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Analysis of the applicability of some risk assessment models associated with exposure to radon for evaluation of effectiveness of radon mitigation actions in schools

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The paper presents the results of risk assessment from exposure to radon before and after radon mitigation actions in school. Twofold reduction of radon EEC (from 231 to 109.6 Bq/m3) in the long term can lead to decrease of lifetime attributable risk by 2.2–2.4% for the entire population (depending on the standard population used), 2.7% for men, 1.2% for women. These results were obtained using «FCZ» model. Models «EPA-2003» and «Wismut-2006» were not sensitive enough for use in such tasks.

Key words: *radon and progeny, radon-induced lung cancer, risk assessment, model, lifetime attributable risk, standard population.*

Introduction

The paper presents the results of the analysis of practical application of three modern lung cancer risk assessment models associated with exposure to radon and progeny (further – radon) in complex exposure scenarios, in combination with Russian medical and demographic data, and the impact of different standard populations on the results of risk assessment at the population level. In fact, it is the next iteration step towards the development of method of lung cancer risk assessment associated with exposure to radon that could be officially used in Russia. According to the three-level structure of risk assessment methods [1,2], it is a particular method. The exposure-response relation and the description of necessary medical and demographic data are the central elements of the method. The choice of an exposure-response relation doesn't seem possible without practical tests of some existing modern models. The results of the first test application of the model developed by the United States Environmental Protection Agency (EPA) in 2003 were published earlier [3].

In this original work the evaluation of effectiveness of radon mitigation actions in schools was used as a test task. In such cases it is usual to evaluate the reduction of directly measured value (radon equivalent equilibrium concentration (EEC)), which is the radiation safety indicator. Methods of risk assessment allow to produce a long-term forecast of the consequences of mitigation actions – that is the reduction of the number of radon-induced lung cancer deaths at the population level. The results of radon mitigation actions carried out by the specialists of Saint-Petersburg Research Institute of Radiation Hygiene after Professor P.V. Ramzaev in the school No. 289 in Krasnoselsky district of Saint-Petersburg in 2002-2006 were used as the basic material.

Methods

By the end of the XX century a number of radon-induced lung cancer risk assessment models were developed. They were based on the results of joint epidemiological studies of uranium and some other underground miners. In accordance with the recommendations of ICRP Publication 65 [4,5], these models were multiplicative. However, over the last 20 years there were ongoing debates about the applicability of these models for risk assessment associated with exposure to radon in dwellings and public places. At the beginning of the 2000s the results of three pooled analyses of data from residential case-control studies, started in the late 1980s and early 1990s, were published [6-10]. At the same time the results of several large cohort studies of underground miners exposed to relatively low levels of radon came out [11-13]. All these results were carefully analyzed by the Task Group of ICRP Committee 1 specially established in 2005. In November 2009 the Commission approved the “Statement on Radon” and in 2010 ICRP Publication 115 was released [14,15], which states that “the cumulated excess absolute risk of lung cancer attributable to radon and its progeny estimated for residential exposures appears to be consistent with that obtained from miners at low levels of exposure”. In addition, there is evidence from the European pooled residential case-control study that there is a risk of lung cancer even at levels of long-term average radon EEC below 100 Bq/m^3.

ICRP Publication 115 prioritizes risk models derived from pooled analyses (instead of individual studies). The following models meet this criterion:

– BEIR VI model (combined of two models – EAD and EAC) [16] developed in 1999 by the United States National Academy of Sciences is one of the most widely used in the world [17-20] and the basis for a number of more advanced models;

– EPA-2003 model [17] developed in 2003 by EPA on the basis of BEIR VI model;

– Wismut-2006 model [18] developed in 2006 in Germany on the basis of BEIR VI model;

– joint French-Czech model FCZ [12,21] developed in 2003 by the international team under contract with the European Commission [11].

In accordance with the multiplicative relation, radon-induced lung cancer mortality is the product of the age-specific lung cancer mortality from all causes (spontaneous mortality) and the excess relative risk (ERR). The ERR in BEIR VI model is a linear function of cumulated exposure to radon, multiplicative and no-threshold, and it varies according to time since exposure, attained age and either exposure-age-duration (EAD model) or exposure-age-concentration (EAC model). The model is expressed as follows:

$$ERR(t) = \beta \cdot (\theta_{5\text{-}14} \cdot \omega_{5\text{-}14} + \theta_{15\text{-}24} \cdot \omega_{15\text{-}24} + \theta_{25+} \cdot \omega_{25+}) \cdot \phi_{age} \cdot \gamma_z, \qquad (1)$$

where β is the slope parameter of exposure-response relation, WLM-1;

$\omega_{5\text{-}14}$, $\omega_{15\text{-}24}$, ω_{25+} are exposures to radon cumulated 5-14 years, 15-24 and ≥25 years before age t, WLM;

$\theta_{5\text{-}14}$, $\theta_{15\text{-}24}$, θ_{25+} parameters represent the relative contributions to risk from exposures cumulated 5-14, 15-24 and ≥25 years before age t;

ϕ_{age} parameter represents multiple categories of attained age (see also [22]);

γ_z parameter represents the modifying effect of either the duration of radon exposure (in the EAD model) or radon concentration (in the EAC model).

BEIR VI model takes into account a lag time (minimum latency) of 5 years, so exposure to radon cumulated in 5 years prior to age t is not considered in the expression (1). More details of this model and its implementation can be found elsewhere [16,17,20].

In this work three models were used to estimate the ERR attributable to exposure to radon: EPA-2003, Wismut-2006 (both derived from BEIR VI) and original FCZ. Population lifetime attributable risk (LARpop) was calculated as the measure of risk. This indicator represents the fraction of the total number of lung cancer deaths in the population that could be radon-induced. According to [23], the calculation of LARpop is a two-stage operation: individual lifetime attributable risk (i.e. the probability of a premature cancer death from exposure to radon) is calculated first and then population lifetime attributable risk is calculated as a weighted average of the attained age specific LAR.

1. In 2003 EPA released the second report which presented revised risk assessment for residential exposure to radon [17]. EPA constructed a model (let’s call it EPA-2003) that yields numerical results midway between what would be obtained using the two BEIR VI models (EAD and EAC). In fact, EPA chose to modify EAC model because the concentration model avoids ambiguities that may arise when assessing risk from residential exposure at levels that change over time.

EPA-2003 model form is as expression (1). Values of the parameters β, θ, ϕ_{age} and γ_z were obtained from [17].

2. Wismut-2006 model is based on the results of the cohort study of German uranium miners, former employees of the Wismut Company from 1946 to 1998 [18]. An important advantage of this study is the cohort size (59,001 men, mean duration of follow-up was 30.5 years with a total of 1,801,630 person-years), which is comparable to the cohort size in some of the joint studies (for example, 11 cohorts in BEIR VI report included 60,705 people with a total of 892,547 person-years).

The authors also preferred EAC model to EAD model. Wismut-2006 model form is as expression (1). Values of the parameters β, θ, ϕ_{age} and γ_z were obtained from [18].

3. FCZ is based on the results of the joint study of French and Czech uranium miner cohorts (the joint cohort included 10,100 people with a total of 248,782 person-years) exposed to relatively low levels of radon.

The model is expressed as follows:

$$ERR(t) = \beta \cdot W \cdot \exp[\alpha \cdot (AE(t) - 30) + \theta \cdot (TE(t) - 20)], \qquad (2)$$

where β is the slope parameter of the exposure-response relation, WLM^{-1};

W is exposure to radon cumulated until the age t-5, WLM;

AE (t) is the age at median exposure, years;

TE (t) is the time since median exposure, years;

α, θ are numerical parameters of the model.

Values of the parameters β, α and θ were obtained from [21]. FCZ model also takes into account a lag time of 5 years, so exposure to radon cumulated in 5 years prior to age t is not considered in the expression (2).

Materials

In this work LAR_{pop} was calculated up to the attained age of 100 years. Special scenario was developed to calculate lifetime exposure to radon. It included 5 years of education in the kindergarten No. 52 in Krasnoselsky district of Saint-Petersburg (high levels of radon EEC exceeding Russian allowed level were measured in this kindergarten, which is located close to the school No. 289, in 2008) and 11 years of education in the school No. 289 (scenario #1 – before radon mitigation actions, scenario #2 – after radon mitigation actions). The sanitary regulations SanPiN 2.4.1.3049-13 [24] were used to determine the maximum possible annual time spent by a child in the kindergarten. The maximum admissible weekly educational load in different school grades was obtained from the sanitary regulations SanPiN 2.4.2.2821-10 [25]. According to the scenario, a person spends the rest of life time indoors with average radon EEC level in dwellings and public places located in Saint-Petersburg (the proportion of time spent by a person indoors was taken equal to 0.8 in accordance with [26]).

1. Original data on radon EEC levels in dwellings and public places located in Saint-Petersburg were obtained from the “Federal data bank on the radiation doses to the population of the Russian Federation from naturally occurring and artificial sources”. This data bank contains results of the measurements carried out in 2002-2013. According to the UNSCEAR reports [13,27], the distribution of radon EEC values appears log-normal. Therefore, median values were used as the average values to calculate the exposure to radon (Table 1).

Two assumptions were made to calculate the ERR:

(A) person’s dwelling is permanent throughout life;

(B) radon EEC level in dwelling is permanent throughout life.

These two assumptions mean that the situation of permanent lifelong exposure with the exception of 16 years of education in kindergarten and school is considered.

More than 1000 radon measurements were carried out in the school No. 289 in 2003-2012, before and after radon mitigation. Instant, short-term and long-term methods of measurement were applied in all months of the year to obtain the correct annual average of radon EEC, which has significant seasonal variability. More than 100 measurements were carried out in the kindergarten No. 52 in 2008-2012. Instant, short-term and long-term methods of measurement were applied both in warm and cold periods of the year.

2. Age and sex distributions of the probability of survival from birth to a certain were not available from the official vital statistics, however, it was easy to build these distributions on the basis of other demographic index ¬– age-specific mortality rates, which were obtained from the Unified Interdepartmental Statistical Information System (UniSIS) [28] (Figure 1).

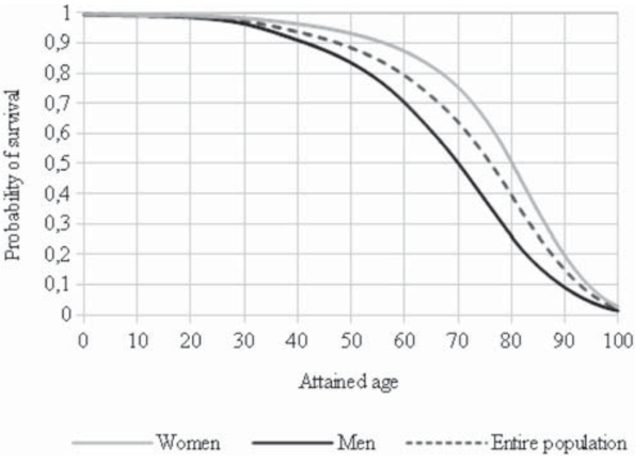

Figure 1. Probability of survival from birth to a certain age based on the UniSIS data for the population of Saint-Petersburg in 2012

3. Data on lung cancer deaths from all causes and the age and sex distributions of this index for Russia came from the reference book “Malignant neoplasms in Russia in 2012 (morbidity and mortality)” [29]. However, age and sex distributions of lung cancer mortality rates from all causes for specific regions of Russia are not presented there, which is a weakness of the current structure of Russian medical statistics. Therefore, it was necessary to make the following assumption:

(C) Age and sex distributions of lung cancer mortality rates from all causes for the population of Saint-Petersburg and for the population of Russia as a whole are equal.

These distributions were build on the basis of age and sex distributions of lung cancer deaths from all causes and the age distribution of the population of Saint-Petersburg using the method described in [30].

The oldest age group in the morbidity and mortality datasets is defined as “85+”. However, it is necessary to exactly define the upper limit of the attained age interval for LARpop estimation. There are age groups “85-89”, “90-94”, “95-99” and “100+” in the demographic datasets, so the maximum attained age was taken equal to 100 years. Lung cancer mortality rates for the age groups “85-89”, “90-94”, “95-100” were set equal to that of the age group “85+”.

Table 1

Characteristics of the dataset and parameters of the log-normal distribution of radon EEC values

Place of measurement	N	Min	Max	Med	σ_g
Dwellings and public places in Saint-Petersburg	53603	5	2045	23,0	1,5
School No. 289 (before radon mitigation actions)	501	10	1816	231,0	2,4
School No. 289 (after radon mitigation actions)	504	5	1859	109,6	3,1
Kindergarten No. 52	108	15	447	43,5	2,5

Legend: N – number of measurements; Min – minimum, Bq/m^3; Max – maximum, Bq/m^3; Med – median, Bq/m^3; σ_g – geometric standard deviation.

4. The actual age-sex distribution of the population of Saint-Petersburg on 01.01.2013 (5-year age groups for EPA-2003 and Wismut-2006 models; single ages for FCZ model) were obtained from the UniSIS [28]. The size of the age group "95-100" was calculated as a sum of the sizes of age groups "95-99" and "100+".

5. In this paper two standard populations were used alongside with actual age distribution of the population: the new WHO World Standard Population (WSP) for the period 2000-2025 [31] and the new European Standard Population (ESP-2013) [32] (Figure 2). It is worth noting that, in fact, WSP is designed and suitable for developing countries. ESP-2013, which replaced the outdated European ("Scandinavian") standard used since 1967, is regarded as the most suitable for the developed countries of the European Union. However, both of these standards are intended for the entire population without distinction of sex, which can lead to overestimated mortality rates for men and underestimated rates for women. As a result, the difference in mortality rates for men and women in Russia could be even larger than it really is nowadays [33].

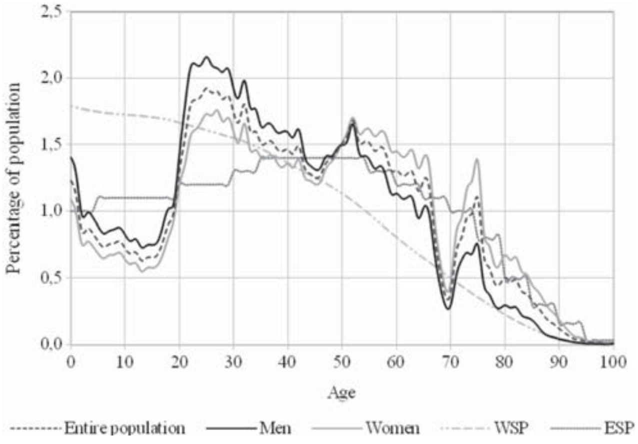

Figure 2. The actual age distribution of the population of Saint-Petersburg (01.01.2013) in comparison with WSP and ESP-2013

Results

Table 2 shows estimated lifetime attributable population risk calculated using three considered models and two exposure scenarios. The third scenario of lifetime exposure to the constant radon EEC level of 23 Bq/m^3 was used for comparison.

Figures 3-5 show the ERR calculated using three considered models and three exposure scenarios. The overall shape of the curves is consistent with that given in [21].

Table 2

LARpop estimation results

LAR$_{pop}$, %	Risk model		
	EPA-2003	Wismut-2006	FCZ
Before radon mitigation actions in school			
Entire population	8,5	4,7	16,2
Men	11,6	6,1	20,6
Women	3,9	2,3	8,5
WSP	5,0	2,7	9,6
ESP-2013	9,7	5,5	18,3
After radon mitigation actions in school			
Entire population	8,5	4,7	14,0
Men	11,6	6,1	17,9
Women	3,9	2,3	7,3
WSP	4,9	2,7	8,3
ESP-2013	9,7	5,5	15,9
Lifetime constant exposure			
Entire population	8,5	4,7	12,1
Men	11,6	6,1	15,4
Women	3,9	2,3	6,2
WSP	4,9	2,7	7,2
ESP-2013	9,7	5,5	13,7

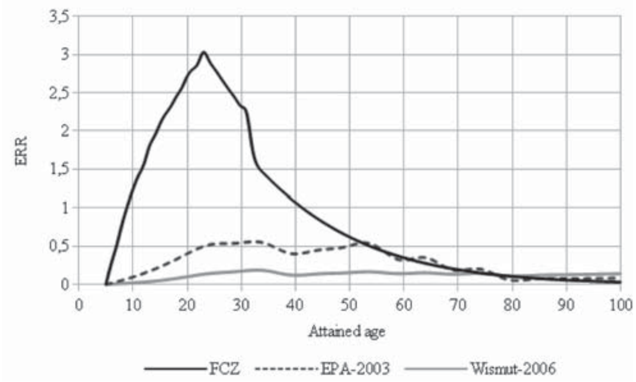

Figure 3. ERR in dependence on attained age: before radon mitigation actions in the school

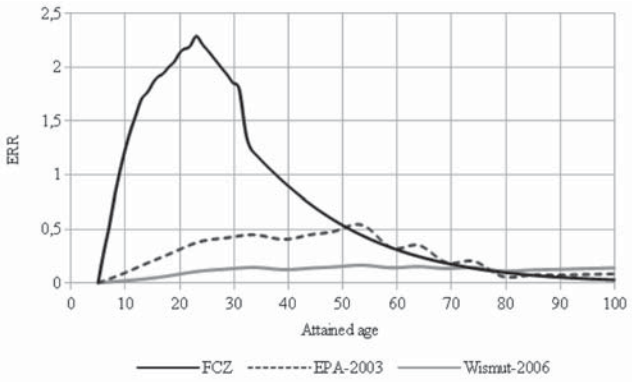

Figure 4. ERR in dependence on attained age: after radon mitigation actions in the school

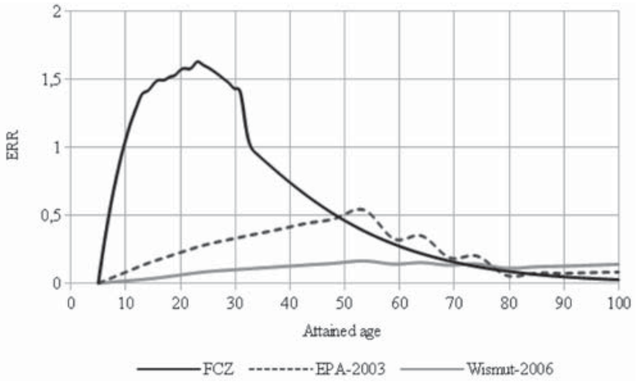

Figure 5. ERR in dependence on attained age: lifetime exposure to the constant radon EEC level of 23 Bq/m^3

Discussion

Table 2 reports that the difference in exposures to radon cumulated after 16 years of education in the kindergarten and the school, in fact, has no impact on the final result (LAR$_{pop}$) obtained with EPA-2003 and Wismut-2006 models. For additional comparison, radon EEC level was set constant to 1000 and 2000 Bq/m^3 in lifetime exposure scenario. Under this condition LAR$_{pop}$ for the entire population increased only to 8.6 and 8.7%, respectively. These two models have the same form, but different parameters, and the reasons for this paradoxical result could be as follows: firstly, exposures cumulated later in life (close to the age of risk assessment) have more weight; secondly, low baseline lung cancer death rate and high probability of survival at early ages additionally reduce the weight of exposures cumulated in youth. Apparently, both of these models, derived from BEIR VI and based on the results of epidemiological studies of miners who had been exposed for a long time to relatively high radon concentration, are not suitable for use in complex exposure scenarios with relatively low levels of exposure to radon cumulated in the early years of life. This supposition is supported by the fact that the models were used with only one value of the γ_z parameter corresponding to the minimum level of radon concentration (less then 0,5 WL).

FCZ model is based on the results of epidemiological studies of miners who had been exposed for a long time to relatively low radon concentrations and it has different form and dependence on age at exposure and time since exposure. It proved to be much more sensitive than two previous models to variation within one order of magnitude (23÷231 Bq/m^3) of radon EEC level in the early years of life. FCZ model gives the highest value of LARpop among three considered models, which is consistent with the results presented in [20].

Analysis of the impact of different standard populations on the result of risk assessment shows that the use of WSP leads to the underestimation of LARpop in 1,7-2 times (depending on the risk model) compared to the actual age distribution or ESP-2013. This is due to the fact that younger age groups prevail in WSP (this distribution is suitable for developing countries) and it reduces the contribution of exposure cumulated later in life, which has more weight, to the lifetime risk.

Conclusion

Twofold reduction of indoor radon EEC (from 231 to 109.6 Bq/m3) in the school No. 289 in the long term can lead to decrease of lifetime attributable risk by 2.2÷2.4% for the entire population (depending on the standard population used), 2.7% for men, 1.2% for women. The reason of the smaller decrease of lifetime attributable risk for women is the much lower baseline lung cancer death rate for women than for men. According to statistical data [29], tumors of the trachea, bronchus and lung in the structure of mortality from malignant neoplasms are ranked as the first for the male population of Russia (26.8% of all cases) and as the fourth for the female population (6.6%). Further reduction of indoor radon EEC in the school No. 289 to the average level of 23 Bq/m^3, i.e. fivefold, would result only in a slight decrease of LAR$_{pop}$ (up to 2.5% for men and 1.1% for women), and seems inappropriate.

These results were obtained with FCZ model. EPA-2003 and Wismut-2006 models were not sensitive enough for use in such tasks. WHO 2000-2025 world standard population describes the current demographic situation in Russia much worse than the new European standard population (Figure 3).

The issue of lung cancer risk assessment for the staff of the school No. 289 from exposure to radon was beyond the scope of this work. This task requires the development of specific exposure scenario and will be solved in the future work related to the testing of various modern radon-induced lung cancer risk assessment models with Russian medical and demographic data.

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