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Natural radioactive nuclides in cigarettes and dose estimation for smokers

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Abstract ^{210}Po and ^{210}Pb contained in cigarettes might contribute to an increase in an effective dose. This article reports the effective dose of radionuclides to smokers based on results of a review of various parameters related to dose estimation for smokers. The annual effective dose to smokers was found to be 0.27 mSv year^{-1}, which was lower than an intervention exemption level (1 mSv year^{-1}) given in International Commission on Radiological Protection (ICRP Publ. 82).

Keywords NORM · Dose estimation · Cigarette · Tobacco leaf · Smoking

Introduction

Natural radioactive nuclides (primarily ^{238}U series nuclides, ^{232}Th series nuclides, and ^{40}K nuclides), which exist in soil and air, are absorbed by various agricultural products through roots and leaves. Because tobacco leaves are familiar products and consumers have a high affinity for them [1, 2], newspaper and magazine articles have highlighted the issue regarding an effective dose of natural radioactive nuclides contained in them. Although the effective dose of radionuclides to smokers was reviewed by Iwaoka and Yonehara [3] in 2010, some original studies related to the effective dose to smokers have recently been reported. This article reports the effective dose of radionuclides to smokers based on the results from a review of various recent parameters related to dose estimation for smokers with the inclusion of the data from the past. From among the different types of tobacco products such as cigarettes, cigars, and snuff, this article deals with cigarettes.

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Parameters for dose estimation

Natural radioactive nuclides such as ^{238}U, ^{232}Th, ^{210}Po, and ^{210}Pb are contained in cigarettes [4–6]. Among these radionuclides, ^{210}Po and ^{210}Pb are volatilized at the temperature of a burning cigarette and are taken into the human body [7, 8]. Therefore, activity concentration of ^{210}Po and ^{210}Pb in cigarettes, transfer factors of ^{210}Po and ^{210}Pb from cigarettes to mainstream smoke, and dose conversion factors of ^{210}Po and ^{210}Pb are important parameters for dose estimation.

Activity concentration of cigarettes

There are two basic pathways of absorption of ^{210}Po and ^{210}Pb by plants: direct deposition of ^{210}Po and ^{210}Pb in the atmosphere and absorption of ^{210}Po and ^{210}Pb through the roots in the ground. Regarding tobacco leaves, the direct deposition is main pathway [8–11]. ^{210}Po and ^{210}Pb in tobacco leaves reach radioactive equilibrium, while tobacco leaves are processed for the production of cigarettes [10, 12–15]. The activity concentration of ^{210}Po and ^{210}Pb in cigarettes is about 8.0–24 mBq per cigarette with arithmetic mean of 14 mBq per cigarette (Table 1). Cigarettes were categorized into those just sold at origin and those produced at origin (Table 1). Even if cigarettes are produced at origin, cultivation of tobacco leaves and producing may not occur in the same origin, such as in Japan where tobacco leaves are imported [29].

Table 1 The activity concentration of ^{210}Po and ^{210}Pb in cigarettes (mBq/cigarette)

Origin	Type of origin[a]	^{210}Po (^{210}Pb)		
		Number of bland	Average[b]	Range[b]
Bulgaria [16]	Production	10	12.4 (11.2)	9.2–15.3 (13.9–16.4)
Brazil [17]	Production	8	15.5 (15.5)	8.0–20.0 (8.7–22.0)
China [18]	Production	1	12.5	–
China [19]	Sell	7	14.6	11.1–18.3
China [15]	Production	12	23.5 (21.2)	18.0–29.0
Egypt [10]	Production	2	16.6	–
Egypt [20]	Sell	5	15.0	11.3–19.2
Finland [21]	Sell	8	11.0	7.8–14.4
Greece [8]	Sell	7	10.5 (10.7)	2.9–13.4
Hungary [14]	Sell	29	22.0 (20.9)	10–33.5
Italy [13]	Sell	17	11.8	6.8–17.5
Japan [18]	Production	8	11.5	10.1–15.0
Japan [22]	Production	5	18.8	12.1–27.8
Japan [23]	Sell	24	8.0 (8.0)	2.0–14.0 (2.0–14.0)
New Zealand [24]	Production	8	11.6	8.7–16.7
Poland [9]	Sell	14	13.3	4.2–24.1
Portugal [25]	Sell	3	14.1	2.6–27.7
Turkey [26]	Sell	6	14.3[c]	12.6–16.0
USA [27]	Production	2	12.2	11.8–12.6
USA [28]	Production	4	15.7	14.4–17.8
USA [15]	Production	3	9.3 (7)	6.0–11.0
Arithmetic mean[d]			14.0	

[a] "Sell" means cigarettes just sold at place of origin. "Production" means cigarettes produced at place of origin

[b] The number shown in parentheses means the activity concentration of ^{210}Pb

[c] The average of minimum and maximum values

[d] Arithmetic mean of the average values

Transfer factor of ^{210}Po and ^{210}Pb

^{210}Po and ^{210}Pb in cigarettes are volatilized at the temperature (600–800 °C) of a burning cigarette and transfer from cigarettes to smoke [7, 8]. The transfer factor of ^{210}Po from cigarettes to mainstream smoke has been reported in various studies [15, 16, 18, 21, 25, 28, 30–34]. The transfer factor of ^{210}Po from cigarettes to mainstream smoke is about 0.09–0.49 with arithmetic mean of 0.18 (Table 2). The transfer factor of ^{210}Po from cigarettes to ashes, cigarette butts, and sidestream smoke is 0.09–0.21, 0.29–0.37, and 0.25–0.61, with arithmetic means of 0.16, 0.32, and 0.37, respectively (Table 2). The number of reports on transfer factors of ^{210}Pb from cigarettes to mainstream smoke is limited, among which, reports from Ferri and Christiansen [35], Sakanoue et al. [34] and Schayer et al. [15] are particularly useful. The transfer factor of ^{210}Pb from cigarettes to mainstream smoke is 0.08–0.18 with arithmetic mean of 0.12 (Table 3). The transfer factors of ^{210}Pb from cigarettes to ashes, cigarette butts, and sidestream smoke have not yet clearly perceived.

Dose conversion factors for ^{210}Po and ^{210}Pb

In some studies, effective dose conversion factors provided by International Commission on Radiological Protection (ICRP Publ. 72) [36] have used for dose estimation. These dose conversion factors are calculated by using standard inhalation conditions, which are an inhalation speed through the nose of 0.45–3.0 $m^3 h^{-1}$ and an aerosol particle size of 1 μm (activity median aerodynamic diameter; AMAD). Since smoking conditions are not the same as standard inhalation conditions, dose conversion factors calculated by using smoking conditions are preferable to dose conversion factors provided by ICRP Publ. 72. The inhalation speed through the mouth for smoking will be 31.5 $m^3 h^{-1}$, assuming 4 s for a puff (inhale for 2 s, then exhale for 2 s) and using internationally recognized standards [37] (35 ml/puff). Regarding definite particle sizes of mainstream smoke, a study by Chen et al. [38] reported a size of 0.45 μm (mass median aerodynamic diameter; MMAD) and a study by Hinds [39] reported a size range of 0.37–0.52 μm (MMAD). If it is assumed that ^{210}Po and ^{210}Pb are equally dispersed in aerosol particles on mainstream smoke, the MMAD and AMAD are equal and about 0.4 μm. Based on these smoking conditions, effective dose conversion factors for ^{210}Po and ^{210}Pb calculated by the LUDEP [40] were 1.4×10^{-5} and 1.4×10^{-6} Sv Bq^{-1}. These dose conversion factors are several times larger than those in ICRP Publ. 72 (Table 4). Specific parameters for LUDEP are shown in Table 5.

Table 2 The transfer factor of ^{210}Po from cigarettes to mainstream smoke, ashes, cigarette butts, sidestream smoke, and total smoke

Reference	Sample	Experimental condition	Transfer factor of ^{210}Po from cigarettes to mainstream smoke		Transfer factor of ^{210}Po from cigarettes to sidestream smoke		Transfer factor of ^{210}Po from cigarettes to ashes		Transfer factor of ^{210}Po from cigarettes to butts		Transfer factor of ^{210}Po from cigarettes to total smoke	
			Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
Carvalho and Oliveira [25]	3	–	0.18	0.05–0.37	0.61	0.49–0.84	–	–	–	–	–	–
Ferri and Baratta [30]	5	54 ml/puff, 3 s/puff, puff/26 s	0.19	0.11–0.31	0.33	0.25–0.41	–	–	–	–	–	–
Ferri and Baratta [31]	4	54 ml/puff, 3 s/puff, puff/26 s	0.20	0.11–0.31	0.33	0.24–0.41	–	–	–	–	–	–
Hill [32]	3	35 ml/puff, 2 s/puff, puff/60 s	0.10	0.07–0.12	0.30	0.28–0.32	0.18	0.16–0.19	0.37	0.34–0.41	0.40	0.37–0.44
Kelley [33]	11	35 ml/puff, 2 s/puff, puff/58 s	0.09	0.07–0.11	–	–	–	–	–	–	–	–
Mussalo-Rauhamaa and Jaakkola [21]	1	35 ml/puff, 2 s/puff, puff/60 s	0.10	–	–	–	–	–	–	–	–	–
Nikilova and Parfenov [16]	10	–	0.19	0.15–0.23	–	–	–	–	–	–	–	–
Radford and Hunt [28]	4	35 ml/puff, 2–3 s/puff, puff/50 s	0.22	0.18–0.25	0.25	0.21–0.29	0.09	0.07–0.11	0.29	0.24–0.38	0.47	0.43–0.54
Sakanoue et al. [34]	4	35 ml/puff, 2 s/puff, puff/58 s	0.49	0.15–0.98	–	–	–	–	–	–	–	–
Schayer et al. [15]	2	35 ml/puff, 2 s/puff, puff/30 s	0.13	0.12–0.14	–	–	–	–	–	–	–	–
Takizawa et al. [18]	9	35 ml/puff, 2 s/puff, puff/60 s	0.10	0.07–0.13	0.41	0.29–0.51	0.21	0.16–0.27	0.29	0.21–0.39	0.51	0.38–0.64
Arithmetic mean[a]			0.18		0.37		0.16		0.32		0.46	

[a] Arithmetic mean of the average values

Table 3 The transfer factor of ^{210}Pb from cigarettes to mainstream smoke

Reference	Sample	Experimental condition	Transfer factor of ^{210}Pb from cigarettes to mainstream smoke	
			Average	Range
Ferri and Christiansen [35]	6	54 ml/puff, 3 s/puff, puff/26 s	0.11	0.0–0.14
Nikilova and Parfenov [16]	10	–	0.10	0.08–0.12
Sakanoue et al. [34]	4	35 ml/puff, 2 s/puff, puff/58 s	0.18	0.10–0.34
Schayer et al. [15]	2	50 ml/puff, 2 s/puff, puff/30 s	0.08	0.08–0.08
Arithmetic mean[a]			0.12	

[a] Arithmetic mean of the average values

Table 4 Effective dose conversion factor

Nuclide	Effective dose conversion factor (Sv Bq^{-1})	
	Smoking conditions [3]	ICRP Publ. 72[a] [36]
^{210}Pb	1.4E−06	9.0E−07
^{210}Po	1.4E−05	3.3E−06

[a] ^{210}Pb: type F, ^{210}Po: type M

Table 5 Specific parameters for LUDEP

Category	Parameter	Input value
Intake	Inhalation	1
Time	Period for dose calculation ($year^{-1}$)	50
Deposition	Respiration rate ($m^3\ h^{-1}$)	31.5
	Ratio of nasal breathing	0
	AMAD (μm)	0.4
Absorption	$^{210}Po/^{210}Pb$	M/F
Biokinetics	$^{210}Po/^{210}Pb$	ICRP Model/ICRP Model

Dose estimation of smokers

Arithmetic means of activity concentration of ^{210}Po and ^{210}Pb in Table 1, arithmetic means of ^{210}Po and ^{210}Pb transfer factors from cigarettes to mainstream smoke in Tables 2 and 3, and effective dose conversion factors based on smoking conditions in Table 4 are used for dose estimation. A consumption of 20 cigarettes per day as the standard was used for dose estimation [41]. The annual effective dose to a smoker calculated by using those values and Eqs. (1)–(3) was 0.27 mSv $year^{-1}$, which was lower than an intervention exemption level (1 mSv $year^{-1}$) given in ICRP Publ. 82 [42]:

$$E_{po} = A_{popb} \times F_{po} \times D_{po} \times T \times C \tag{1}$$

$$E_{pb} = A_{popb} \times F_{pb} \times D_{pb} \times T \times C \tag{2}$$

$$E_{popb} = E_{po} + E_{pb} \tag{3}$$

where E_{popb} is the annual effective dose (mSv $year^{-1}$), E_{po} is the annual effective dose of ^{210}Po (mSv $year^{-1}$), E_{pb} is the annual effective dose of ^{210}Pb (mSv $year^{-1}$), A_{popb} is the activity concentration (mBq/cigarette) of ^{210}Po (^{210}Pb) in a cigarette, F_{po} is the transfer factor of ^{210}Po from cigarettes to mainstream smoke, F_{pb} is the transfer factor of ^{210}Pb from cigarettes to mainstream smoke, D_{po} is the effective dose conversion factor (Sv Bq^{-1}) of ^{210}Po, D_{pb} is the effective dose conversion factor (Sv Bq^{-1}) of ^{210}Pb, T is 365 (day $year^{-1}$); and C is the daily consumption of cigarettes. Furthermore, a reverse calculation of the number of cigarettes consumed per day so that the effective dose became 1 mSv $year^{-1}$, yielded about 70, an extremely rare number.

Conclusions

The annual effective dose to smokers was much lower than the intervention exemption level of 1 mSv $year^{-1}$. However, there is a need to evaluate aggregate effects to health, because smoking involves introduction of harmful elements (cancerous particles or cancer-inducing particles such as dimethylnitrosamine and formaldehyde) and radioactive material. Furthermore, there is a need to assess effective doses in sidestream smoke; thus, continued study of missing parameters is needed.

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