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ORIGINAL ARTICLE

Determination of oncological disease risks caused by radon in urban ecosystems of Rivne

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It is supposed that radon in the apartment and the products of its decay facilitate the increase of lung cancer morbidity rate and other oncological diseases risks of total population. The main source of radon getting into apartment (up to 90%) for most buildings is soil gas. For the inhabitants of Rivne, situated on the western hill-side of the Ukrainian crystal shield concentrated with uranium and radium, broken by a complicated system of fracture by which radon easily go up with the help of soil waters and on its own, increasing its concentration in surface soils, is extremely important. The article gives the results of complex determination of average volumetric activity of Radon 222 in the air of low-ground apartments of 48 testing areas of Rivne urban ecosystems, compares the received results with the indices of lung cancer morbidity and mortality of population, that died in the given areas during the period of 2014-2016. The values of additional relative risk concerning the given disease are calculated, using the models of permanent relative risk and GSF (Jacoby Model). It is ascertained that average geometric value of Radon 222 volumetric activity (VA) in the apartments of the ground floors of testing areas under research made up 200 Bk/m^3 with standard geometric error 0.7865, average arithmetic value of radon volumetric activity in the air of the same apartments made up 262.5 Bk/m^3 with standard error 194.4 Bk/m^3. That is evidence of considerable variations of radon level in the air of houses in the territory of Rivne. Maximum measured value of volumetric activity makes up 1000 Bk/m^3 and maximum prognosticated value is 1420 Bk/m^3. Under 70-years-old radon exposition with volumetric activity 200 Bk/m^3, value of additional relative risk make up 0.0446 for the model of permanent relative risk and 0.0633 for Jacobi model, according to the same time period radon exposition with volumetric activity 1426 Bk/m^3-0.26 for the model of permanent relative risk and 0.33 for Jacobi model. According to permanent radon exposition in the apartment with volumetric activity 200 Bk/m^3 the upper level of adopted individual risk (individual risk border) for the inhabitants of Rivne come approximately at the age of 30-34 when calculated after model of permanent relative risk and at the age of 25-29 when calculated according to Jacobi model.
Keywords: Radon; apartment; air; volumetric activity; equivalent balanced volumetric activity; lung cancer; models of permanent relative risk and Jacoby model

Introduction

The risk of radon irradiation as one of the radioactive factors for the arising of the population oncological morbidity (lung cancer) has a number of peculiarities comparing to other types of risks and, first of all, it lies in the boundlessness of distant carcinogenic effects. It makes the usual way of irradiation regulation impossible and requires the determination of limited doses and safety coefficients just for given specific type or irradiation that, as a consequence, gives the task for researchers to determine the radioactive risk, acceptable risk in every case of the specific territory and to realize the optimization of measures for radioactive protection from the given type of irradiation.

Nowadays, there are three approaches to the realization of complex investigations of radon impact on the lung cancer morbidity (Zhukovskiy et al., 1997):

1. cohort investigations on the base of which the number of mortality cases of lung cancer for various groups of professional workers or population under known individual doses of irradiation or average doses of irradiation for every group are compared. Similar investigations have been mainly used to estimate the radioactive risk for the miners of uranium mines;
2. "case - control" type of investigation based on the determination of radon irradiation of people with identified cases of lung cancer and comparison of these levels with the levels of radon irradiation for the group under control that coincides with the main group according to its parameters. The given type of investigations is considered to be the most correct one for epidemiologic estimation under everyday radon irradiation. Unfortunately, in most cases it's impossible to make identical conditions conducting investigations for the main group and the group under control;

3. ecological (geographically correlated) investigation based on the comparison of lung cancer mortality for various urban ecosystems with different radon average volumetric activities (VA) in the apartments (mainly in houses).

Due to their relative simplicity the investigation of such a type are quite prevailing. But the influence of a great number of additional factors, as a rule, doesn't let estimate their results properly.

In the world urban ecosystems the problem of the determination of population lung cancer morbidity risk caused by radon irradiation is extremely acute. According to the data of US Public Health Service radioactive radon irradiation is the second reason in the world for the lung cancer growth (average-12.5% out of all the reasons) next after smoking. According to the British Radiation Protection Agency calculations 2500 people die annually of lung cancer caused by radon in Great Britain. According to the data of Environment Agency in the USA under average radon activity in the apartments 55 Bq/m3 and summary exposition 0.2 WLM annually from 15 to 22 thousand oncological morbidity cases are initiated by radon and products of its decay, exceeding admissible ones by standard growth of mortality by 300 times. More than one billion dollars is annually spent on the treatment of morbidity caused by radon inhalation in the USA.

The given problem is actual for Ukraine and Rivne, in particular, as the city is located within the boundaries of Ukrainian Crystal Shield rich in uranium which is the intensive source of radon.

Taking into account that radon is referred to cancirogens of the 1st class by the International Agency of Cancer Investigations (Kononenko, 2013), the aim of our work is to determine oncological morbidity risks of Rivne population irradiation by radon and its decay products (DPR) because of their getting into people's lungs in the apartments, offices, working places, kindergartens, schools, etc.

To achieve the aim it was necessary to carry out the following tasks:

1. to measure out and mediate radon VA in the low-ground apartments of the chosen testing areas of Rivne urban ecosystem;
2. to determine the average exposition capacity for Rivne urban ecosystem;
3. to analyze lung cancer morbidity and mortality of population in the urban ecosystem during the period of 2014-2016 and compare them with the received values of VA.
4. to determine additional relative risk of lung cancer morbidity and mortality of population in the urban ecosystem using models of permanent relative risk and GSF (Jacoby Model).

The object of investigation is the process of radon accumulation in the apartments, lung cancer morbidity and mortality of population in Rivne.

The subject of investigation is indices of radon volumetric activity, lung cancer morbidity and mortality of population in certain testing areas of Rivne.

Methods of investigation

General scientific methods (analysis, synthesis), experimental methods (measuring radon volumetric activity with radiometer "Alfarad Plus") and statistic methods of determination lung cancer mortality of population in Rivne urban ecosystem.

Results of investigation

It is suggested to differentiate the following categories of radiological risk of lung cancer morbidity of population:

1. absolute risk, that is probability of rising lung cancer for the life term or for a set period of time;
2. relative risk, that is ratio of absolute risk of rising oncological morbidity (lung cancer) among irradiated population to the risk for the similar non-irradiated population;
3. excess relative risk, that is relative risk minus a unit.

There are two main models of extrapolation of radiological risk:

- a model of absolute risk (additive);
- a model of relative risk (multiplicative).

To calculate the risk of mortality (morbidity) of lung cancer caused by radon two principal kinds of risk coefficients are used: gender/age coefficients of mortality q(t) and morbidity λ(t).

These coefficients are determinated as density of conventional probability of mortality (morbidity) at the age t.

If $\lambda_0(t)$ is oncological morbidity at certain age t of all the reasons in specific nonirradiated population (basic frequency), then morbidity caused by irradiation is expressed by the following ratio:

$$\lambda(t,t_0,H) = \lambda_0(t) + h(t,t_0,H) \qquad (1)$$

where h (t, t_0, H) is surplus morbidity at certain age t connected with irradiation by dose H at the age t_0. Such dependency can be given to mortality q(t) as well.

It is supposed that multiplicative model of extrapolation of radioactive risks is the most acceptable for lung cancer.

According to the given model, irradiation causes increase of morbidity probability that is proportional to the frequency of spontaneous rise of oncological morbidity of this or that organ or tissue:

$$h(t,t_0,H) = \begin{cases} 0, & t \le t_0 + \tau \\ C_{t_0,H}.\lambda_0, & t \ge t_0 + \tau, \end{cases} \qquad (2)$$

where τ is a latent period;

$C_{t_0,H}$ is some stability which depends on the age irradiation and dose received.
It is considered to be proved that:

- the rise of lung cancer is the main and the only veritably proved effect at the moment of the influence of radon inhalation getting DPR into human being's organism;
- the coefficient of additional relative risk of lung cancer rise is proportional to cumulative exposition received by miners in the working process (Figure 1);
- the general estimation of lung cancer morbidity risks can be done following the similar methods both for miners and for cases of morbidity rise in apartments caused by everyday radon, changing a little only the coefficients.

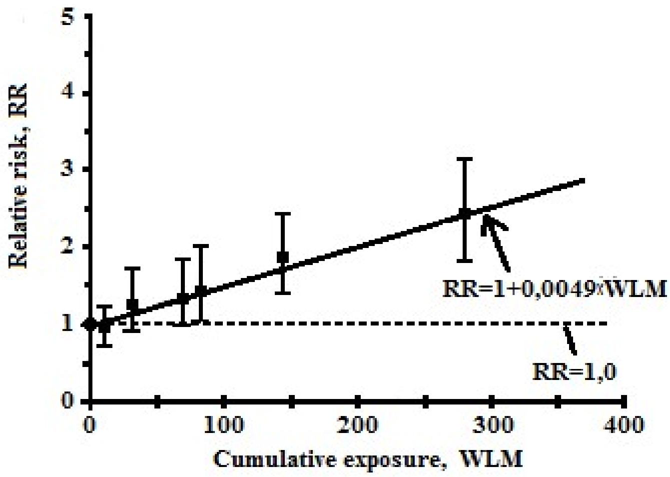

Figure 1. Dependency of relative risk of lung cancer rise on cumulative exposition received on the base of combined data of eleven cohorts of miners (Health et al., 1999).

Nowadays to calculate the risks of population oncological morbidity caused by radon irradiation and its DPR various models are used. The first one historically was the model "Vismut" worked out after the results of experimental research carried out from 1946 to 1990 in the cohort of 59001 people. All the workers under research were those ones who worked at the uranium mines of the campaign "Vismut" of Germany. 2388 death cases caused by lung cancer were registered among them. One of the peculiarities of the use of functioning nowadays models of radioactive risk estimation caused by radon and its DPR irradiation is the fact that coefficients of risk models are standardized (rated) to the exposition in the units WLM. The capacity of exposition P caused by radon and its DPR impact (in the units WLM/year) correspondingly both for population (P(p)) and miners (P(m)) is calculated after the formulas:

$$\begin{cases} P^{(\mathrm{p})} = \mathrm{k}\,.\,\mathrm{VA}, \\ P^{(\mathrm{m})} = 1.59\times10^{-6}.N_{wd}\,.N_{wm}.VA, \end{cases} \qquad (3)$$

where k=0.014·F·σ,
σ is a relative time of person's staying in the apartment (normative documents ICRP (International Commission on Radiological Protection) suggest σ=0.7);
F is a coefficient of balance between radon and its products of decay (normative documents ICRP suggest FUSA=0.4);
N_{wd} is a number of working days a month;
N_{wm} is the number of working months of miners in the specific region of the country or in the country in general;
VA is volumetric radon activity in the apartment or in the mine in Bq/m^3.
According to (Demin et al., 2014; Lipnitskiy et al., 2004) average annual capacity of exposition P one can determine using the known average annual values (equivalent balanced volumetric activity) $EBVA_a$ after the formula:

$$P^{(\mathrm{p})}\left(\frac{WLM}{year}\right) = \frac{EBVA_a\left(\frac{Bk}{m^3}\right).T\left(hours\right)}{170.3700}. \qquad (4)$$

The value 1 WLM approximately corresponds to exposition at EBVA that is equal to 100 nKi/l (3700 Bq/m^3) for a period of 170 hours.

Where:

$$EBVA_a = F.VA_a \qquad (5)$$

Radon VA measuring was made in 600 apartments on the ground floors, semi-basements and basements of residential and industrial stocks in 48 testing areas of Rivne (Klimenko et al., 2017). Statistic parameters of distribution for VA of subsidiary products of radon isotopes were determined: mathematics expectation (VAg) for VA, geometric standard declination VA(σ) and prognosticated maximum value (VA_{max}). As the last parameter the value on the level of limited magnitude of density probability of corresponding declination from distribution maximum in the distance 3σ (the rule of three sigma) was considered. Average arithmetic value VAar in all apartments under investigation made up 262.5 Bq/m^3 with standard declination 194.4 Bq/m^3, that affirms considerable variation of radon levels in the air of living accommodation in the territory of Rivne. Average geometric value of VA while measuring in 600 apartments made up 200 Bq/m^3. Being maximum measured value VAm make up 1000 Bq/m^3, maximum prognosticated probable value VAmax after the results of our measuring, is estimated by the quantity that doesn't exceed 1420 Bq/m^3. Measured values are chosen as the principal ones to calculate the risks of population lung cancer morbidity in the city.

Average values of Radon VA in the apartments of testing areas under investigation are shown in Figure 2.

Calculations of the capacity of DPR radon exposition that population of Rivne receive in the units WLM/year are shown in Table 1.

Table 1. The value of exposition P(p) capacity for the principal values of VA (Bq/m^3) in the apartments under investigation in Rivne.

P(WLM/year)	$VA_g = 200$	$VA_{ar} = 262,5$	$VA_m = 1000$	$VA_{max} = 1420$
	1393	1827	6.96	9.88

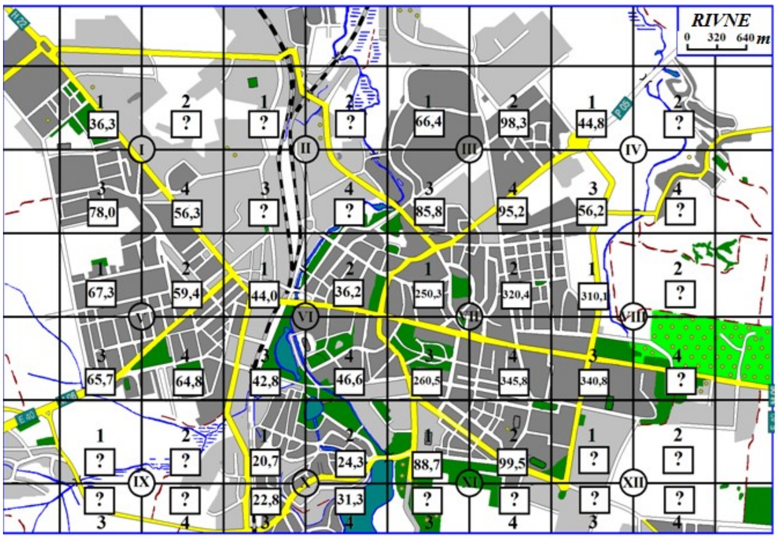

Figure 2. Average interior apartment values of radon VA (in Bq/m^3) for testing areas of Rivne.

In calculations P(p) we used values F=0.5, as we consider that because of climatic conditions our population stays more time in houses and correspondingly gets bigger dose of irradiation than US population.

As models for determination of additional relative risks of population lung cancer morbidity and mortality in urban ecosystem, models of permanent relative risks and GSF (Jacoby Model) will be used ICRP. For the model of permanent additional risk the main one is suggestion that additional relative risk R of lung cancer rise of the population at the age t is determined by the coefficient of the basic age-specific frequency of morbidity $\lambda_0(t)$ and the coefficient of additional relative risk KR, which, in its turn, depends on the quantity of exposition PWLM for radon DPR, distribution of exposition according to the period of time and age at the moment of risk estimation and some other parameters. It is determined by the formula:

$$R = \sum \lambda_0(t) p_0(t) K_R(t).\exp\left[-\sum_{t'=0}^{t} K_{let}\lambda_0(t') KR(t')\right] \qquad (6)$$

where $p_0(t)$-is the function of living long that is determined as the probability of reaching by a person the age t (since birth). It takes into account the demographic peculiarities of the territory, as well as the fact of death caused by various reasons, and not only by the influence of radioactive factor;

k_{let} is the coefficient of lethal outcome (for lung cancer k_{let}=0.95);

$K_R(t)$ is determined by the capacity of DPR radon exposition received at the age t_e, PWLM (t_e), and doesn't depend on the other factors:

$$K_R(\mathrm{t}) = 0.0083.P_{WLM}(\mathrm{t_e}), \text{ for } \mathrm{t} \geq \mathrm{te}+\tau \qquad (7)$$

where τ is the lethal period for 5 years.
The coefficient of additional relative risk caused by cumulative exposition DPR of radon, within the whole period of life or at a certain period (industrial activity), is calculated after the formula:

$$K_R(\mathrm{t}) = 0.0083.\sum_{t_e=0}^{t-\tau} P_{WLM}(\mathrm{t_e}) \qquad (8)$$

Unlike the model of permanent relative risk the model GSF takes account of the coefficient KR dependency of time passed from the moment of radon DPR $\varphi(t-t_e)$ impact and the age, at the moment of irradiation, $s(t_e)$.
The coefficient of additional relative risk caused by cumulative exposition of radon DPR within the whole period beginning with the life point for the given model is calculated after the formula:

$$K_R(\mathrm{t}) = \int_0^{t-\tau} K_R(\mathrm{t}, \mathrm{t_e}).dt_e \approx \sum_{t_e=0}^{t-\tau} P_{WLM}(\mathrm{t_e}) \sim .s(\mathrm{t_e}).\varphi(\mathrm{t}-\mathrm{t_e}) \qquad (9)$$

where $s(t_e)$ is the coefficient of proportionality which takes account of carcinogenic perception of lungs which is reduced with the age growth of a person under irradiation;
function $\varphi(t-t_e)$ defines the distribution of relative latency and is standardized by a unit in maximum. Then after this maximum the reduction of additional relative frequency of morbidity is prognosticated with a period of two times decrease that is equal to 10 years.
For the coefficient $s(t_e)$ the following values given in Table 2 are suggested.

Table 2. Values of coefficient $s(t_e)$ for the model GSF (Jacoby).

t_e, age in years	**$s(t_e)$**
$t_e<25$	0.036
$25 \le t_e<30$	0.032
$30 \le t_e<35$	0.03
$35 \le t_e<40$	0.0285
$40 \le t_e<45$	0.027
$45 \le t_e<50$	0.0255
$50 \le t_e<55$	0.024
$t_e \ge 55$	0.018

For the function $\varphi(t-t_e)$ the following dependencies given in Table 3 are suggested.

Table 3. The type of function φ(t-te) for the Model GSF (Jacoby).

$t-t_e$, years	**$\varphi(t-t_e)$**
≤ 4	0
>4, but ≤ 8	$0.25(t-t_e-4)$
>8, but ≤ 12	1
>12	$\exp(-\frac{\ln 2(\mathrm{t}-\mathrm{t_e}-4)}{10})$

To calculate the functions of living long p0(t) we used the data of statistic central administrative board in Rivne region (calculations for the year 2014 are given in Table 4). The probability of death at certain age q(t) was calculated in the table as a part of quantity those who died in a certain age group comparing to the summary quantity of those who died for a year. The probability that a person at the age from t to t+1 will live on during a certain year was calculated as 1-q(t).

Table 4. Distribution of those who died in Rivne region according to the age groups in 2014.

Age group, years	**Number of the died**	**Probability of death, q(t)**	**Probability that a person aged from *t* to t+1 will remain alive during a certain year**	**Probability of survival from birth to age t ($p_0(t)$)**
0-4	176	0.01196	0.98804	0.98804
5-9	18	0.00122	0.99878	0.98683
10-14	20	0.00136	0.99864	0.98549
15-19	50	0.0034	0.9966	0.9821

20-24	93	0.00632	0.99368	0.97593
25-29	161	0.01094	0.98906	0.96526
30-34	237	0.01611	0.98389	0.94971
35-39	276	0.01876	0.98124	0.93189
40-44	341	0.02318	0.97682	0.9103
45-49	477	0.03242	0.96758	0.88078
50-54	743	0.0505	0.9495	0.8363
55-59	1048	0.07122	0.92878	0.77674
60-64	1131	0.07687	0.92313	0.71703
65-69	1119	0.07605	0.92395	0.6625
70 and older ones	8822	0.59957	0.40043	0.26528
total	14714	1	0	0

It's difficult to make calculation of the function of living long separately for men and women $p_{0m}(t)$ and $p_{0w}(t)$ as in Rivne region the administrative board of statistics doesn't determine the distribution of those who died separately according to the gender.

There appears a specific problem of calculation of age-specific frequency of lung cancer rise $\lambda_0(t)$ inherited for the territory under investigation, as in medical statistics reports of Rivne region there is no statistics of lung cancer mortality depending on age, there can be only found the data of average mortality for a year $\overline{\lambda}_0(t)$.

In such cases, suggestions that age-specific lung cancer morbidity for any specific region corresponds to age-specific morbidity $\lambda_0^{ref}(t)$ for so called "positive population" given in ICRP Publication (ICRP, 1987), are used as a working hypothesis, being different from it only by permanent multiplier k:

$$\lambda_0(t) = k\lambda_0^{ref}(t) \qquad (10)$$

where value k for men and women can be determined from the following expression (9):

$$k = \frac{\overline{\lambda}_{0m,w}\int_0^\infty p_{0m,w}(t)\,dt}{\int_0^\infty \overline{\lambda}_{0,m,w}^{ref}(t)\,p_{0m,w}(t)\,dt} \qquad (11)$$

where $p_{0m,w}(t)$ is probability of living long for men and women in Rivne region.

The coefficient k which was calculated for inhabitants of Rivne region in 2014 makes up 4.83. It is worth admitting that values k received by us exceed analogical values presented by some other countries. For example, in (Zhukovskiy, 2007) the coefficient k for Sverdlovsk region of Russia is calculated. For the men of this region k=2.15 and for women k=1.29. Average arithmetic value k=1.72 is approximately 3 times smaller than the value k for Rivne region, what indirectly testifies the correspondingly fewer cases of lung cancer morbidity. According to the given data, Rivne region can be compared to the most radon hazardous regions of Russian Federation-Altai Territory, Leningrad region and Jewish autonomous region (Kormanovskaya, 2007).

Calculation of additional relative risk (probability) of lung cancer (R) rising caused by radioactive inductive radon DPR irradiation when inside house VA=200 Bq/m^3 and VA=1420 Bq/m^3, depending on age and the chosen model, is made after the formula (6) and shown in Figures 3 and 4.

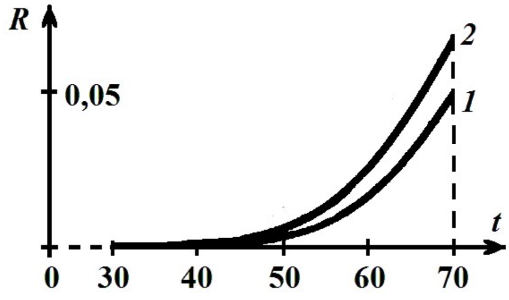

Figure 3. Dependency of relative individual life additional risk R on the time of exposition t under life radon exposition in the apartment where VA=200 Bq/m^3 for the models: 1- permanent relative risk; 2- Jacoby model.

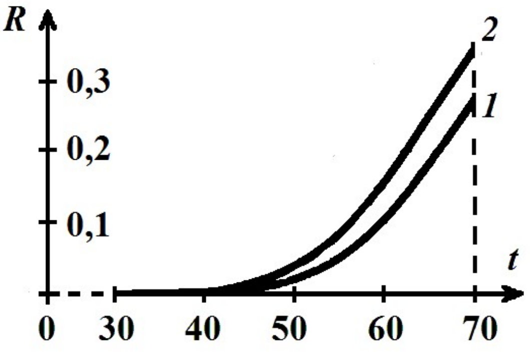

Figure 4. Dependency of relative individual life additional risk R on the time of exposition t under life radon exposition in the apartment where VA=1420 Bq/m^3 for the models: 1- permanent relative risk; 2 -Jacoby model.

The received results coincide with the data (Trifonova et al., 2008) for the city of Vladimir (Russia) where for VA=232.5 Bq/m^3 in the apartments, where the value R for the exposition 70 years was received 0.062 (our values where VA=200 Bq/m^3 make up 0.0469 for the model of permanent relative risk and 0.0633 for Jacoby model). While using possible maximum data after the value of radon VA of inside house air in the apartment of Rivne where a person lives (1420 Bq/m^3), then value R for the exposition of 70 years of living there makes up from 0.26 for the model of permanent relative risk to 0.33 for Jacoby model. According to international practice, risk is considered to be very low when probability of death is less than 10^{-6} a year-1. The risk is acceptable for the staff of the manufacturing linked with the use of radioactive materials if probability of death does not exceed 10^{-4} years-1, for the population it is 10^{-5} years-1. The upper level of acceptable individual risk (the limit of individual risk) caused by man-made irradiation of people out of the number of corresponding staff responds to probability of death 10^{-3} year-1, under population irradiation- $5 \cdot 10^{-5}$ a year-1 (Zhukovskiy, 2007). The calculations show that under permanent radon exposition in apartments with VA=200 Bq/m^3 , the upper level of acceptable individual risk (the limit of individual risk) for Rivne inhabitants comes approximately at the age of 30-34 being counted after the model of permanent relative risk and at the age of 25-29 being counted after Jacoby model.
Taking into account that certain quantity of Rivne inhabitants lives in houses all their life where VA=1420 Bq/m^3, then the upper level of acceptable individual risk comes just at the age of 20. We have analyzed the statistics of lung cancer morbidity and mortality of the city inhabitants within the period of 2014-2016 for the chosen testing areas. Their corresponding data are given in Figure 5.

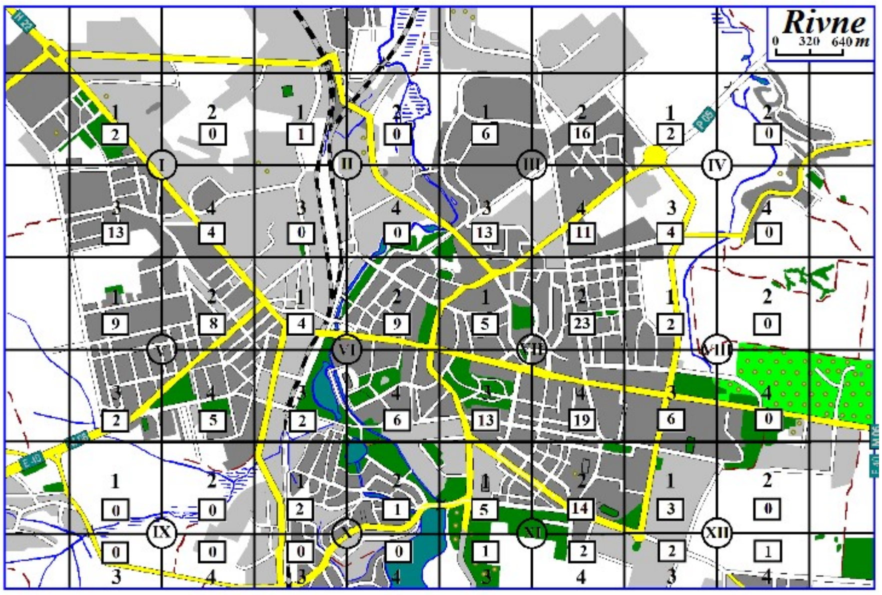

Figure 5. The number of city inhabitants that got ill or died of lung cancer within the period of 2014-16 for subdistricts of Rivne.

Comparison of the data in Figures 2 and 5 indicates exact correlation between values of VA of interior house air and the number of those who got ill and died of lung cancer within the period of 2014-16 in the testing areas of Rivne. Thus, for example, during the indicated period of time there wasn’t a single inhabitant of the city district called Basiv Kut fallen ill with this disease (testing areas X.3 and X.4). Just here ones of the lowest values of radon VA in the air of the houses were registered. At the same time in the testing areas close to Hrushevskiy St. (VII.2 and VII.4), where the number of those who died of lung cancer within the indicated period made up 23 and 19 relatively, the value of radon VA are the highest in Rivne, what is proved by the calculations given by us in the article.

Conclusions

1. Average geometric value of Radon-222 volumetric activity in the apartments of the ground floors which were under investigation in testing areas of urban ecosystems of Rivne made up 200 Bq/m3 with geometric standard declination 0,7865, average arithmetic value of radon volumetric activity in the air of these apartments made up 262,5 Bq/m3 with standard declination 194,4 Bq/m3, that proves considerable variability of radon levels in the air of apartments within the territory of Rivne. Maximum measured value of VA makes up 1000 Bq/m3 , and maximum prognosticated value is 1420 Bq/m3.
2. Basic age-specific frequency of lung cancer morbidity and the function of population living long in Rivne for the year 2014 are calculated.
3. Using models of permanent relative risk and GSF (Jacoby), dependencies of relative individual life-long additional risk of morbidity and mortality beginning with the time of radon exposition under life-long exposition in the apartments with VA = 200 Bq/m3 and 1420 Bq/m3 are calculated. Under 70-year radon exposition with VA = 200 Bq/m3, the values of additional relative risk make up 0,0469 for the model of permanent relative risk and 0,0633 for the Jacoby model, under the same radon exposition with VA = 1420 Bq/m3 – 0,26 for the model of permanent relative risk and 0,33 for the Jacoby model.
4. During permanent radon exposition in the apartment with VA = 200 Bq/m3, the upper level of acceptable individual risk (the limit of individual risk) for Rivne inhabitants approximately at the age of 30-34 when calculated after the model of permanent relative risk and at the age of 25-29 when calculated after Jacoby model.
5. Precise correlation between values of radon VA and the number of those fallen ill and died because of lung cancer among city inhabitants within the period of 2014-16 in the testing areas of Rivne is observed.

Considering that certain quantity of Rivne population lives in houses all their life, then the upper level of acceptable individual risk comes at the age of 20.

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