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OCCUPATIONAL EXPOSURE TO RADON FOR UNDERGROUND TOURIST ROUTES IN POLAND: DOSES TO LUNG AND THE RISK OF DEVELOPING LUNG CANCER

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Abstract
Objectives: Radon concentrations for 31 Polish underground tourist routes were analyzed. The equivalent dose to the lung, the effective dose and the relative risk were calculated for employees of the analyzed routes on the grounds of information on radon concentrations, work time, etc. **Material and Methods:** The relative risk for lung cancers was calculated using the Biological Effects of Ionizing Radiation (BEIR) VI Committee model. Equivalent doses to the lungs of workers were determined using the coefficients calculated by the Kendall and Smith. The conversion coefficient proposed by the International Atomic Energy Agency (IAEA) in the report No. 33 was used for estimating the effective doses. **Results:** In 13 routes, the effective dose was found to be above 1 mSv/year, and in 3 routes, it exceeded 6 mSv/year. For 5 routes, the equivalent dose to lungs was higher than 100 mSv/year, and in 1 case it was as high as 490 mSv/year. In 22.6% of underground workplaces the risk of developing lung cancer among employees was about 2 times higher than that for the general population, and for 1 tourist route it was about 5 times higher. The geometric mean of the relative risk of lung cancer for all workers of underground tourist routes was 1.73 (95% confidence interval (CI): 1.6–1.87). Routes were divided into: caves, mines, post-military underground constructions and urban underground constructions. **Conclusions:** The difference between levels of the relative risk of developing lung cancer for all types of underground tourist routes was not found to be significant. If we include the professional group of the employees of underground tourist routes into the group of occupational exposure, the number of persons who are included in the Category A due to occupational exposure may increase by about 3/4. The professional group of the employees of underground tourist routes should be monitored for their exposure to radon. Int J Occup Med Environ Health 2017;30(5)

Key words:
Occupational exposure, Radon, Effective dose, Relative risk of lung cancer, Equivalent dose to lung, Underground tourist routes

INTRODUCTION

Radon is an inert gas that is ubiquitous in all environments. It is formed during α decay of radium and it is also radioactive itself. Radon ^{222}Rn is formed as a result of natural transformation of radioactive uranium isotope ^{238}U which is found in the Earth's crust in average quantities of 2.4 parts/million. Radon short-lived decay products (known as "radon daughters") include polonium ^{218}Po, lead ^{214}Pb, bismuth ^{214}Bi, and polonium ^{214}Po. Initially, these products are positively charged free ions which,

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sooner or later, depending on environmental conditions, are partly neutralized in the air by recombination with small ions in the air. These new structures may remain unbound to form a so-called free fraction or they may be attached to the aerosol particles, forming a bound fraction known as radioactive aerosol [1].

The potential harmful effect to humans of the radon isotope is associated mainly with its short-lived decay products. The percent contribution to the dose to individual organs and tissues is greater from the radon products than the radon itself. This is so because the half-life of radon is approximately 4 days, and almost all inhaled gas is exhaled from the lungs before total radioactive disintegration takes place [2]. Unlike radon, aerosols (including radioactive ones) tend to settle on surfaces.

Inhalation of the air contaminated with radon and its daughters causes that part or all of radioactive aerosols are deposited in various parts of the respiratory tract (i.e., the upper respiratory tract and nose) and subsequently in the cells of mucous membranes, bronchi and pulmonary tissues, where they continue to disintegrate. The total amount of energy emitted by the daughters is several hundred times greater than that produced during the initial decay of radon.

Radon decays with the emission of α particles. Since these particles are more massive and their charge is higher than that of other types of radioactive products, they are more damaging to the living tissue. By breaking the electron bonds that hold molecules together, radiation may damage human deoxyribonucleic acid (DNA), the compound that regulates the structure and function of cells.

Radiation may damage DNA directly (by displacing electrons from the DNA molecule) or indirectly (by changing the structure of other molecules in the cell, which may then interact with the DNA). Once one of these events occurs, a cell may be destroyed quickly or its growth or function may be altered through a change (mutation) that may be imperceptible for several years. A single α particle may cause major genomic changes in a cell. The energy of α particles causes DNA alterations, cell cycle stress, and occasional cell death. These particles may lead to a wide array of DNA mutations [3]. Although induction of mutation and tumor transformation is one of the most important genetic effects of ionizing radiation, the exact molecular mechanism of radon-induced lung cancer development is not clear.

Since radon is a gas and it easily migrates in the soil, it may seep into ground facilities through slits in the Earth's crust. Furthermore, radon is 8 times heavier than the air, so it accumulates in enclosed areas. Such spaces undoubtedly include all underground vaults, caves and mines, as well as other man-made objects, e.g., post-military constructions and, in cities, for example cellars [4].

The article presents the estimation of risk of developing lung cancer as a result of exposure to radon among employees of companies that organize touring trips for tourists wishing to visit Polish underground tourist routes. Risk estimation was based on measuring radon concentrations in selected Polish underground tourist routes. The equivalent dose to the lung and the relative risk was calculated and considered as a hazard to the group of employees working in Polish underground tourist routes.

MATERIAL AND METHODS

We measured radon concentrations for 66 Polish underground tourist routes. Distribution of radon concentration at all measurement points for all 66 surveyed routes is shown in the Figure 1.

A brief summary of the major results of the measurement campaign is as follows:

- in the case of 98.5% of the surveyed Polish underground tourist routes, the average radon concentration exceeds 100 Bq/m^3,
- in the case of 67.7% of the surveyed routes, the radon concentration exceeds the reference level of 300 Bq/m^3 recommended by the European Union [5],

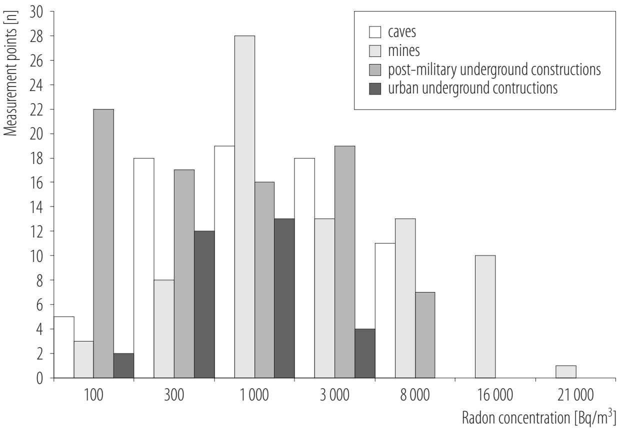

Fig. 1. Radon concentration in every measurement point (N =259) in underground tourist routes in Poland

– in the case of 1.5% of surveyed routes, the radon concentration exceeds 10 000 Bq/m^3.

All results are described elsewhere [4]. Out of the 66 surveyed routes, there are only 31 routes employing workers whose work time in exposure may have a significant impact on the received radiation doses from radon. These 31 routes employed 263 people. In other tourist routes, there are no tourists guides, so estimating radiation doses for the employees of these routes would miss the point. The analysis of the data [4] was narrowed down only to those underground tourist routes, for which data on employee work time was accessible.

The questionnaire survey, including among others: work time, number of employees, was carried out. The equivalent dose to the lungs, and the relative risk (RR) of developing lung cancer among the employees for selected tourist routes in Poland were estimated from the measured radon concentrations and information about work time in the tourist routes.

The equivalent doses to the lungs of workers of tourist routes were determined using the coefficients calculated by the Kendall and Smith [6], based on the human respiratory tract model and computer calculations. The dose coefficient from inhaled radon decay products to lung (calculated for 1 h spent in 1 Bq/m^3) was assumed to be equal to 8.95×10^{-5} $(mSv \times m^3)/(Bq \times h)$ (the dose coefficient to lung: 35.8 $(mSv \times m^3)/(Bq \times h)$, obtained from Kendall and Smith (see Table 2 in their publication [6]) was recalculated into 1 Bq/m^3 and 1 h/year). It should be noted that the authors of the paper [6] admitted that the doses to the respiratory tract they calculated could not be regarded as definitive, however, they provided a useful tool for the assessment of other doses.

The relative risk (RR) represents the ratio of the probability of developing lung cancer among people who were exposed to the impact of the sum of natural and occupational exposure to radon, to the probability of developing lung cancer among people who were not occupationally exposed. The relative risk of developing lung cancer was calculated using the Biological Effects of Ionizing Radiation (BEIR) VI Committee model [7].

This model is based on cumulative exposure to radon and its derivatives, expressed in terms of a work level month (the WLM represents the exposure to radon and its daughters, and combines the amount of radon-origin α particles energy with the exposure time interval, and is: 1 WLM = 170 h × 20.8 $\mu J/m^3$ = 3.54 $mJ \times h/m^3$). The model assumes that radon exposure has multiplicative effect on the baseline rate of lung cancer and the relative risk – decreases with increasing time since exposure and increases with attained age.

The model has been chosen because it does not include an adjustment for smoking, and this project has not been concerned with the analysis of the risk from smoking. According to this model, the exposure received during the last 5 years prior to the date of the analysis is assumed not to increase the risk of lung cancer. The model considers various exposure time intervals prior to lung cancer death, i.e., the cumulative radon exposure is a sum of 3 exposure time windows: 5–14 years, 15–24 years, and ≥ 25 years, prior to the attained age (i.e., w_{5-14} refers to the mean exposure accumulated in the period between 5 years prior to the attained age and 14 years prior to the attained age). The model is expressed as [7]:

$$RR = 1+\beta(w_{5-14}+0.78w_{15-24}+0.51w_{\geq 25})\theta_{age}\lambda_{z} \quad (1)$$

where:

RR – relative risk,

β – the slope of the exposure-risk relationship ($\beta = 0.0768$),

w_{5-14}, w_{15-24}, $w_{\geq 25}$ – cumulative radon exposure (expressed in terms of the WLM) received during time windows 5–14 years, 15–24 years and ≥ 25 years prior to the attained age, respectively, the values before every w – the parameters taken from BEIR VI for exposure-age-concentration model – the WLM contains a cumulative radon exposure both at workplace (work time is within the range 40–2200 h/year, and it depends on the policy of a particular tourist route), and at home (5000 h at estimated radon concentration equal to 100 Bq/m^3) and outdoors (annual hours minus time spent at home, and minus work time; it is assumed that radon concentration outdoors is 10 Bq/m^3),

θ_{age} – the attained age-related modification factor (categorized as: $\theta_{age < 55} = 1$, $\theta_{age\ 55-64} = 0.57$, $\theta_{age\ 65-74} = 0.29$, $\theta_{age \geq 75} = 0.09$),

λ_z – the effect of the exposure rate ($\lambda_z = 1$).

All calculations of the relative risk were made assuming that the age of employees was up to 64 years old.

The dose conversion coefficient proposed by the International Atomic Energy Agency (IAEA) in the report No. 33 [8] was used for estimating the effective doses received by people working in underground tourist routes. In that report it was assumed that 1 h of occupational exposure to 1 Bq/m^3 of radon concentration and the equilibrium factor F = 0.4 correspond to an effective dose of 3.2 nSv [8]. We assumed that the equilibrium factor for underground tourist routes was the equivalent of F = 0.4 because, according to the International Commission on Radiological Protection's (ICRP) report [9], if the equilibrium factor is unknown, for most purposes it is adequate to use the equilibrium factor of 0.4 for work and indoor occupancy.

To find out which type of workplace offers highest risk to the workers' health, we included all underground tourist routes into one of the 4 types: caves, mines, post-military constructions, and underground urban constructions.

Due to log-normal distribution of resultant concentrations, doses and relative risk of developing lung cancer, our data was statistically analyzed using one-way ANOVA for geometrical mean, and significant differences between the groups were evaluated using *post hoc* analysis by means of the Scheffe's test, at $p < 0.05$ selected for statistical significance [10]. We performed Shapiro-Wilk's normality test and Levene's test of homogeneity of variances. And no outliers were noticed. ANOVA was applied to the log-transformed data. All tests checking the assumptions for ANOVA were also performed on transformed data.

RESULTS

General description of dose distribution for employees of routes is as follows.

For 13 routes, the effective dose was over 1 mSv/year (N = 161 employees). For 3 routes, the mean effective dose exceeded 6 mSv/year (N = 27 employees). For 5 routes (with 34 employees), the equivalent dose to lungs was over 100 mSv/year, and in 1 case it was even as high as 490 mSv/year (3 employees).

Radon concentrations, equivalent doses to the lung and relative risk distribution in various types of underground tourist routes are compared in the Table 1.

Out of all the analyzed tourist routes, in 22.6% of cases the individual coefficients of the relative risk (RR) after 40 years of work (the average value for each route) reached the value over 2, and in 1 case the maximum individual value reached even 5.2 (for this particular cave the average radon concentration was 6790 Bq/m^3 and the average work time was 807 h/year). This means that

Table 1. Radon doses and concentration in different types of underground tourist routes in Poland

Underground route	Employees	Radon concentration [Bq/m^3]			Equivalent dose to lung [mSv/year]			Effective dose [mSv/year]			40 year RR		
		GM	min.–max	95% CI	GM	min.–max	95% CI	GM	min.–max	95% CI	GM	min.–max	95% CI
Caves (N = 8, 26%)	127	717	100–4 218	346–1 486	12.7	0.5–102.7	5.3–30.6	0.5	0.0–3.7	0.2–1.1	1.60	1.38–2.18	1.46–1.74
Mines (N = 9, 16%)	53	1 279	153–9 248	623–2 628	37.7*	1.0–490.2	16.4–86.5	1.4**	0.0–17.5	0.6–3.1	1.96	1.38–5.21	1.62–2.38
Post-military underground constructions (N = 9, 29%)	36	421	129–3 526	220–806	7.0*	0.9–269.9	2.8–17.5	0.3**	0.0–9.7	0.1–0.6	1.60	1.38–3.48	1.38–1.85
Urban underground constructions (N = 5, 29%)	47	485	210–1 267	298–789	23.8	1.5–249.4	6.5–87.6	0.8	0.0–8.9	0.2–3.1	1.82	1.38–3.32	1.11–1.43
Total (N = 31, 100%)	263	682	100–9 248	486–959	16.0	0.5–490.2	10.2–25.8	0.6	0.0–17.5	0.4–0.9	1.73	1.38–5.22	1.60–1.87

GM – geometric mean; min. – minimal value; max – maximal value; CI – confidence interval; RR – relative risk.
* Values statistically different $p < 0.05$.
** Values statistically different $p < 0.05$.

for 22.6% of workplaces mentioned above (56 employees), the risk of developing lung cancer among employees is about 2 times higher than that for the average person living in Poland, and for 1 tourist route (3 employees) it is about 5 times higher.

DISCUSSION

In order to compare our data, we have related it to the limit values that are obligatory in Poland [11]. According to the relevant law, for the purposes of monitoring and surveillance, the exposed workers are classified into the Category A (annual effective dose > 6 mSv) and Category B (1–6 mSv). That is why we divided all effective doses possible to be received by employees in underground tourist routes into 3 groups of occupational exposure (0–1 mSv/year, 1–6 mSv/year and > 6 mSv/year).

For 13 routes, the effective dose was over 1 mSv/year, which according to Polish law [11], qualified the staff for the Category B of radiation exposure. This group included 161 employees. For 3 routes, the mean effective dose exceeded 6 mSv/year (N = 27 employees). If that occupational group (workers of the underground tourist routes) were included into the dosimetry control program, it is likely that it would be necessary to classify additional 27 people annually into the Category A exposure. According to the National Atomic Energy Agency (according to notifications to the central register of doses submitted until 30 April 2015) [12], every year about 41 people in Poland are classified to that category of exposure. Thus, including the group of employees of underground tourist routes into the dosimetry control program would increase the number of people working in a Category A of radiation exposure by about 3/4.

For 5 routes (with approx. 34 employees), the equivalent dose to lungs reaches over 100 mSv/year, and in 1 case it is even as high as 490 mSv/year. The Polish law [11] has no established dose limits to the lungs, although the lungs have one of the highest tissue weighting factor w_t (0.12), according to the Directive [5]. This is probably due to the relatively poor knowledge about the contribution of the absorbed dose to the lung injury. The need to increase this knowledge is indicated by the example of a similar compound affecting the lens of the eye. For many years it was thought that the clouding of the lens of the eye [13] had been caused by doses greater than about 100–150 mSv. The recent research has shown the need to lower the limit equivalent dose for the lens of the eye over 7-fold [5]. Due to the high radiosensitivity of the lung to α radiation specified above (epithelial in particular), in-depth studies such as those performed in the case of the lens of the eye seem necessary.

The Table 1 shows that the highest average dose to the lungs occurs in underground routes such as mines and urban underground constructions. Interestingly, the highest concentration of radon, of the order of 1000–9200 Bq/m^3, is found in adapted mines rather than in urban constructions (except for single cases of high radon concentrations in other types of underground routes). High doses to lung in underground urban constructions are caused by characteristics of the work, i.e., by long work time rather than the high radon concentrations. The average radon concentrations in this type of the routes except for one single case (1270 Bq/m^3) did not exceed 1000 Bq/m^3. The difference between the origin of received doses shows how important it is to measure radon concentration at workplace and suitably adjust the work time in order to ensure proper protection against radiation.

The statistical data indicates [14] that over a 40-year period, approx. 2.2% of the Polish population should develop lung cancer (the summarized data for 2013 year; for both sex; for site: C34). We analyzed the data from 66 out of over 200 Polish underground tourist routes. We assume that the number of employees in 200 underground tourist routes is approx. 1400 people. The statistical data [14] indicates that during 40 years of working life, around 31 people out of 1400 people (2.2% of 1400 people) develop lung cancer. The analysis of the relative risk leads to the conclusion that among the group of 31 people (working in the underground tourist routes under the same work time schedule and radon concentration as at present), about 42.3% (13 people) lung cancer cases would be caused by exposure to radon.

For the sake of comparison, we created an artificial control group that also included 1400 people. We used the same equations as in calculating doses and risks but we assumed that an average person works in the place where average radon concentration is as low as that found in conventional buildings (we assessed it to be equal to 100 Bq/m^3). The value of 100 Bq/m^3 was chosen deliberately because according to the new Council Directive 2013/59/Euratom of 5 December 2013 [5], this radon concentration level statistically significantly increases the risk of developing lung cancer as a result of prolonged exposure to this radon concentration inside the premises. The average person spends at work the same time as employees in underground tourist routes do. We also assumed home exposure to radon similar to that experienced by the employees in the underground routes. The comparison showed that among artificial control group there will be 13.2% less of radon induced lung tumors (9 of 31 people) relative to radon induced lung tumors caused by the same time exposure but developed among people working at higher radon concentrations in underground tourist routes (13 of 31 people).

The statistical analyses were performed only for those underground tourist routes, for which data on work time of employees was accessible. Thus, most of spectacularly high radon concentrations found in some underground tourist routes described by Olszewski et al. [4] do not contribute to the calculated doses and the relative risk. This is also the reason why the statistical significance in the distribution of radon concentrations is different in our discussion than that described in the publication quoted above [4].

We did not find any significant difference between radon concentrations in different types of tourist routes.

The statistical analysis indicated that there was a statistically significant difference in calculated equivalent doses to the lung in the mines and the post-military constructions ($p = 0.047$). There was also a statistically significant difference in calculated effective doses to workers in the mines and the post-military constructions ($p = 0.044$).

The geometric mean of relative risk after 40 years of work varies for different types of underground tourist routes between 1.6 and 1.96 (Table 1) but the difference between the values was not found to be significant. This is very informative because it means that despite of different statistical significance of the dependencies between the doses, the relative risk for all underground tourist routes is on a comparable level (mostly because of relatively high background radon concentration common for all guides we assumed: 5000 h in home with average radon concentration equal to 100 Bq/m^3).

Referring to the classification of the tourist routes into 3 groups with respect to effective doses received by employees (dose ranges: 0–1 mSv/year, 1–6 mSv/year, and > 6 mSv/year, which correspond to categories: no category, Category B, and A respectively, according to applicable Polish law) we found statistically significant differences between almost each of these groups in respect of effective doses, relative risks and radon concentrations. We did not find a significant difference in radon concentrations only between the Category A and B of exposure.

The statistical analysis confirmed the need to classify workers of underground tourist routes to one of the above categories of exposure and their inclusion in all of the provisions governing the categorization of workers, with further consequences thereof [11].

Synopsis

From the cohort of all employees of the surveyed tourist routes, after 40 years of work, about 42.3% cases of lung cancer will be caused by exposure to radon. If we analyze the same size group of employees who spend the same time in the workplace, not in routes underground but in places that do not cause an obvious exposure to radon (assuming that the average concentration of radon is 100 Bq/m^3), after 40 years of work the number of people who develop lung cancer caused by exposure to radon would be about 13.2% less.

For 13 routes, the effective dose was above 1 mSv/year. For 3 routes, the mean effective dose exceeded 6 mSv/year. For 5 routes, the equivalent dose to lungs reaches above 100 mSv/year, and in 1 case it was as high as 490 mSv/year.

The number of persons who are included into the Category A of radiation exposure due to occupational exposure (from the point of view of the Polish Atomic Law) is 41 (according to notifications to the central register of doses submitted until 30 April 2015 [12]) . If we include the professional group of the employees of underground tourist routes into the group of occupational exposure, the number of persons who are included to the Category A due to occupational exposure could increase by about 3/4.

The geometric mean of the relative risk of developing lung cancer among employees of all types of underground tourist routes is 1.73 (95% confidence interval (CI): 1.6–1.87). In 22.6% of workplaces quoted above (56 employees) the risk of developing lung cancer among employees is about 2 times higher than that for the general population, and for 1 tourist route (3 employed) it is about 5 times higher.

In contrast to calculated doses for different kind of underground tourist routes, the differences between values of the relative risk for them were found to be not statistically significant.

CONCLUSIONS

The relative risk of developing lung cancer is higher for people working in underground tourist routes than for general population, i.e., in places that do not cause an obvious exposure to radon (assuming that the average concentration of radon is 100 Bq/m^3).

The professional group of the employees of underground tourist routes should be monitored for their exposure to radon.

The level of the relative risk of developing lung cancer for all types of underground tourist routes examined by us is comparable.

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