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REVIEW ARTICLE

RADON – OCCURRENCE AND IMPACT ON THE HEALTH

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ABSTRACT

Radon is noble, monatomic, radioactive, heavier than the air gas. It is colorless, odorless, tasteless. It exists in natural environment as a result of the decay of radium, and emits mainly *alpha* radiation and less *beta* radiation. Residential radon concentrations vary widely by geographic area. The higher concentration of radon is expected globally in the grounds where uranium, radium and thoron are present. Radon may gather in caves, tunnels, mines as well as in other lowest-lying spaces, such as basements, and cellars. In accordance with Atomic Law (2000), the reference level for the average annual concentration of radioactive radon in rooms intended for human habitation is 300 Bq/m^3. The most dangerous damages caused by ionizing radiation i.e. radon and its derivatives are changes to DNA, which may disturb the functions of cells and in the consequence lead to induction of cancer of respiratory tract, mainly of lungs and also leukaemia. So, the main consequence of exposure to high amount of radon are cancers of respiratory system. Radon enters the human organism mainly through inhaled atmospheric air. Moreover, radon significantly increased a risk of induction cancer in smokers and vice versa, smoking promotes the development of lung cancer after the exposure to radon and its derivatives. Radon may also have beneficial effect on the human body. Therefore it is used in medicine; mainly in radonbalneotherapy i.e. bath treatments, rinsing the mouth and inhalation. Beneficial effects of radon confirms the validity of the theory of radiation hormesis, which assumes that low doses of radiation may stimulate the repair of DNA damage by activation of protective mechanisms, which neutralize free radicals.

Key words: *radon, lung cancer, smoking, residential radon concentration, radon exposure*

INTRODUCTION

Ionizing radiation, which is present in the life of our planet from the beginning of its existence, constantly accompanies man. However, the phenomenon of radioactivity is known only from the end of 19th century. In 1895 *Wilhelm Conrad Roentgen* discovered the X-rays, whereas in 1896 Henri Becquerel discovered natural radioactivity. Constant presence of ionizing radiation in the human environment means that it affects our body continuously. Its effects depend on a number of factors, such as size and power of dose as well as exposure time.

Ionizing radiation causes the ionization of medium through which it passes. This phenomenon consists in detaching electrons from atoms, as a result of which, in place of electrically neutral atoms, pairs of ions are formed: positive ions and released electrons. Mechanism of ionization may be direct as a result of collisions of the ionizing particle with atoms and particles of the medium, or indirect that is via other particles which are formed by the interaction of radiation with matter or to which radiation has given its energy. Ionizing radiation causes damage to the DNA of cells, both directly by disrupting its integrity and indirectly e.g. as a result of the formation of intracellular oxygen free radicals [7, 72].

Human exposure to ionizing radiation results from two main sources: natural (radionuclides and cosmic rays) and artificial (e.g. X-rays machines, accelerators, nuclear reactors). Annual total effective dose of ionizing radiation obtained by a statistical resident of Poland in 2021 was 4.19 mSv (64% from natural and 36% from artificial sources) and has remained at a similar level for the last few years. Radon and its decay products have the greatest share in human exposure to ionizing radiation from natural sources, from which a statistical inhabitant of Poland receives a dose of 1.2 mSv/year which constitutes 28.6% of annual effective dose [66].

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ORIGIN AND OCCURRENCE OF RADON

There are naturally radioactive substances present in the earth's crust. Natural radioactivity is generated by the decay of atomic nuclei of natural radioactive elements present in soil, rocks, air and water. Atomic nuclei spontaneously decay, emitting *alpha* or *beta* particles or γ-rays. Natural radioactive radicals are present in minerals, assimilated from the atmosphere by plants and animals and used as construction materials. They are synthesized in the atmosphere from where they penetrate into the hydrosphere as a result of the reaction of atmospheric components with cosmic rays. They penetrate environment as a result of human industrial activities. One of the reactive radical, radioactive radium (^{226}Ra), was discovered by the Nobel award winner *Maria Skłodowska-Curie*. In turn, radon (Rn) was discovered in 1900 by Fridrich Ernst Dorn. Radon arises from decay of radioactive radium, which is one of decay products of radioactive uranium (^{238}U) [61, 72].

Radon is noble, monatomic, radioactive, and eight times heavier than the air gas. It is colorless, odorless, tasteless, incombustible. It dissolves in water, especially in cold and organic solvents, glows in dark and is almost completely chemically inert [12].

Different geologic rock units have varying concentrations of uranium, and therefore produce fluctuating amounts of radon. Residential radon concentrations vary widely by geographic area [32]. Emission of radon depends on geological structure. On the basis of substrate type we can expect the enhanced concentration of this gas. The higher concentration of radon is expected globally in the grounds where uranium, radium and thoron are present, especially in regions with granites, metamorphosed igneous rocks and shales with uranium deposits. In Europe high concentration of radon was observed in granite areas such as Czech Massif, Iberian Peninsula, Central Massif, Baltic Shield, Corsica, Cornwall, Vosges, Central Alps, Swiss Jura, Dinarides, Northern Estonia and in volcanic parts of Italy. Arithmetic mean of radon concentration for Europe was 98 Bq/m^3, and median was 63 Bq/m^3 [25].

The most uranium-bearing and thoron-bearing are the acidic igneous rocks containing granitoids, which content 3 g/t of uranium and 10-20 g/t of thoron. In Poland, the Karkonosze (part of Sudety Montains) granitoid has the characteristics of uranium bearing granitoid. Other igneous rocks are definitely poorer in uranium and thoron (less than 1 g/t uranium and 3g/t thoron) [12]. According to the report of The Polish Geological Institute - National Research Institute the 70 % of Poland area, the surface of which is made up of postglacial Quaternaly rocks, is characterized by low or medium radon potential. The highest radon potential was noted in Sudets and in the Sudetes Foothills, where there are granitoid massifs and metamorphics rocks with an increased content of uranium and thorium. Sudetes rocks have a mosaic geological structure with a lot of cracks, brittle rock and tectonic dislocations which makes it easier for gas to rise upwards. Radon was found also in ground water with concentration up to 2000 Bq/dm^3. Until the 70 years of XX century there were located uranium mines [5, 66]. The second area of high radon concentration is mining region of Upper Silesia. Relatively high radon concentration may occur in Suwałki region, where the surface of the area is made up of rocks of the youngest glaciation. Increased radon concentration may occur in Świętokrzyskie Mountains, where the surface of terrain is made of Devonian and Silurian clay rocks [25].

A typical value of the specific activity of radium in the subsurface layer of the Earth's crust is approximately 35 Bq/kg. In Poland shapes up in the range between 5 Bq/kg and 120 Bq/kg, with the average at 26 Bq/kg [35, 71].

The mean concentration of ^{222}Rn in atmospheric air in Poland is about 10 Bq/m^3. For instance, in Kowary 30 Bq/m^3, in Świeradów Zdrój 24,1 Bq/m^3, in Karpacz 8,7 Bq/m^3, in Warsaw 2,7 Bq/m^3 [70].

PENETRATION OF RADON INSIDE THE BUILDING

Radon exists in natural environment as a result of the decay of radium, and emits mainly *alpha* radiation and less *beta* radiation. Since it is a gas, it can get out of the Earth's crust into the atmosphere as part of the atmospheric air. The most stable of radon isotopes ^{222}Rn constitutes about 80% of all radon isotopes. It is the most widespread in the environment and is believed to be the most dangerous. During the decay of radon the a particle is generated and next isotopes are formed, which undergo decay within minutes to form two more *alpha* particles and emit *beta* and *gamma* radiation [12].

Since radon is heavier than the air it may gather in caves, tunnels, minnes as well as in other lowest-lying spaces, such as basements, and cellars. It is formed in rocks in the earth's crust and then migrates to the surface of the earth through geological faults, cracks, permeable soils. The concentration of radon outside of the buildings depends on the rate of emission from the surface of the earth and on atmospheric conditions, such as sunlight, wind. Radon is present in every building and apartment in different concentrations depending on the geological structure of the area on which it is located. Radon transport is most active in the vicinity of faults, fissure rocks and condensed formations through interconnected systems of fissures and cracks [41, 49].

In Poland, about of 25% of the investigated area indoor radon concentration exceeding 100 Bq/m^3, and in 5% was at least 300 Bq/m^3 [25].

Radon enters the building along with air sucked in from the ground through gaps in the foundations, cracks in the building walls and floor, sewer manholes, leaks around water pipes, electrical wiring, structural connectors and building materials (Figure 1) [25]. Inside the building, radon moves using water and sewage channels, and by buildings with a large slab gaps between the plates [63].

Radon concentrations observed in residential buildings depend on the processes of formation and decay of radon and radium in the ground, permeability and porosity of the soil. The radon concentration in buildings is also influenced by the parameters of the building, especially the type of basement (concrete screed, ceramic tiles, earth) and the speed of ventilation of the rooms. Radon concentration in buildings can also be influenced by the tightness of rooms and ventilation (gravitational and forced) as well as weather conditions for example temperature and wind, as well as residents' habits like airing and smoking [80].

Radon decays to form the so-called series of short-lived, also radioactive derivatives, which include, inter alia, isotopes of polonium, bismuth and lead. Hence the potential threat to human health. Radon decay products, which are solids, easily attach to aerosols existing in the air and, as a result of breathing, enter the lungs.

In accordance with the Act of 29 November 2000 – Atomic Law (2000), the reference level for the average annual concentration of radioactive radon in rooms intended for human habitation is 300 Bq/m^3 [6]. However, international organizations, including WHO recommended reference level as 100-300 Bq/m^3 and suggest taking further steps to reduce this level [74].

The mean concentration of radon in living quarters in the world is about 39 Bq/m^3, whereas in Europe 21-110 Bq/m^3 [38, 62]. On the basis of printed results, it is believed that high-risk areas cover 10% of country's areas. On these areas the concentration of radon in the ground exceeds the value of 50 Bq/m^3. Measurements of radon concentration in 2011, showed that in Poland the highest concentration of radon in the buildings appeared in Sudety (845 Bq/m^3), whereas the highest geometric mean (231 Bq/m^3) was reported in Mazury and Podlasie regions [1, 41, 67]. The report of WHO from 2009 showed the arithmetic average of indoor radon concentration in many countries, for instance 140 Bq/m^3 in Czech Republic and Mexico, 49 Bq/m^3 in Poland, 46 Bq/m^3 in USA, 28 Bq/m^3 in Canada, 20 Bq/m^3 in United Kingdom, 16 Bq/m^3 in Japan and 11 Bq/m^3 in Australia. World average was 39 Bq/m^3 [74].

The risk of exposure to ionizing radiation inside the building is approximately of several dozen higher than outside [15]. The sources of radon in living quarters are radon penetrating from the ground, from building materials of mineral origin, and in the much less level radon in tap water and gas installation [48, 58]. According to the Environmental Protection Agency USA (EPA), 86–90% of radon in the building come from soil, 2–5% from building materials and less than 1% from water [18].

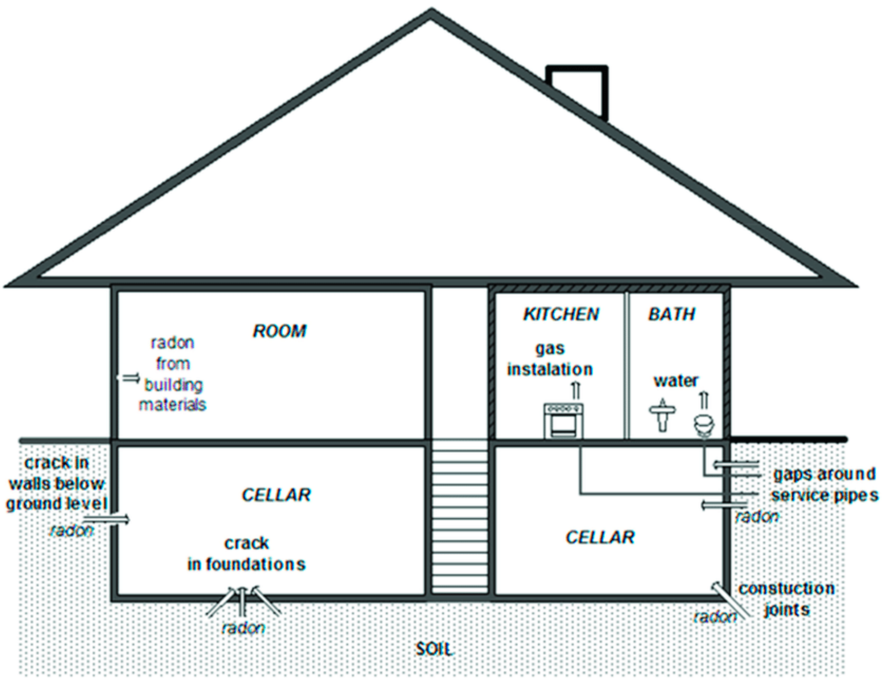

Figure 1. Radon ways into building [25]

The buildings intended for the stay of people should meet the requirements for contents of natural radionuclides in used building materials and mean yearly concentrations in the indoor air [15]. According the current Atomic Law the benchmark for risk of people from γ-rays emitted by buildings materials inside of the building has been established as 1 mSv per year. As was mentioned earlier, the source of radon is building materials used in the construction of house. This is due to use for the production of buildings materials from natural occurred minerals. Such materials may contain radium and thorium [10].

The radon concentration in the air depends on the intensity of radon emission from its source and on atmospheric conditions, such as wins speed, air humidity, and atmospheric pressure. Therefore, radon concentration shows both daily and seasonal fluctuations [57]. During the year, the lowest radon concentration occurs in the summer, whereas the highest in the autumn and winter periods (Figure 2). In turn, during the day the lowest concentration of radon is noted at noon, and the highest at night [42].

The concentration of radon in the air of buildings is the highest near the ground, so in the basement, next on the first floor and the lowest on the higher floors. In the kitchen the radon concentration is higher than in rooms because of radon released from tap water and natural gas (Figure 3) [63]. In turn, on the higher floors, the concentration of radon coming from the ground is decreasing whereas increasing this one coming from building materials.

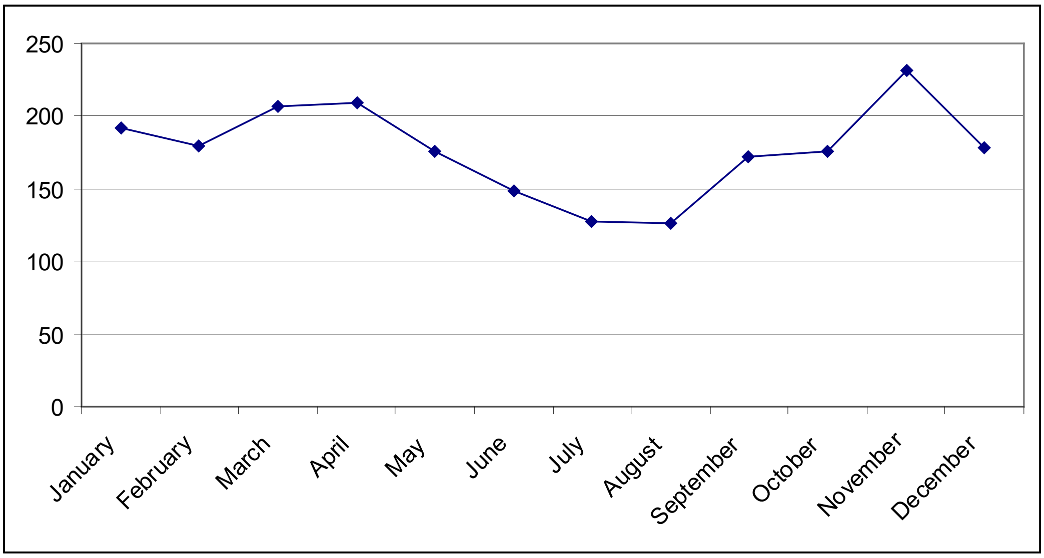

Figure 2. The mean radon concentration (Bq/m^3) in flats in Poland in following months [42]

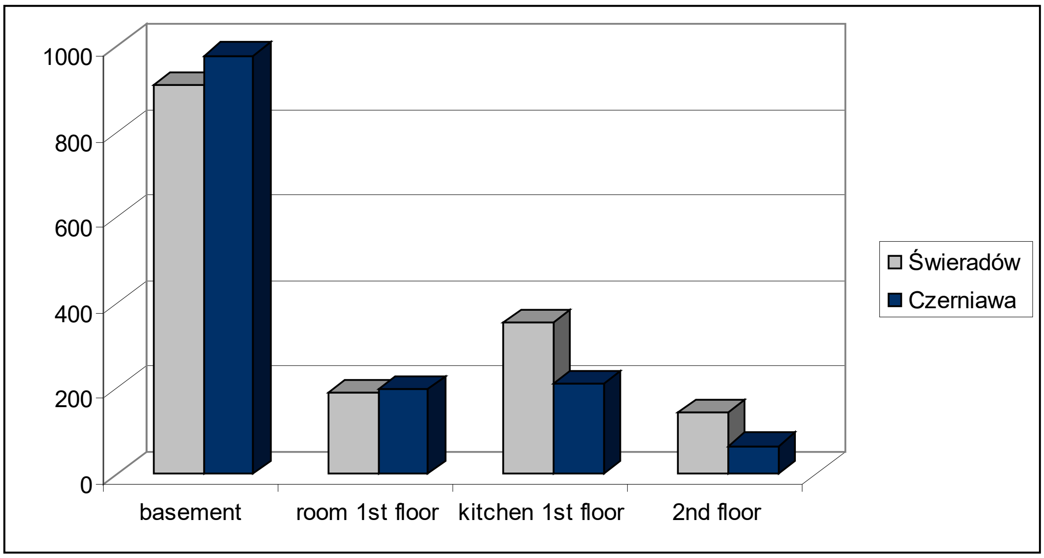

Figure 3. The mean concentration of radon ^{222}Rn on different floors of buildings in Świeradów Zdrój and Czerniawa Zdrój (Bq/m^3) [63].

THE EFFECT OF RADON ON THE ORGANISM

Since 2015 with initiative of European Radon Association on birthday of *Maria Skłodowska-Curie* (7 November) the European Radon Day is celebrated. The aim of the European Radon Day is increasing the public awareness regarding presence of radon in the environment and its health consequences.

Radon can pose a threat to human health because it gets from the ground to the residential buildings as a result of the pressure differences and accumulate in the lowest level, especially in basements. The main consequence of exposure to high amount of radon is cancers of respiratory system. Radon enters the human organism mainly through inhaled atmospheric air. Everyone breathes in radon every day, usually at very low levels. The inhaled dose depends, among others, on its concentration in the air, respiration rate, area of the lungs and the depth of penetration of radioactive particles into them. Although, there are mechanisms in the airways that prevent foreign particles from reaching the lungs, some of them is able to get there [27, 43, 59].

In the air, short-lived ^{222}Rn decay products, such as polonium ^{218}Po or lead ^{206}Pb combine with fluid molecules to form so-called radioactive aerosols. Radon, as noble gas, does not make a high health risk. However, it is a short-lived element (half-life about 3.8 days) and decays into a number of others elements that are solids and can be deposited in the aveoli and then undergo further decays during which a and b particles are emitted [21]. Only the smallest particles at diameter less than 0.1 µm are able to rich aveoli. Particles of larger diameter settle in the upper respiratory tract from where they can be removed by coughing within a few hours. Soluble aerosol particles are rapidly absorbed from the respiratory system into the blood. The insoluble particles are deposited in the walls of the alveoli and then transferred through the capillary endothelium to the lymph vessels and then to the lymph nodes. The smallest particles may stay in aveoli for months and years contributing to the irradiation of internal organs [8, 9, 56]. The decay of radon derivatives through the emission of α particles in lungs has a significant effect on the dose received by the organs of the respiratory system. Radon derivatives may increase the risk of lung cancers and they are the second factor behind the incidence of such cancer after smoking [38]. Scientists estimate that lung cancer deaths could be reduced by 2 to 4 percent, or about 5,000 deaths, by lowering radon levels in homes exceeding the EPA's action level [59].

Particles *alpha* and *beta* have the ionization capacity, i.e. causing of series of damages as a result of collisions with macromolecules such as proteins, fats, or nucleic acids and stimulating the formation of an increased amount of harmful free radicals. The most dangerous damages caused by ionizing radiation are changes to DNA, which may disturb the functions of cells and in the consequence lead to induction of cancer of respiratory tract, mainly of lungs and also leukaemia [53, 54]. Especially, a particles may cause DNA damage leading to cancer initiation [17, 68].

Stable lead ^{206}Pb is a final product of radon decay. It may be permanently incorporated into the body's tissues. ^{206}Pb builds up in the alveoli from which it enters the bloodstream and then along with blood, it enters other organs. With a high absorption of this element over time symptoms of lead poisoning so called saturnism and, as a result, damage to the kidneys, liver and then the nervous system [16].

For the first time, nearly 500 years ago *Paracelsus* and *Agricola* reported the high mortality due to respiratory disease of miners in Saxony and Bohemia. It was only in 1879 that this disease was identified as lung cancer by German doctors Hartling and Hesse [51]. Until then, this disease was called Bergkrankheit. It was not until 1921 that a possible association of this disease with radon was found by analysing the cases of miners from Czech Republic and Germany [12].

Collective analysis of Committee on the Biological Effects of Ionizing Radiation (BEIR), took into account 11 of the studies conducted up to 1990 in Europa, North America, Asia and Australia, which concerned a total of 60,000 miners, including 2,600 who died from lung cancer, and measurements conducted in Germany among men (59,001 people of whom 2,388 died of lung cancer) employed by the Wismut Company [7, 74].

Radon may achieve harmful concentration also in living and office spaces. Analysis of results of European, Chinese and American population covering in total 11 712 peoples with lung cancer and 20 962 of healthy individuals show the linear relationship between the time of exposure and a risk of lung cancer development [74]. The results suggest the rightness of the so-called linear hypothesis, which assumes that effects of irradiation i.e. mutations, cancers may to appear not only at high but also at low doses equal to that received from natural radiation.

Lung cancer is the most common disease in terms of incidence and death among all cancers. In US annually 15-20 000 cases of lung cancer mortality connected with indoor radon exposure is registered [25]. According to *Sung* et al. [62] paper in 2020, 2,2 mln new cancer cases were diagnosed and 1,8 mln deaths were reported. Radon is the moist often factor causing cancer in non-smokers [24]. All histological types of lung cancer may be caused by radon, but the most often is adenocarcinoma [25]. The results of *Grzywa-Celińska* et al. [26] showed that the radon exposure in homes at average concentration of

69 Bq/m^3 was connected with non small cell carcinoma (78.4%) and small cell carcinoma (21.6%) among Lublin region (Poland) patients.

Studies of *Darby* et al. [13] and *Gawełek* et al. [17] showed also association of lung cancer and radon exposure. In Norway, where radon average concentration was only 88 Bq/m^3, radon was estimated responsibly for 12% of lung cancer cases [31]. Other studies calculated lung cancer risk increase by radon exposure as from 8.5% [13] to 11% [37].

Several meta-analysis showed the increased risk of lung cancer connected with radon indoor exposure. For example, *Malinovski* et al. [47] reported the linear correlation between a risk of lung cancer and exposure to radon at the level of 300 Bq/m^3. Similar results obtained *Li* et al. [45]. This study indicated several subtypes of lung cancer connected with residential radon exposure for example adenocarcinoma, small-cell carcinoma. *Cheng* et al. [11] confirmed the risk of lung cancer following indoor radon exposure, however the risk for smokers and nonsmokers were similar. No effect of radon exposure on the risk of lung cancer was reported only by *Dobrzyńsk*i et al. [14]. In turn, *Moon* and *Yoo* [54] showed dose-dependent significant risk of leukemia in children and adults exposed to indoor radon.

Due to reports on the relationship of exposure to radon with the risk of lung cancer in 1988 International Agency for Research on Cancer (IARC) classified radon as group 1 carcinogens [33]. The increase in the number of lung cancer cases is already observed at the radon concentration below 200 Bq/m^3 [50]. According to WHO data from 3 to 14% cases of lung cancer on the world were caused by indoor radon [74]. Whereas, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates that radon causes 1 in 10 lung cancer cases [73]. In turn, Polish researches suggest that radon causes 9% cases of lung cancer [76].

RADON AND SMOKING

Harmfulness of smoking is commonly known. There is believed that active smoking is responsible for approximately of 90% lung cancer cases. However, few people are aware that ionizing radiation, namely inhalation of radon and its decays is another factor determining the incidence of lung cancer [4, 38].

According to World Health Organization (WHO) radon is the second most dangerous factor in lung cancer induction in the world after smoking, and may even be the leading cause of this cancer in non-smokers [74]. Similar findings are described in other papers [38, 46, 52, 60].

Moreover, radon significantly increased a risk of induction cancer in smokers and vice versa, smoking promotes the development of lung cancer after the exposure to radon and its derivatives [30, 46]. This phenomenon called synergism, i.e. mutual reinforcement of the action of two harmful agents. The harmful effect of radon and smoking acting together is bigger compared to the sum of action of both agents. The toxic cigarette smoke inhaled in the room with a high concentration of radon causes the smoke to penetrate deeply into the lung. Tobacco may be fertilized with uranian-containing phosphates. The content of radioactive elements in tobacco smoke can vary depending on cultivation area, method of fertilization and technology of cigarette production. It is difficult to determine what dose of radiation smokers are inhale. However, American doctor estimate that a person smokes one and a half packs a cigarettes a day for a year receives a dose of radiation equivalent to 300 X-rays images [64].

The risk of the occurrence of lung cancer in smokers exposed to radon is approximately 6-10 times higher compared to non-smokers [2].

According to the Environmental Protection Agency (EPA) exposure to radon at the level up to 148 Bq/m^3 during the life will induce the lung cancer in 7 persons among 1000 nonsmokers and in 63 persons among 1000 smokers [75]. This is recognized that smoking increases the risk of cancer caused by exposure to radon at the population level. The results of Swedish investigators confirmed that in the case of the same level of exposure to radon, the risk of lung cancer in non-smokers was 4 times lower compared to general population and 10 times lower than among people smoking one pack of cigarettes daily [44].

The passive smoking is believed third, after alcohol abuse and active smoking, avoidable cause of death. According to the presently existing prohibition of smoking in public places, we are exposed to the second-hand smoking in ours homes, if other residents are active smokers. There was proved that the person who every day inhaled passively tobacco smoke has higher by 15% risk of mortality than the person who is not staying with smokers [23]. It is believed that children are 1,5-2 more sensitive for inhaled radon than adults [12]. Studies from United Kingdom showed that indoor radon exposure causes 1100 of deaths from lung cancer in smokers and former smokers yearly [3].

PRO-HEALTH PROPERTIES OF RADON

There is known that constant inhalation of radon and its derivatives may be harmful, but simultaneously it has been known for many years that radon may also have beneficial effect on the human body. Therefore it is used in medicine; mainly in radonbalneotherapy i.e. bath treatments, rinsing the mouth and inhalation [39, 40].

There was demonstrated that at doses below of 100 mSv defense mechanisms are activated leading to the elimination of damaged cells or to repair of DNA damage [1]. According to the global observations, beneficial effects of low doses of irradiation outweigh potential risk. For instance, residents of Japanese region Misasa, who use the known since 800 years naturally radioactive hot springs (9.5 kBq/ dm^3, temp. 65°C). Although, local population uses them even several times a day, there were not reported increase in mutations, infertility nor disturbances in the blood picture. Contrary, the number of cancer deaths in this population is lower (3.66%) than in surrounding towns (6.68%) [55].

Beneficial effects of radon confirms the validity of the theory of radiation hormesis, which assumes that low doses of radiation may stimulate the repair of DNA damage by activation of protective mechanisms, which neutralize free radicals. In contrast, radiation in high doses is harmful. Radon therapy is considered to work in two steps. In the first stage, directly and short-term works a-radiation, emitted during the decay of radon. This includes the duration of the treatment and a short term afterwards. In the second step, works b and g radiations coming from further decay of radon derivatives. The main effect is connected with direct or indirect influence on endocrine glans. The effect can be noticed abort 2 weeks after the start of treatment and it lasts even for 2-3 months after the end of the therapy [28].

For radon therapy, curative waters are used coming from natural springs or from boreholes, less often from uranium mine workings**.** Radon waters are considered to be those with the radon content above 74 Bq/dm^3, and those with Rn content above 370 Bq/l are considered to have therapeutic effect during bathing (34). Action of radon waters, i.e. showing activity at least 74 Bq/dm^3 is based on assumption that small doses of radiation induce DNA repair in cells [9]. In Poland waters with high radon content occurs in Sudetes, where in spas, bath and inhalations are used. The content of Rn in curative waters in Lądek Zdrój is 650-1000 Bq/dm^3, and in Świeradów Zdrój 400-650 Bq/dm^3 [36].

During the radon bath an air-radon „cushion" rises above the water surface, which is inhaled by patients, therefore the lungs are the main organ through which the greatest amount of radon is absorbed [29]. The increase of the blood radioactivity during radon bath comes in 68% from radon inhaled above the water surface, and only 33% from radon penetrating through the skin [65].

Scientific investigations confirmed the beneficial effect of radon bath in the peripheral nervous system diseases, rheumatism and musculoskeletal system diseases. They are also used in coronary insufficiency, bronchial asthma, arterial hypertension and peripheral vascular diseases as well as in male and female infertility. Radon has also anti-allergic, anti-inflammatory and anti-itching properties. Above all, radon baths showed analgesic effects lasting up to 12 months after the end of the treatments [19].

However, there are contraindications to use inhalation or radon baths, the most important of which are already existing cancer, circulatory failure or epilepsy [9]. Moreover, there is a lack of studies confirming complete safety of using radon inhalation. However, above all their positive and long-lasting analgesic effect and other health benefits make them still a popular therapy.

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Conflict of interest

The authors declare no conflict of interest.

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