer was observed for radon and its progeny concentrations. The annual effective dose equivalent resulting from indoor and outdoor inhalation of radon progeny totalled 0.93 mSv. Of the 109 million people living in Sichuan, 3000-6800 may die annually from lung cancer induced by the inhalation of radon progeny.

KEY WORDS:
Radon, Radon progeny, Indoor, Survey, Dose.

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Introduction

The hazards of radon are well known. It is one of the carcinogens listed by the World Health Organization (WHO). The International Agency for Research on Cancer (IARC) has also emphasized the carcinogenicity of radon and its progeny (IARC, 1988). The U.S.Environmental Protection Agency announced that radon has the highest carcinogenic risk among all environmental problems (USEPA, 1987a, 1987b). The Sichuan province of China has a population of 109 million, and a varied topography and geomorphology. From the end of 1988 to the end of 1989 we monitored the indoor and outdoor radon concentrations in 195 counties involving 1967 houses in Sichuan. We also measured the radon concentrations in mines, railway tunnels, and underground buildings. On the basis of the data accumulated, we estimated the effective dose equivalent of the population exposed to radon and its progeny.

Survey of Sichuan Geography and Dot Design

Geographical Survey

Sichuan is located in south-western China and has an area of 570 000 km^2. According to geomorphological characteristics, the whole province can be divided into four areas, i.e., the Sichuan basin, the hilly regions around the basin, the Sichuan south-western mountainous regions, and the Sichuan western plateau. Within the boundaries of Sichuan, flatlands cover 2.5%; hills cover 18.7%; and mountainous regions and plateaus cover the rest. Over 93% of the population live in the basin area and the eastern part.

Dot Design

A total of 1967 radon samples and 1239 radon progeny samples were taken in the whole province. The following are the principles considered in the dot design.

Population density. The population factor was mainly considered in dot design: more samples were taken in densely populated cities (about one sample per 25 000-30 000 persons) and fewer samples in sparsely populated areas.

Topography and geomorphology. Varied topography and geomorphology were considered in dot design, e.g., samples were taken in mountains, on plains, hills and grasslands, etc.

Building materials. Different content of Uranium-238 in different building materials directly affects indoor radon concentrations. The building materials in Sichuan include cement brick, wood brick, cinder brick, grey-sand brick, wood, stone, earth brick and gangue brick.

Administrative region. The whole province is divided into 7 administrative regions. In each region, samples were taken according to its population, house structural styles and building materials.

Materials and Methods

Indoor Radon and its Progeny

The samples were collected in the centre of the bedroom or living room of a house or building with natural ventilation, keeping the occupants' living environmental conditions unchanged.

Outdoor Radon and its Progeny

The samples were collected at a distance of 10 metres from the buildings. The sampling height was 1.5 metres, and most of the sampling time was from 9.00 a.m. to 12.00 a.m.

Measurement Methods for Radon Concentrations

Scintillation Method for Radon Concentrations

Radon gas was measured with a ZYW-8501 Radon Monitor, background counting rate, 0.04 cpm; counting efficiency, 92%;volume of the scintillation chamber, 0.7 *l*; calibration coefficient, 17.2-23.7 Bqm^{-3}/cpm, obtained from the calibration by Radium-226 standard sources provided by ICRP.

Two-filter Method for Radon Concentrations

Radon concentrations were also measured using a two-filter method with a FD-3015 Radon Gas Monitor, tube length, 100 cm; radius, 8.04 cm; volume, 20.3 *l*; flow rate, 30 *l*/min; sampling time, 30 min; counting interval, 1-30 min; background counting rate, 0.3-0.5 cpm; counting efficiency, 30% (Thomas, 1972); calibration coefficient, 0.045 cpm/Bqm^{-3}; fraction of Radium-A atoms formed in tube arriving at exit filter, 0.65. Numerous comparisons and calibrations have been made between the above two methods. The data for the eastern, southern, and northern areas of Sichuan were collected using the two-filter method, and the data for the remaining areas were collected using the scintillation method.

Thomas Three-Interval Method for Radon Progeny Concentrations

Radon progeny concentrations were measured with 1355B Tiny Dust Sampler using the Thomas three-interval method (Thomas, 1972). The flow rate was about 250 *l*/min. After 5 minutes' sampling, the filter was counted between 2 and 5, 6 and 20, and 21 and 30 minutes. The radon progeny concentrations were then calculated according to Thomas (1972).

Results

Distribution of Indoor Radon and its Potential Alpha Energy Concentrations

The indoor and outdoor concentrations of radon and its decay products in the whole province fitted, as a first approximation, a log-normal distribution. The cumulative frequency distribution of indoor radon is shown in Figure 1 where it can be seen that 73% of the indoor radon concentrations were less than 20.0 Bqm^{-3}, and 0.1% was higher than 100 Bqm^{-2}.

Indoor Concentrations of Radon and its Progeny in Survey Areas

Table 1 gives the indoor radon concentrations in various survey areas. The highest indoor radon concentrations were found in western Sichuan, the arithmetic mean being 25.6 Bqm^{-3} and the geometric mean 21.9 Bqm^{-3}. The provincial arithmetic and

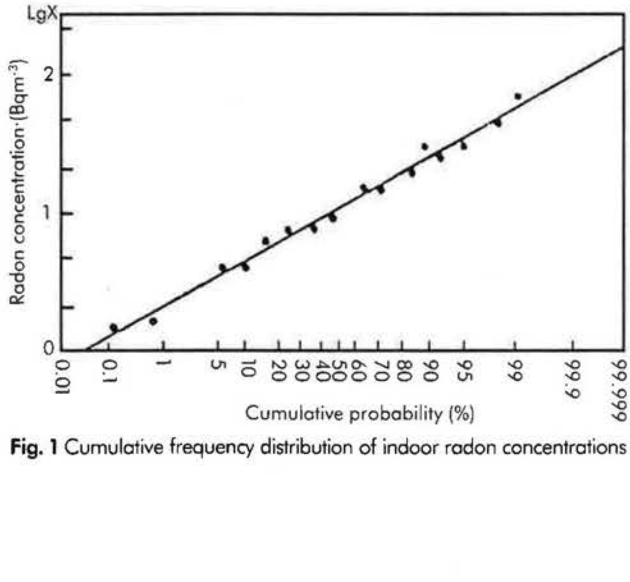

Fig. 1 Cumulative frequency distribution of indoor radon concentrations

Table 1 Indoor concentrations in various survey areas (Bqm^{-3})

City or area	No. of samles	Range	X*	SD	Xg	Sg
Chengdu	399	2.2-170.2	19.9	8.9	14.8	2.2
Chongqing	115	1.0- 29.6	13.6	6.9	11.4	1.9
East Sichuan	86	5.0-112.2	22.8	12.4	19.5	1.7
South Sichuan	130	4.8- 68.9	18.8	8.6	16.6	1.9
West Sichuan	405	5.5-134.9	25.6	12.0	21.9	1.6
North Sichuan	335	3.0- 61.1	14.5	6.9	12.3	1.5
Central Sichuan	497	1.0-114.9	12.2	10.7	9.8	1.6
Whole Sichuan	1967	1.0-170.2	17.8	14.4	14.0	2.0
Population-weighted means			19.4	10.2	17.1	1.7

*X --arithmetic mean; SD --standard deviation; Xg --geometric mean; Sg --geometric standard deviation

geometric mean concentrations of indoor radon were 17.8 Bqm^{-3} and 14.0 Bqm^{-3}, respectively, and the provincial population-weighted mean was 19.4 Bqm^{-3}. Similar results were obtained in Canada (Mcgregor et al., 1984) (geometric mean, 5.2-32.6 Bqm^{-3}), and higher values were found in northern European countries (UNSCEAR, 1982). The provincial arithmetic and geometric mean concentrations of outdoor radon were 13.4 Bqm^{-3} and 11.3 Bqm^{-3}, respectively. There is not much difference between the provincial indoor and outdoor mean concentrations of radon, primarily because Sichuan is in the temperate zone. Residents in Sichuan leave doors and windows open, even in winter, so the rooms are well ventilated and the indoor radon concentrations greatly reduced. Table 2 gives the indoor radon progeny concentrations in various survey areas. The provincial arithmetic and geometric mean concentrations of indoor radon progeny were 10.8 Bqm^{-3} EER (2.9 mWL) and 9.1 Bqm^{-3} EER (2.5 mWL), respectively, similar to those obtained in Canada (Mcgregor et al., 1984). The provincial mean of indoor and outdoor equilibrium factors F were 0.58 and 0.62, respectively.

Seasonal and Diurnal Variations of Radon Concentrations

Radon concentrations in air are closely related to the amount of radon emanating from surface soil and building materials, as well as to atmospheric diffusion patterns. Because these diffusion patterns are dependent on temperature and other climatic conditions, for the same dot there may be variations in different seasons, different months, and even different times of a 24-hour day. Therefore, variations of indoor and outdoor radon concentrations with time in Sichuan province were investigated. Because the size of the Sichuan territory is relatively large, two dots for the measurement of seasonal and diurnal variations were selected, one in northern Sichuan and the other in eastern Sichuan.

Northern Sichuan

Seasonal and diurnal variations of radon concentrations were obtained (Figures 2 and 3) by monitoring radon and its progeny concentrations for 48 hours in the middle of every month (seasonal division: spring, March-May; summer, June-August; autumn, September-December; winter, December-February). Figure 2 shows the maximum radon concentrations in December, and a minimum in May and July. From this Figure we have derived the maximum radon concentrations (26.6 Bqm^{-3}) in winter, the median in autumn (18.7 Bqm^{-3}) and in spring (16.1 Bqm^{-3}), and the minimum (14.7 Bqm^{-3}) in summer. A seasonal pattern of the maximum in winter (19.0 Bqm^{-3} EER) and the minimum in summer (9.4 Bqm^{-3} EER) was observed for radon progeny con-

Table 2 Indoor radon progeny concentrations in various survey areas (Bqm^{-3} EER)

City or area	No. of samples	Range	X	SD	Xg	Sg
Chengdu	188	3.0-62.6	12.9	6.8	11.7	0.5
Chongqing	279	1.5-25.3	7.9	2.9	6.3	1.0
East Sichuan	193	2.3-93.5	10.9	6.4	8.9	0.9
South Sichuan	101	3.1-83.0	10.8	4.7	9.3	1.0
West Sichuan	66	2.5-31.9	14.7	5.6	12.7	0.8
North Sichuan	335	3.3-58.3	11.3	4.3	10.0	0.9
Central Sichuan	77	4.0-27.3	7.6	6.6	6.1	1.0
Whole Sichuan	1239	1.5-93.5	10.8	7.7	9.1	0.3

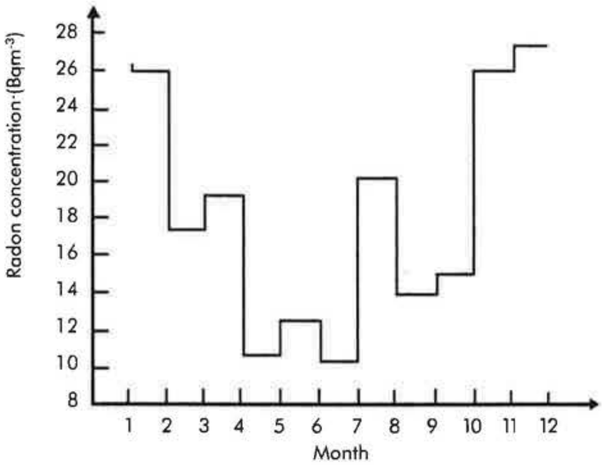

Fig. 2 Seasonal variation of indoor radon concentrations

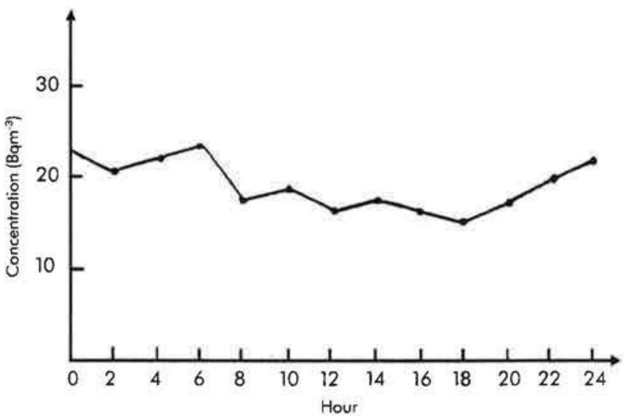

Fig. 3 Diurnal variation of indoor radon concentrations

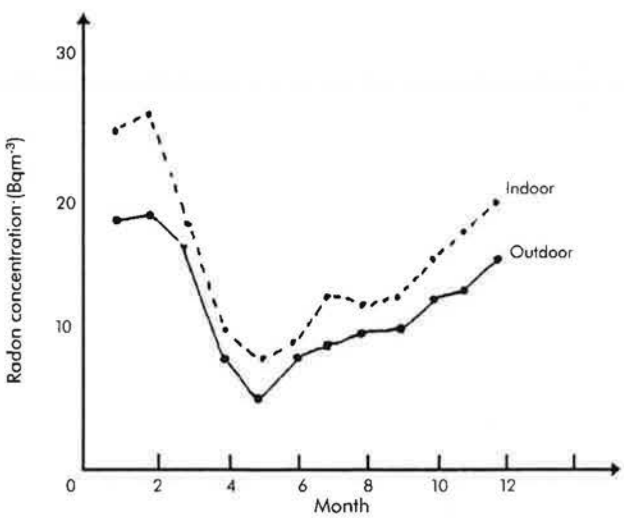

Fig. 4 Seasonal variation of radon concentrations in eastern Sichuan

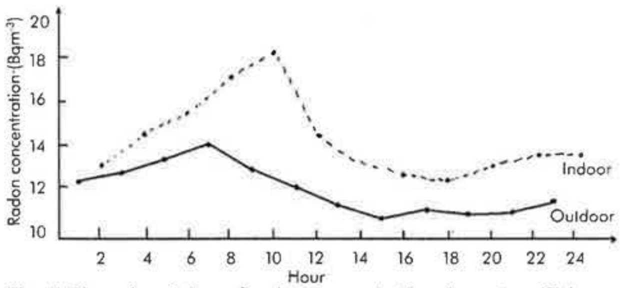

Fig. 5 Diurnal variation of radon concentrations in eastern Sichuan

centrations as well. By diurnal variation, the radon concentration has a maximum at 6 a.m. and a minimum at 6 p.m.

Eastern Sichuan

Seasonal (monthly) variations of indoor and outdoor radon concentrations in eastern Sichuan are shown in Figure 4. It shows that the monthly variations of indoor radon concentrations were almost the same as variations of outdoor radon concentrations with a minimum in May and a maximum in January and February. The maximum indoor and outdoor radon concentrations were 3.5 and 3.7 times as much as the minimum concentrations, respectively. With regard to seasonal variations, a pattern of the maximum in winter and the minimum in summer was observed. The variation pattern was close to that in northern Sichuan. Diurnal variations of indoor and outdoor radon concentrations in eastern Sichuan are shown in Figure 5. The pattern of variation of indoor and outdoor radon concentrations was similar, that is, higher in the morning with a maximum at 8-10 a.m. and 5-7 a.m., respectively, and lower in the afternoon with a minimum at 4-6 p.m. and 3 p.m., respectively. In a day, the maximum indoor and outdoor radon concentrations were 40% and 30% higher than the minimum concentrations, respectively.

Concentrations of Radon and its Progeny in Different Building Materials

Table 3 gives the concentrations for radon and its progeny in houses built with different building materials. The highest radon and radon progeny concentrations were detected in gangue bricks (mainly composed of phosphate rock) houses and the lowest radon concentrations were found in grey-sand brick houses.

Radon Concentrations at Specific Sites

Table 4 gives the radon concentrations in selected localities. The equilibrium factors in these localities

Table 3 Radon concentration levels in houses of different building materials

Building materials	Radon concentration (Bqm^{-3})					Radon potential alpha energy (Bqm^{-3} EER)				
	No. of samples	X	SD	Xg	Sg	No. of sampling	X	SD	Xg	Sg
Cement brick	1246	17.4	13.4	13.8	2.0	575	11.2	6.9	9.8	0.3
Wood brick	257	17.6	11.6	14.3	2.0	125	10.3	2.1	7.9	0.3
Cinder brick	120	18.4	12.8	15.4	1.9	182	8.5	5.8	7.2	0.3
Grey-sand brick	11	6.5	5.6	5.6	1.6					
Wood	49	14.5	9.2	12.3	1.8	47	8.6	3.4	7.9	0.3
Stone	28	21.7	20.6	17.3	1.9	44	12.1	13.5	9.3	0.4
Earth brick	46	18.7	8.1	17.0	1.6	78	8.7	4.7	7.6	0.3
Gangue brick	23	69.0	29.9	63.1	1.5	23	31.5	12.4	29.1	0.3

Table 4 Radon concentrations (Bqm^{-3}) at specific sites

Sites	No. of sampling	Range	X	SD	Xg	Sg
Mines	185	5.4-1363.8	126.3	240.7	57.3	3.0
Railway tunnels	86	11.2- 211.0	43.9	36.5	34.2	2.0
Underground building	111	3.17-897.8	76.2	140.8	34.6	3.3

Table 5 Radon and its potential alpha energy concentrations in different types of houses

Type of house	Population ($x10^4$ person)	Radon concentration (Bqm^{-3}) X (Xg)	Potential alpha energy concentration (Bqm^{-3} EER, mWL) X (Xg)	X (Xg)
Multi-storey building	5021.9	17.9(13.8)	11.2(13.8)	3.0(2.5)
Single-storey house	1432.9	17.4(14.6)	9.7(8.5)	2.6(2.3)
Wood house	238.8	14.5(9.2)	8.6(7.9)	2.3(2.1)
Stone house	1970.3	21.7(17.3)	12.9(9.3)	3.3(2.5)
Mud brick house	2198.6	18.7(17.0)	8.7(7.6)	2.3(2.1)
Indoor population-weighted means	10862.5	18.6(15.1)	10.8(8.3)	2.8(2.4)
Outdoor population-weighted means	10862.5	13.5(11.3)	8.6(7.3)	2.3(2.1)

varied greatly (from 0.29 to 0.61) under various ventilating conditions.

Dose Estimation

Occupancy Factors

From a survey of the hours spent indoors and outdoors by workers, children, students, soldiers, officials, businessmen, the retired, and peasants living in Sichuan, occupancy factors of 0.79 and 0.21 have been obtained for indoor and outdoor exposure, respectively.

House Types

Table 5 presents the radon and its potential alpha energy concentrations and their population-weighted means in the five types of houses in Sichuan.

Dose Equivalents

The annual mean effective dose equivalents from indoor and outdoor exposure of radon progeny have been calculated as 0.66 mSv and 0.27 mSv, respectively, using recommended dose estimation coefficients of 0.061 and 0.031 mSv/Bqm^{-3} for inhaled indoor and outdoor radon progeny, respectively (UNSCEAR, 1982). The dose from indoor and outdoor exposure adds up to 0.93 mSv.

Death Rate from Lung Cancer resulting from the Inhalation of Radon Progeny

The indoor and outdoor exposures due to the inhalation of progeny were 7.2×10^4 Bq h m^{-3} and 1.6×10^4 Bq h m^{-3}, respectively, and they added up to 8.8×10^4 Bq h m^{-3} (0.14 WLM). Using the UNSCEAR (1982) risk coefficient R of $(200\text{-}450) \times 10^{-6}/$

man WLM, we estimate that 3000-6800 people may die annually from lung cancer resulting from the inhalation of radon progeny, and that in 45 years the number may be as high as 1.4×10^5-3.1×10^5.

Conclusions and Discussion

- The population-weighted means of concentrations of indoor radon and its progeny in Sichuan were 18.6 Bqm^{-3} and 10.8 Bqm^{-3} (EER), respectively. The indoor and outdoor concentrations of radon and its progeny all fitted log-normal distribution. A seasonal pattern of the maximum in winter and the minimum in summer was observed for concentrations of radon and its progeny as well. The maximum concentrations of radon and radon progeny in winter were a factor of 1.8 and 2.0 higher than the minimum concentrations in summer, respectively.
- The individual effective dose equivalent from the inhalation of radon progeny was 0.93 mSv, and about 3000-6800 people may die annually from lung cancer induced by the inhalation of radon progeny in Sichuan.
- The highest radon concentrations were found in houses built with gangue brick. Usually the highest is more than 10 times higher than the lowest.

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