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ORIGINAL ARTICLE

Impact of radon exposure upon dynamics of mortality rate from lung cancer for population of Rivne city, Ukraine

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A certain connection exists between the level of radon in the air and diseases of the human respiratory system. The prersent research evaluates the risk of disease incidence with oncologic lung illnesses and mortality rate from them on the account of exposure during the inhalement of internally in-built radon by the population in Rivne city dwellings. We measured radon in 2011-2016 and used radonometer «Alfarad Plus». The method proposed by Covello and Merkhofer (1993) and NRC (1983) is used. In accordance with it, the assessment of mortality rate of city inhabitants from lung cancer due to internal exposure to radon was carried out in four stages. This, in particular, is the identification of population, the analysis and selection of the most optimal dependence of «dose-effect», the direct evaluation of radon influence on population and the calculated risk of lung cancer. The measurement of radon concentration in premises in Rivne testify its substantial variability. The average geometric value of VA for basement premises amounts to 365 Bk/cub.m and for semi-basement premises-161 Bk/cub.m. The prognosticated maximum possible value of VA in buildings by results of our measurements is assessed as 1.420 Bk/cub.m. Thus, the calculated expected shortening of life duration for population of Rivne by different models of DDE constitutes from 1.2 to 4.0 years for the whole population and from 2.5 to 7.41 years for those share of population who smokes.
Keywords: Radon; coefficient of additional relative risk; exposure; lung cancer

Introduction

The impact of radioactive gas Radon on population health causes anxiety in many countries of the world. Thus, in particular, it is considered that in the USA it provokes approximately 21,000 deaths per year from lung cancer deseases (Samet, 2011). In fact, this makes radon the second most important cause of this ilness after smoking. Such mortality rate exceeds twice the mortality on account of accidents because of driving cars in intoxicated state (National Highway, 2017) and exceeds the number of many other disclosed death causes, for example, murders (Statistics, 2016). Studies conducted in the USA show that the risk of diseases from lung cancer (mainly, at adenocarcenoma, scale-like carcenoma and sarcoma of lymphatic nodes) increases by 11% with the increased radon concentration in residences per every 200 Bk/cub.m (Krewski et al., 2005).

The start of the real splashing of researches into "radon problem" may be regarded as 1984. Then in the state of Pennsylvania a building had been found with radon concentration inside of which there were 96,000 Bk/cub.m. In accordance with the present-day notions the risk of of the emergence of lung cancer while dwelling in auch a building was equivalent to the emergence of such desease from smoking by a human being of 250 packets of cigarettes per day.

With time there had been discovered also other radon dangerous zones in the USA and countries of Europe. The research into the radon problem in dwellings attracted close attention at first of media, and then in the USA Congress (King, 1993; Shabecoff, 1985). In 1986 the Environment Protection Agency (EPA) of the USA had established the level above which it is recommended to carry out special measures to decrease the content of this gas (building and ventilation ones). This level for buildings in the USA is 148 Bk/cub m. About 7% buildings in the country have radon concentrations higher the said level. In 1987 radon had been recognised as the most serious danger for Americans' health. In 1988 The Congress of the USA adopted the Law about banning radiation in air which specified the ain and taska on decreasing radon in buildings and other premises in the country. By this law EPA received the permission to get 10 million dollars annually for developing programs against radon in the country. The wide information of population via press and television about "radon problem" and ways and means of its prevention became possible. In addition to large-scale media information via food stuff shops of the country and post office there began to spread cheap ($ 5.00) testing sets for determining radon concentrations in dwellings. In 29 states the determination of radon concentrations in dwellins had become a necessary element of transactions with real estate (National Conference, 2015).

Unfortunately, these measures were sort-lived. From 1997 to 2007 the financement anti-radon programs in the USA was curtailed by two thirds and at present approaches the complete cessation (Angell, 2008; Eiperin et al., 2017).

In contrast to the USA European institutions during last decades suggest more harder requirements concerning the limitationof radiation pollution of territories of resdences in Europe and world. In particular, in Council Directive 2013/59/EUEATOM (Council of the European Union, 2014) particular requirements are formulated for mational legislations of countries-members of EU concerning the solution of the general problem of the impact of radon exposure which is 300 Bk/cub.m for dwellings and working places. Besides, the states of EU are suggested to develop own «plans of actions concerning radon». Such actions foresee the development of methods and indices for measuring and evaluating radon concentrations.

In Ukraine the information of population about "radon problem" is very low, though the pollution by radon of dwellings in some places exceeds by several times the norm set up in EU (Lebed et al., 2018).

The aim of this research was the assessment of the risk of lung cancer emergence through the radon inhalation in interior building air into the respiratory ways of Rivne city inhabitants. We used the results of our own studies and epidemiological data about the mortality rate of region inhabitants, we compared these results with similar French studies. In particular, we used several models of «dose-effect» dependency with the aim of determining the number of deaths of city inhabitants from lung cancer during the period of 2011-2015 which could be connected with radon exposure. The object of research: indices of Radon-222 concentration in dwelling premises in Rivne city. The subject of research: depeneence of mortality rate of inhabitants of Rivne city on lung cancer provoked by radon during the period of 2011-2015. The complex of tasks which faced research and development work were the following:

- To carry out research to determine indices of volume activity of Radon-222 in premises of Rivne.
- To analyse statistical mortality data and diseases of Rivne inhabitants from oncological lung illnesses.
- By results of studies to determine the dependence of mortality rate on the cancer of trachea, bronchi and lungs of city inhabitants on the rodon concentratio in their dwelling. To determine mortality rate from this disease on account of radon.
- To compare data obtained with data of similar researches by other authors.

Materials and methods

During recent decades international scientific community made substantial efforts to develop methods for assessing doses and risks from the harmful impact of radon on human population. In particular, a number of scientists (Dalby et al., 2006; Groche et al., 2006; Lubin et al., 1994) and other experts (EPA…, 2003; WHO…, 2009; Health…, 1999) performed a series of epidemiological studies directed at determining the risk of mortality rate of miners and other categories of population of countries of Europe and North America from lung cancer caused by radon impact. By results obtained a number of models were developed of the dependence of «dose-effect» (DDE); two models BEIR VI (Health…, 1999); a model "Bismuth" (Grosce et al., 2006); a model of constant relative risk (CRR), a model GSF (Yacobi); a model TSE/AGE/WL; a model of Lubin and other methods of evaluating doses and risks. The procedure of assessing the risk was suggested by Covello and Merkhofer (1993) and NRC (1983). In accordance with them, the assessment of mortality rate from lung cancer due to the interior exposure by rodon of population of Rivne it is necessary to carry out in four stages which include the identification of population, the selection of DDE, the assessment of radon impact and the calculation of risk from lung cancer.

Characteristics of population of Rivne city

We conducted the calculation of mortality rate from lung cancer of inhabitants of Rivne caused by various reasons during 2011-2015. Data on population including age and sex are obtained from «Collection of health indices of population and activity of medical institutions of Rivne region during 2014-2015» (Collection of …, 2016). In accordance with these data as on January 1, 2015 the total population number amounted to 246,217 people. The proportion by age is: 16% population <15 years, 2.5%-15-17 years, 81.5%-at the age of 18 and older. Interrelationship of able-bodied males and females amounts to 47% and 53% correspondingly. The number of Rivne region territory patients with malign growths in trachea, bronchi, lungs by 2015 data amounted in the following: registered in the current year-218 persons, from the patients number with the first established diagnosis of I-II illness stage-60 persons, III-71, IV-70, registered by the end of the year-633 persons. The dynamics of mortality rate from malign new growths in trachea, bronchi and lungs for Rivne inhabitants is presented in Figure 1.

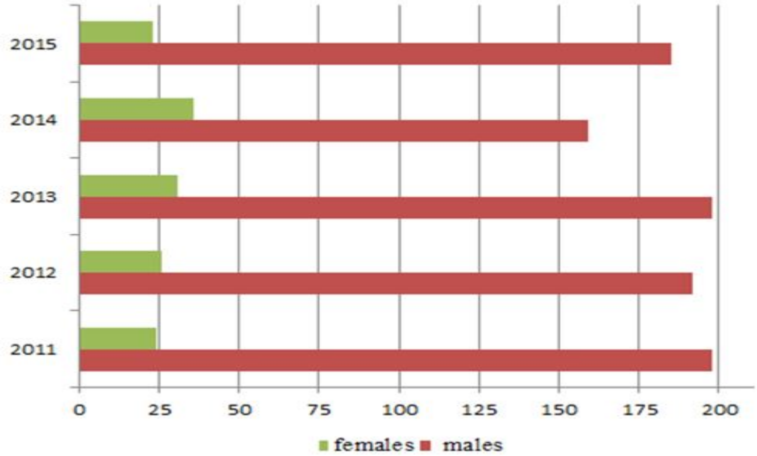

Figure 1. Mortality rate from maling new growths in traches, bronchi, lung in 2011-2015 in Rivne city.

If we compare the mortality rate of population from «radon problem» in our region with France, then by the data of French institute of health and medical studies (INSEE, 2000), the Centre responsible for compiling the national statistics of mortality rate, then in 1999 because of lung cancer in France died 25,144 persons (20,823 males and 4,321 females). In accordance with our data to Rivne region the nearest by the above specified problems is the region of Corsica island (French Republic). They are almost identical by indices of geology and geomorphology of soils, population number and structure of dwellings (Lebed et al., 2018). This region is characterized by the mortality rate from lung cancer in the period from 1990 to 1999-155 persons per year from the total population of the island-246,215 persons in 2015.

Data about the spreading of tobacco smoking within different sex and age groups of Rivne population are unknown to us as they on the regular basis in Ukraine are not collected. In fact, among post-Soviet countries only the Russian Federation has similar data. In 2009 Russia carried out «Global survey of adult population concerning tobacco consumption (GATS)» (Global ..., 2009), having fulfilled in this way the requirement of «Framework convention of World Health Organization on fighting against tobacco» with the aim of collecting data for comparison. By data of survey of GATS Russia became the first among countries of the world in the percentage of smoking population. Taking into account common Soviet past it is possible to assume that the attitude to tobacco smoking in our countries is approximately the same, then its spreading among various sex and age groups of Rivne, by data (Kononenko, 2013) will be the following: 15-18 (males-30%, females-18%), 19-24 (65% and 39% correspondingly), 25-44 (69% and 30% correspondingly), 45-64 (63% and 18% correspondingly), 65 and over (40% and 5% correspondingly). Here we made such assumptions:

- Sex and age distribution of smoker's part in Rivne city coincides with the total Russian one.
- 100% population in the age younger15 is regarded as such that does not smoke.

The proposed distribution of population by factor of tobacco smoking in Rivne we compared with the data about the tobacco consumption in France which by tradition is characterized by the high level of smoking. Information about the part of those who constantly smoke in the total quantity of population comes from researches carried out in the 1990s by French research and information institute of health protection economy (Hill, Laplanche, 2003). This research testifies to the fact that on the average 65% males and 31% females in France smoked during certain, rather long period of their life. Though in France the part of males smoking increases with age (approximately 55% of those who are 16-39 and 70% of those who are ≥40), the female part decreases with age (approximately 47% of females who are 16-39 up to <30% 0f those who are ≥ 30) (Hill, Laplanche, 2003). In the 2000s due to the strong anti-nicotine campaign the number of smokers in France decreased approximately twice. Since 2003 the substantial decrease is observed of cigarettes sale (decreased by 13.5% within 2002 and 2003). It is possible to consider that by the level of smoking in 2015 Ukraine and France became even.

Choice of exposure-response relations (ERR)

Historically to calculate risks of oncological diseases of population from exposure by radon and its daughter products of decay (DPD) first was used the model «Bismuth» developed in the German Democratic Republic by results of experimental studies conducted from 1946 to 1990 on a sample of 59,001 miners of uranium mines of «Bismuth» company. Among them 2,388 cases were registered of deaths from lung cancer. Such model had shortcomings which did not take into account the whole series of parameters influencing the risks of oncological diseases of miners. In us researches we oriented ourselves at the following epidemiological data concerning the radon influence: general analysis of 11 samples of American miners (Health ..., 1999; Lubin et al., 1994), joint analysis of radon impact upon French and Chekh miners (Tirmarche et al., 2003), two available joint analyses of «case-control» (Darby et al., 2005; Lubin, 2003). We analyzed the following models:

Model of constant relative risk (CRR): For this model basic is the assumption that coefficient of additional relative risk in age t-ERR(t) depends only on the capacity of exposure by radon DPD obtained at age t_e, $P_{WLM}(t_e)$ and does not depend on other factors:

$$ERR(t)=0.0083 \cdot P_{WLM}(t_e), \text{ for } t \geq t_e+\tau \quad (1)$$

where τ-latent period constituting 5 years. ERR (by physical content)-is the function of cumulative influence of radon exposure dependent on the time of exposure, age, duration and intensity of exposure.

The coefficient of additional relative risk stipulated by the cumulative exposure of radon DPD during all the period of life or during a certain period (industrial activity) is calculated by formula:

$$ERR(t) = 0.0083 \bullet \sum_{t_e=0}^{t-\tau} P_{WLM}(\mathrm{t_e}) \quad (2)$$

Under exposure P_{WLM} (in WLM units) during impact time period T is understood the following expression:

$$P_{WLM} = \int_0^T EEVA_{Rn} dt = (\mathrm{EEVA_{Rn}})_{\mathrm{av}} \bullet T \quad (3)$$

where $EEVA_{Rn}$-equivalent equilibrium volumetric activity, or it is variable in time value of equivalent balanced voluminous radon activity, $(EEVA_{Rn})_{av}$-is the average value of radon $EEVA_{Rn}$ during time T of radon impact. The re-calculation of measured values of average annual exposure P(Bk.h/cub.m) into an exposure value in WLM is done by formula (Demin et al., 2014; Lipnitsky & Kostitskaya, 2004):

$$P_{WLM} = \frac{P(\mathrm{Bk.h/cub.m})}{170.3700} \quad (4)$$

Value 1 WLM corresponds approximately to exposure under EEVA which equals 100 nKi/l (3,700 Bk/cub.m) during 170 hours.

Model GSF (Yacobi's model)

In contrast to model of constant relative risk, in GSF model it is calculated that coefficient ERR (t) depends on time passed from the moment of radon DPD $\varphi(t-t_e)$ and age at the moment of exposure (t_e). For one-time action of radon DPD at age with exposure capacity $P_{WLM}(t_e)$:

$ERR(t,t_e)=P_{WLM}(t_e).s(t_e).\ \varphi(t-t_e)$, (5)

Where $s(t_e)$-coefficient of proportionality which takes into account the carcinogenic receptivity of lungs which decreases with age increase of a human being exposed, the function $\varphi(t-t_e)$ characterizes the distribution of relative latency and is normed per unity in maximum. By the next maximum the decrease is envisaged of additional relative frequency of illnesses with the period of double decrease equivalent to 10 years.

The coefficient of additional relative risk stipulated by the cumulative exposure of radon DPD during all the period starting from life beginning is calculated by formula:

$$ERR(t) = \int_0^{t-\tau} ERR(t,t_e).dt_e \approx \sum_{t_e=0}^{t-\tau} ERR(\mathrm{t,t_e}) \quad (6)$$

Model BEIR-IV: In 1988 a method was proposed of using risk models BEIR-IV on the basis of the statistical analysis of results of epidemiological studies of radon impact on four groups of miners. In this model the coefficient of additional relative risk of lung cancer ERR in age t depends on exposure to radon DPD in the past:

$$ERR(t) = 0.025.\gamma(t).(P_{WLM,1} + \frac{1}{2}P_{WLM,2}), \quad (7)$$

where is an age individual coefficient of matching the coefficient of additional relative risk, namely:

$$\begin{cases} \gamma(t) = 1.2 \ at \ t \le 55 years; \\ \gamma(t) = 1.0 \ at \ 55 \le t \le 65 years; \\ \gamma(t) = 1.2 \ at \ t \ge 65 years; \end{cases} \quad (8)$$

$P_{WLM,1}$-exposure obtained by a human being during the time from (t-15) years to time (t-5) years, $P_{WLM,2}$-exposure obtained by a human being till time (t-15) years. Hence, model BEIR-IV takes into account ERR decease with the age of a human being and does not depend on last 5 years.

In extrapolating risk assessments from exposures to DPD received in mines to exposures obtained in buildings model developers assumed that risk is proportional to a dose received by cells-targets that pave the respiratory ways of lungs. Hence, to evaluate the risk from exposures received in dwellings the right part of equation (7) it is necessary to multiply by a certain coefficient K which depends on many parameters which may differ for mines and buildings. They include: the frequency of human breathing, the deployment of cells-targets in lungs, the thickness of mucous membrane, the distribution of aerosol particles on which radon DPD sediment by size, the relative concentrations of radon DPD also. The BEIR committee came to the conclusion that K is to be near 1 and recommended equation (7) to be used for the case of radon exposure in dwelling premises. In 1991 after a deeper research of this issue the decision was taken that the best assessment for K will be the value of 0.7. Therefore, the following formula was adopted to determine the coefficient of additional relative risk for lung cancer K_{ERR} from the radon exposure in a dwelling (EPA, 1992):

$$ERR(t) = 0.00175.\gamma(t.(P_{WLM,1} + \frac{1}{2}P_{WLM,2}) \quad (9)$$

Model BEIR-VI: The initial combined analysis of disease incidence for lung cancer of 11 groups of miners had been published in 1994 (Lubin et al., 1994). In 1999 the National Academy of Sciences of the USA suggested a risk model BER-VI (Health …., 1999) after studying miners of all groups with the total number of 60,606 persons. This model is one of the most up-to-date and takes into account the maximum number of factors which influence the processes of the emergence of radiation induced lung cancer. These factors include:

- time passed from the moment of exposure to radon DPD;
- age at the moment of risk evaluation;
- the fact of tobacco smoking;
- the level of radon EEVA during which was formed exposure to radon DPD.

It is possible to single out two main differences of model BEIR-VI from earlier considered models:

1. model BEIR-VI uses various values of additional relative risk for smokers and for those who do not smoke (the so called sub-multiplicative interaction of smoking factor and exposure to radon DPD);
2. model BEIR-VI prognoses the decrease of relative risk per unit of exposure with the increase of capacity of equivalent dose to lung tissue (increased radon EEVA in the process of exposure).

Depending on initial parameters this model has two variants:

- Variant 1 (EAD)-relative risk depends on the time passed since the moment of irradiation, exposure, age achieved and duration of irradiation (model «exposure-age-concentration»)
- Variant 2 (EAC)-relative risk depends on the time passed from the moment of irradiation, exposure, achieved age and the level of balanced voluminous activity (EEVA) of radon in the premises during the process of irradiation (model «exposure-age-intensiveness»).

The general form of the function ERR (t) in these variants is suggested in the form:

$ERR(t)=\beta.(P_{5\text{-}14}+\theta_{15\text{-}24}.P_{15\text{-}24}+\theta_{25}+.P_{25+}).\varphi_{age}\gamma_z$ (10)

where β-main parameter of dependence ERR («risk-coefficient»),

$P_{5\text{-}14}$, $P_{15\text{-}24}$, P_{25+}-windows of exposure which determine the cumulative radon exposure and its DPD received in time intervals from (5-14) years to time t, from (15-24) years to time t and from 25 years and more to time t for which the risk assessment is carried out;

$\theta_{15\text{-}24}$, θ_{25}-coefficients which determine the relative contribution into the risk of cancer emergence from exposure obtained during the said time intervals to age t;

parameter φ_{age} determines the dependence of carcinogenic receptivity of lung tissue on the age achieved;

γ_z parameter depends either on the duration of irradiation (in years), or on the level of radon EEVA during which the obtained exposure was formed.

In proposed models is also laid out the presence of five-year latent period in developing lung cancer, therefore, exposure obtained during last 5 years to age t in formula (10) is not taken into account. A certain shortcoming of this model may be regarded the consideration of the fixed part of smokers irrespective of the country (58% -males and 42%-females).

Model TSE/AGE/WL: In 2003 the results became available of the European research project (Tirmarche et al., 2003). The analysis of those studies was based on results received by mortality indices among French and Czech groups of miners amounting to over 10,000 miners on the account of the influence of the low level of radon exposure. These data were a good base for the quantitative determination of risks connected with the chronic exposure to radon radiation with relatively low capacity of a dose. The average duration of the exposure observation exceeded the duration by the model BEIR-VI of 11 groups of miners (24 years against 15). The criteria of inclusion permitted to concentrate on miners with highly qualitative evaluations of the influence and the quantitative interrelationship of ERR. ERR increased with the summary radon exposure and decreased with age during exposure and in time after increased exposure. The model obtained on the basis of this joined analysis (French-Czech (FCZ) model) is a linear model which takes into account modifying effects of age with median irradiation and also the time passed after median exposure. It is expressed by such interrelationship:

$ERR(t)= \beta.P(t).\exp[(\varphi.A)+(\gamma.T)]$, (11)

where β-coefficient of ERR inclination («risk-coefficient»), and P(t)-average median exposure during the time of irradiation to 5 years when ERR is determined. Variable values A and T determine the age with the average exposure and time starting from median, correspondingly, and φ, γ-are constants interrelated between themselves. Details of this model and its implementation are presented in (Tirmarche et al., 2003).

Lubin model: In 2003 Lubin informed about the joint analysis of «radon problem» in dwellings by results of seven researches into the cases of illnesses of lung cancer in Northern America (Lubin, 2003) carried out in states of New Jersey, Missouri, Iowa, Connecticut and Utah (USA), province of Winnipeg (Canada). The analysis included 4,081 cases of lung cancer (2,766 females and 1,315 males). To assess ERR Lubin used simple formula:

$ERR(t)= \beta.X$, (12)

where β-coefficient of inclination of DDE interrelationship («risk-coefficient»), X-the average concentration radon in premises in a certain window of exposure (ETW). ETW is chosen in the period of 5-30 years since the time of determination. Lubin believes that the largest harm for a human organism from radon is for this period of irradiation.

Results and discussion

The evaluation of radon impact. As the interior dwelling values of radon VA changes in time depending on the season (they are the largest in winter and lowest in summer), we made a seasonal correction of measured values in accordance with results by Arvela, 1995; Baysson et al., 2003; Pinel et al., 1995. The measurement of voluminous activity (VA) of radon was carried out with the help of radonometer «Alpharad Plus» in 600 premises of ground floors, semi-basement and basement premises of living quarters and industrial fund in 48 testing grounds in Rivne city during 2011-2016 with the correction for a season of measurements (Klymenko, Lebed, 2017). The main tasks of this campaign of measurements were the determination of radon dangerous parts in Rivne, the assessment of the percentage of dwelling premises with values of VA higher the level of action and the research of factors influencing radon concentration. The division of the city into a network of squares with the area of approximately 900 sq.m. guaranteed the homogenous geographic distribution of measurements. The distribution of interior building values of radon VA bears lognonormal character. Statistic parameters were determined of distribution of VA in accompanying products of radon isotopes: mathematical expectation (VA_{2m}) for VA, geometric standard deviation VA(σ) and prognosticated maximum value VA. As a last parameter the value was considered at the level of the threshold value of the probability density of corresponding deviation from maximum distribution at the distance 3σ («the rule of three sigmas»). The average geometric value of VA for basement premises was 365 Bk/cub.m, and for semi-basement premises-161 Bk/cub.m which substantially exceeds building norms for both types of premises. For living quarters of ground floors in Rivne the average geometric value of VA was 127 Bk/cub.m [95% of indeterminancy interval (IIn): 118-137] with the geometric standard deviation σ=0.7987; the average arithmetic-145.6 Bk/cub.m, maximum (at the level of σ)-714 Bk/cub.m. If to evaluate the average arithmetic value for VA for all researched premises, then it was 262.5 Bk/cub/m with the standard deviation 194.4 Bk/cub.m with the average geometric-200 Bk/cub.m under geometric standard deviation σ=0.7865. The maximum measured value of VA_{meas} is 1000 Bk/cub.m, prognosticated maximum possible value of VA by results of our measurements is assessed by the value which does not exceed 1,420 Bk/cub.m. Measured values are chosen as bench-mark ones for calculating risk for illnesses of lung cancer for city population. Results obtained show that a part of dwelling ground floors where the level of radon exceeds the value of EEVA = 200 Bk/cub.m (building norms) is 6.6%, then, if we consider all investigated premises, it is-14.23%. In accordance formulas (2, 6, 9, 10) we got relationships of ERR with time t during which a human being received radon irradiation in his dwelling under certain average value of VA on the average in Rivne (Figure 2). For analysis we stopped on two values of VA-the average geometric value in all researched premises 200 Bk/cub.m and some prognosticated possible maximum value 1,420 Bk/cub.m to compare ERR. Further calculations of mortality rate for inhabitants at the expense of radon were carried out assuming that inhabitants all their life lived in buildings with VA=200 Bk/cub.m.

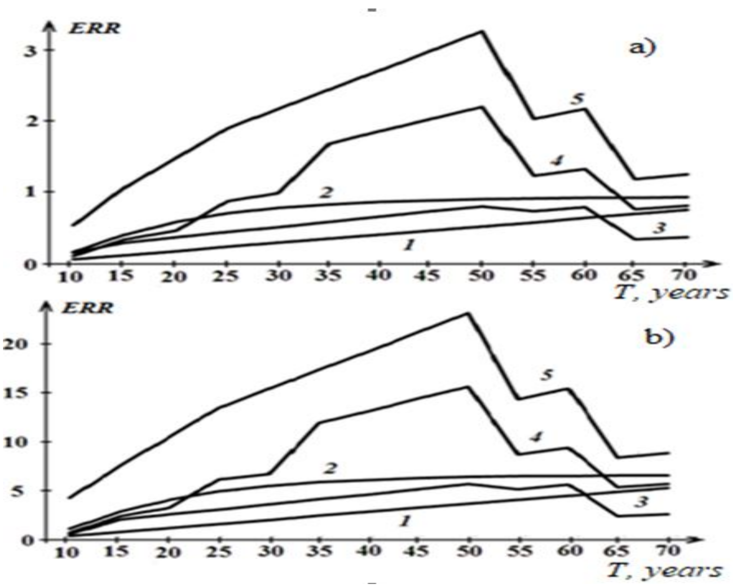

Figure 2. Dependence of coefficient of additional relative risk ERR on the age of inhabitant of Rivne who resides on the ground floor of the building with radon VA equal: a) 200 Bk/cub.m; b) 1,420 Bk/cub.m depending on the chosen model: 1-model of constant relative risk; 2-Yacobi model; 3-model BEIR-IV; 4-EAD; 5-EAC.

To take into account the factor of smoking we conducted the calculation of ERR value separately for smokers, people who do not smoke and for the whole population with the help of models EAD and EAC adopting that people reside in buildings with VA = 200 Bk/cub.m (Figure 3).

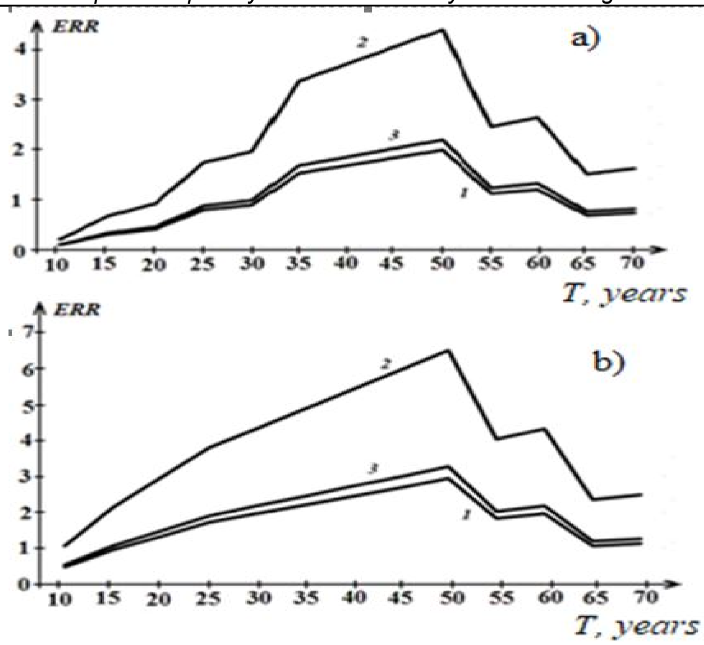

Figure 3. Dependence of coefficients of additional relative risk ERR on the age of inhabitant of Rivne residing on the ground floor of a building with radon VA equal to 200 Bk/cub.m: a) EAD; b) EAC for: 1-smokers, 2-non-smokers, 3-for total population.

The calculation of risk of lung cancer. The assessment mortality rate from lung cancer connected with radon exposure in premises requires the joining of several sets of data: ERR, mortality rate from lung cancer in Rivne city in 2011-2015, a share of smokers and the evaluation of interior building radon irradiation.

The use of the above said interrelated ERR requires the knowledge of a number of spontaneous deaths from lung cancer (that is those, which occurred not at the expense of the exposure to radon). The majority of the analyzed cases of deaths from lung cancer observed in the said period took place, probably, through the use of tobacco, some-only through the breathing in premises containing radon, others-in the interaction between smoking and radon in premises, and the rest-were determined by such factors of risk as air contamination and the professional influence (AFSSE, 2004; Darby et al., 2001).

To evaluate the mortality rate from lung cancer connected with radon exposure in premises there are several methods. We for comparison applied our data and a method (Catelinois et al., 2006) which proposes the following formula:

$$N_{r,a,d,s} = \frac{ERR_{r,a} . N_{a,d,s}}{1 + ERR_{r,a}}, \qquad (13)$$

where $N_{a,r,d,s}$-the mortality rate from lung cancer due to interior building irradiation by radon at age a in a building situated on the territory under number d for sex s,

$ERR_{r,a}$ is a coefficient of excessive relative risk in age a and radon exposure r,

$N_{a,d,s}$-total mortality rate from lung cancer at age a on territory under number d for sex s.

The value of complete shortening of expected duration of life is possible to calculate by the equation:

$$\Delta L_r = \sum_{t=0}^{\infty} p_0(\mathrm{t}) - \sum_{t=0}^{\infty} p_0(\mathrm{t}).\exp\left[-\sum_{t'=0}^{t} k_{let}\lambda_0(t')\,\mathrm{ERR(t')}\right], \qquad (14)$$

where p_0(t)-the function of attaining age (probability of achieving by a human being the age t since birth),

λ_0(t)-age-specific frequency of illness for lung cancer,

k_{let}-coefficient of lethality (k_{let}=0.95).

By formula (13) we calculated the approximate mortality rate for population of Rivne city from lung cancer connected with radon exposure in city premises taking into consideration the indeterminacy concerning the exposure-response relations (see Table 1). Depending on the type of risk model the total mortality rate from lung cancer connected with radon exposure in city premises in 2011-2015 averaged by radon irradiation of population at age a and in a building situated on testing ground under number d is from 5 to 128 for males and from 1 to 23 for females. This constitutes from 3 to 64% of all deaths annually during a researched period from lung cancer for males and from 3 to 77% for females. The least mortality rate at the expense of radon gives the calculation by the model of proportional relative risk (PRR), the largest-by the model EAC. Here it is to be noted that the level of voluminous activity (VA) in 200 Bk/cub.m is not considered to be too high.

Table 1. Assessment of mortality rate from lung cancer connected with level of radon exposure in premises in Rivne in 2011-2015 by different ERR.

DDE	Mortality rate from lung cancer at expense of interior building radon with VA=200 Bk/м^3

	2011		2012		2013		2014		2015	
	male	**female**	**male**	**female**	**male**	**female**	**male**	**female**	**male**	**female**
PRR	6-59	1-7	6-57	1-8	6-59	1-9	5-47	1-11	6-55	1-7
GSF	17-68	2-8	16-66	2-9	17-68	3-11	13-55	3-12	16-63	2-8
BEIR-IV	15-62	2-7	15-60	2-8	15-62	2-10	12-50	3-11	14-58	2-7
EAD	11-110	1-13	11-106	1-14	11-110	2-17	9-88	2-20	10-102	1-13
EAC	46-128	6-16	44-124	6-17	45-128	7-20	37-103	8-23	43-120	5-15

For comparison, depending on applied risk model the total mortality rate from lung cancer connected with radon exposure in premises of France in 1999 was from 543 [90% IIn: 75-1097] to 3108 [90% IIn: 2996-3212] (Catelinois et al., 2006). Calculations show that from 25,134 cases of deaths from lung cancer in France this year from 2% [90% IIn: 0,3-4,4%] to 12% [90% IIn: 11-13%] may be explained by radon exposure in premises. The least mortality rate gave calculations by models TSE/AGE/WL and by Lubin, the largest-by EAC. The comparison shows that taking into consideration the relation of mortality to population number of the researched region the «radon problem» in Rivne (Ukraine) is by far more acute than in France about which testify our previous comparisons with similar studies in island Corsica (Lebed et al., 2018). It is also worth mentioning the comparatively big shortcoming of measurements by radonometer itself which may introduced its contribution into indeterminancy interval of results obtained by us. French researchers (Catelinois et al., 2006) by the result of comparatively small range of IH justly regard a great sample of results (>12,000 measurement points) and the use of passive methods of measurement (films Kodalpha LR115).
We additionally determined mortality rate from lung cancer at the expense of interior building radon with their average geometric value of VA=200 Bk/cub.m using models ERR for smokers and non-smokers-EAD and EAC (see Table 2). It appeared that for smokers, particularly at older age the risk of death at the expense of radon decreases substantially. This paradox was explained already by Cohen & Shah (1991) by results of observing 600 thous. dwellings of the 1601-th election district of America (the researched sample amounted to about 200 mln. persons, approximately 80% of USA population). A man who smokes at the expense of tobacco smoke entering lungs the radon concentration is substantially less and, hence, there is substantially less irradiation. But such decrease of radon exposure is by far exceeded by the decreased probability of illness incidence for lung cancer on the account of smoking.

Table 2. Evaluations of prognosticated mortality rate from lung cancer connected with radon exposure in premises in Rivne in 2011-2015 taking into consideration the interaction of tobacco and radon.

DDE	**Mortality rate from lung cancer at the expense of interior building radon with *VA*=200 *Bk/м*^{3}**									
	2011		**2012**		**2013**		**2014**		**2015**	
	male	**female**	**male**	**female**	**male**	**female**	**male**	**female**	**male**	**female**
EAD (smokers)	10-80	1-10	10-78	1-11	10-80	2-13	8-64	2-15	10-75	1-9
EAD (non-smokers)	21-141	3-17	21-137	-	21-141	3-22	17-113	4-26	20-132	2-16
EAC (smokers)	42-123	5-15	41-120	6-16	42-123	7-19	34-99	8-22	39-115	5-14
EAC (non-smokers)	74-156	9-19	72-151	10-20	74-156	12-24	60-125	13-28	69-145	9-18

We also calculated the expected shortening of life duration for population of Rivne by different models of ERR for last two years of the researched period (see Table 3).

Table 3. Expected shortening of life duration for population of Rivne (in years) with radon exposure VA=200 Bk/cub.m during life for various risk models based on statistical data of 2014-2015.

Year	**Risk model**				
	PRR	**GSF**	**BEIR-IV**	**EAD**	**EAC**
2014	1.87	2.34	1.24	2.52	3.74
2015	1.92	2.48	1.32	2.66	3.96

Hence, residing in a building with the average voluminous activity of radon of 200 Bk/cub.m shortens life of Rivne inhabitants by 1.2-4 years depending on the model of calculating the risk. Though the decrease of life duration is a rather abstract statistical value which may be used only at the level of population but not of a separate individual, however, this value is one of the most important characteristics which permit to assess the ecological and social well-being of this or that region. The additional advantage of evaluating the expected shortening of life duration is the possibility of the transfer from abstract numerical assessments (the probability of the emergence of oncological diseases, the expected number of illnesses also) to evaluations which will permit to economic assessments of health losses via population irradiation.
Similar calculations for that part of the population of Rivne who smokes and resides in buildings with VA=200 Bk/cub.m showed the prognosticated shortening of life duration from 2.5 (for model BEIR-IV) to 7.41 years (for model EAC).

Conclusions

These researches are the first evaluation of disease incidence and mortality from the cancer of trachea, bronchi, lungs connected with radon exposure in Rivne city by the method (AFSSE, 2004; Darby et al. 2001). Similar studies are to be spread to other regions of Ukraine as radon problem is the subject of an acute anxiety of the European community and World Health Organization.

The measurement of radon concentration in premises in Rivne testify its substantial variability, the distribution of VA in buildings is of lognormal character. The average geometric value of VA for basement premises amounts to 365 Bk/cub.m and for semi-basement premises-161 Bk/cub.m which exceeds building norms for both types of premises. For ground floors of living quarters in c. Rivne the average geometric value of VA was 127 Bk/cub.m [95% IIn: 118-137] with geometric standard deviation . The average geometric value of VA of all studied premises is 200 Bk/cub.m under geometric standard deviation. The prognosticated maximum possible value of VA in buildings by results of our measurements is assessed as 1.420 Bk/cub.m.

The calculated mortality rate in Rivne from lung cancer connected with radon exposure in city premises on account of indeterminacy concerning ERR is from 5 to 128 for males and from 1 to 23 for females. This constitutes from 3 to 64% of all deaths from lung cancer by all causes annually in the researched period for males and from 3 to 77% for females. Such mortality rate substantially exceeds indices obtained by analogic calculations of mortality in France (Catelinoiser et al., 2006). This may be connected with the complicated radon situation in Rivne territory, with more large-scale measuring campaign in France which was financed at the expense of EU (our studies were carried out at our own costs by our proper enthusiasm) and by another gadget base with larger shortcoming of measurement.

Thus, the calculated expected shortening of life duration for population of Rivne by different models of ERR constitutes from 1.2 to 4 years for the whole population and from 2.5 to 7.41 years for those share of population who smokes. Similar calculations of the shortening of life duration were not conducted for the population of France.

Models analyzed and tested by us may be efficiently used for determining the level of radon threat for any settlement, including also in other countries.

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