Two sides of radon - a radioactive and healing component of water and air

P Maciejewski¹ and A Kowalska¹
¹Wroclaw University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Na Grobli 15, 50-421 Wroclaw

*Corresponding author: piotr.maciejewski@pwr.edu.pl

Abstract. This work presents two sides of radon - a radioactive, toxic element which has healing properties. Authors in this work present selected data about radon measurements in medicinal waters commonly used for radon therapy, to describe a phenomenon of radiation hormesis and healing properties of radon waters. From the other side, authors present the data about radon as a component of the atmosphere: radon-enriched air in health resorts, buildings (indoor radon). Authors present advantages and disadvantages of radon occurrence in human environment.

In this work there is shown a summary of polish law regulation about monitoring of indoor radon and radon in groundwaters (medicinal or drinking water) and a review of measuring methods.

1. Introduction
Radon was discovered in 1900 by Friedrich Ernest Dorn (“Miss Curie's radioactive air”). It is a colorless, odorless noble gas with radioactive properties. In the environment there are four radon isotopes: ²¹⁸Rn, ²¹⁹Rn, ²²⁰Rn and ²²²Rn. All of these isotopes occur in three natural decay series, and are alpha particle emitters. The most important is its longest-lived isotope: ²²²Rn, with a half-life of 3.8224 days [1, 2]. Radon is formed in rocks (mineral grains) as a product of radioactive decay of ²²⁶Ra nuclei. In the human environment, the source of radon can be air and water (groundwater collected in wells, or tap water, intended for consumption). Radon enters the environment as a gas released from rocks, or as a gas dissolved in water present in the pore space of reservoir rocks. Radon is well soluble in water, and therefore it can be transported with groundwaters, mainly shallow circulation, slightly mineralized, and at the point of outflow or intake of these waters it gets to the surface. Radon in human environment comes mainly from direct sources such as ground water, tap water or soil air. But it also occur in indoor air in buildings (“indoor radon”).

2. Radon in groundwaters
²²²Rn is formed in groundwater as a result of the alpha decay of ²²⁶Ra atoms, most often found in the structures of uranium minerals or minerals containing admixtures of this element. Only some of the resulting radon atoms are dissolved in water or penetrate into gas-filled gaps. The decisive factor for the concentration of radon in groundwater is the distribution and concentration of radon in reservoir rocks. Water flowing through rocks, which are high in uranium, thorium and radium, has the highest concentration of radon. This concentration depends mainly on the geological structure as well as the mineralogical, petrological and geochemical characteristics of the intake or outflow region [3, 4].
2.1. Radon - a toxic, radioactive element occurring in groundwater

Groundwater’s abstraction in Poland in 2016 amounted to approximately 1.68 billion m$^3$ [5]. Their use is very different, ranging from industry, through municipal management, to agriculture and forestry.

Due to their use, whether in the food industry, supplying water supply networks (water intended for human consumption) or as household water, most often taken from home wells, various law regulations regulate the requirements for its quality. In Poland, one of the most important ones regulating the quality of water intended for human consumption as well as those regulating the permissible concentration of $^{222}$Rn activity are:

- Act of 2001 on collective water supply and collective sewage disposal [6],
- Regulation of the Minister of Health 2017 on the quality of water intended for human consumption [7],
- Regulation of the Minister of Maritime Economy and Inland Navigation of 2019 on the requirements to be met by surface waters used to supply water for human consumption [8],
- Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast) [9],
- Council Directive 2013/51/Euratom of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption [10],
- Council Directive 98/83/WE of 3 November 1998 on the quality of water intended for human consumption [11],
- Commission Directive (EU) 2015/1781 of 6 December 2015 amending Annexes II and III to Council Directive 98/83/EC on the quality of water intended for human consumption [12].

From the point of view of $^{222}$Rn activity concentration, the most important is the Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption. It also introduces Council Directive 98/83/WE of 3 November 1998 on the quality of water intended for human consumption and Council Directive 2013/51/EURATOM of 22 October 2013 laying down requirements for the protection of public health in for radioactive substances in water intended for human consumption.

In the above-mentioned Regulation [7], the parametric value for radon is 100 Bq/L. It also precisely describes the minimum frequency of water sampling and the procedure depending on the concentration of radon activity in the water. And so, for $^{222}$Rn activity concentrations lower than or equal to 10 Bq/L, no special measures are required and the test itself is carried out once every 10 years. Exposure is then assessed as negligible or absent. For activity concentrations greater than 10 Bq/L, but not greater than 100 Bq/L, the exposure is assessed as low. In such a case, intensified control is recommended, and the procedure itself depends on the result of the next test, which is carried out after 6 months. If then the radon concentration does not exceed 50 Bq/L, tests should be performed every 5 years. However, if the concentration is greater than 50 Bq/L (and less than 100 Bq/L), the test is performed once every 2 years. For activity concentrations greater than 100 Bq/L and less than or equal to 1000 Bq/L, exposure is assessed as medium. It is then necessary to assess whether the radioactive substances present in the water pose a threat to people who require remedial action to improve the water quality, of course, to the level compliant with the regulations. In the case of an exposure assessed as average, another test is performed after 6 months and then a third test after a further 6 months. And in this case, we also distinguish two thresholds: if the activity concentration is less than or equal to 500 Bq/L, the test is performed once a year, while in the case of higher concentrations, the test is performed once every 6 months.

Therefore, the permissible concentration of $^{222}$Rn activity in drinking water is regulated by law. It is related to the harmfulness of radon. While the element itself is not a major threat, short-lived products of its decay (solids) can accumulate in human body. The resulting $\alpha$ and $\beta$ particles ionize the cells of the human body as a result of collisions with their electrons. Some of the lesions may be removed, but some of them may manifest themselves in the form of cancer or leukemia after many years [13].
2.2. Radon - a specific component of healing waters

Radon present in groundwater could give these waters pharmacodynamic properties. Based on the theory of radiation hormesis, radon waters (i.e. medicinal waters containing appropriate concentrations of radon) can be used, for example, in spas that use balneotherapy.

The radiation hormesis hypothesis itself speaks of a dual response of organisms depending on the radiation dose received. On the one hand, the body can be stimulated (at low doses), on the other hand, its vital functions are inhibited (high doses).

Thus, according to the radiation hormesis, in the case of radiation doses below a certain level, no harmful effects will appear in the body. At low doses of ionizing radiation, stimulating effects (beneficial for the body) may occur, while high doses will not cause stimulating effects and cause toxic and other harmful effects.

Pursuant to the Act of 9 June 2011, Geological and Mining Law [14] in force in Poland, medicinal water is considered to be groundwater that is not contaminated in microbiological and chemical terms, and is additionally characterized by a natural variability of physical and chemical properties with medicinal ingredients in appropriate concentrations. Radon water must have a radon activity concentration of not less than 74 Bq/L. In Poland, these waters are used, for example, in Lądek Zdrój or Świeradów Zdrój.

The concentration of $^{222}$Rn activity in waters used in spas varies from country to country. As mentioned earlier, it depends on the geological structure and mineralogical-petrological-geochemical characteristics of the intake or outflow region. Table 1 shows the values of radon activity concentrations in waters in health resorts in selected countries, and in table 2 in Polish health resorts.

### Table 1. $^{222}$Rn activity concentration in spas in selected countries.

| Country      | Minimum $^{222}$Rn [Bq/L] | Maximum $^{222}$Rn [Bq/L] |
|--------------|---------------------------|---------------------------|
| Slovenia [15]| 1.4 ± 0.08                | 3.3 ± 0.15                |
| Croatia [16] | 2.02 ± 0.41               | 93.79 ± 5.84              |
| Venezuela [17]| 0.1 ± 0.15               | 576 ± 16                  |
| Spain [18]   | 4                         | 840                       |
| Poland [19]  | 41                        | 1780                      |
| Greece [20]  | 87.49 ± 6.56              | 9270.81 ± 695.31          |

Taking into account Poland, it can be concluded that this concentration is at an average level, but much lower than the concentration in Greece, which exceeds 9 kBq/L there.

### Table 2. Selected data of $^{222}$Rn activity concentration in medicinal waters from Polish health resorts.

| City          | Name    | Concentration in water (Bq/L) |
|---------------|---------|-------------------------------|
| Lądek Zdrój [19] | Jerzy 65 | 178 122                       |
| Dąbrówka      | 41      | 189 139                       |
| L-2           | 68      | 171 134                       |
| Skłodowska-Curie | 111   | 378 232                       |
| Wojciech      | 68      | 247 161                       |
| Emilia        | 109b    |                               |
| Długopole Zdrój [21] | Renata 69b |                               |
|                | Kazimierz 65b |                               |
| Przerzeczyn Zdrój [21] | Nr 10 39b |                               |
It is worth remembering that the therapeutic medium is not only water, but also air enriched with radon.

3. Radon in the air
Radon from the pore spaces can move towards the surface of the lithosphere. This has to do with diffusion induced by difference in concentration, convection induced by difference in temperature, or advection induced by difference in pressure. It can also be transported as a result of the movements of the medium itself - a stream of groundwater or, if it fills a certain system of interconnected gaps and pores - gases [24].

Globally, in the average individual annual dose, approximately 50% comes from radon emitted from the ground in gaseous form [25].

In Poland, in 2019, the annual total effective dose of ionizing radiation received by a statistical inhabitant of Poland was 3.86 mSv. About 63.5% (2.45 mSv) comes from natural sources. Radon alone provides an average of 31.1% (1.2 mSv) of the annual dose for a Polish inhabitant [26].

The most important legal regulations regarding airborne radon include:
- The Act of November 29, 2000 - Atomic Law [27],
- National Action Plan to tackle the long-term risks of exposure to radon in human accommodation and workplaces [28].

It is worth noting that while in the case of medicinal (radon) groundwater, a threshold of 74 Bq/L has been established, after which (provided that the other purity criteria are met), the water can be regarded as healing, for air, the minimum value above which the air acquires healing properties has not been designated. Only when dissolved in water, it gives the medium (water) pharmacodynamic properties, although spas also use therapeutic inhalations of air enriched with this gas.

3.1. Radon in residential buildings
Radon, as every radioactive element is toxic, short-lived products of its decay are also toxic. The level of radon in various components of the environment (water, air) in the human environment is subject to
A serious source of radon in the human environment is the air inside buildings (figure 1), which can enter in several ways: as a gas released from tap water that may contain high concentrations of this element, directly from the geological substrate, or from building materials.

Figure 1. Indoor radon concentration in countries of the European Union (a) and in Poland (b) in ground-floor rooms of dwelling (arithmetic mean over 10 km x 10 km grid cells) [29].

The ways of radon migration from rocks and soil air to the interior of buildings are, among others, leaks in walls and foundations or sewage system (figure 2).

Figure 2. Routes of entry of radon gas into the building.
An important factor affecting the risk of exposure to radon inside buildings is the time of the year - in winter, as a result of the temperature difference between the soil and the heated building, a pressure difference arises. This in turn "sucks" the gaseous radon inside (the so-called "chimney effect"). The composition of tap water also largely affects the concentration of radon in the air. In regions (e.g. in Lower Silesia) exposed to increased radon concentrations in the environment, including groundwater, radon concentrations in drinking water - despite monitoring - may be high. In unventilated rooms where radon may be released from water (e.g. in a bathroom), additionally located on lower floors, radon concentrations in the air may be a serious problem. Table 3 shows the results of radon activity concentrations in indoor air. On the basis of the presented results, it can be seen that the concentration of radon activity in basements is higher than in the rooms on the ground floor, which is related to its way of entering the building and the fact that it is a gas heavier than air.

### Table 3. Concentration of radon activity in indoor air in selected cities in Poland.

| City in Poland            | Detector location | Radon concentration (Bq/m³) | Exp. time |
|---------------------------|-------------------|----------------------------|-----------|
| Wojszyce [30]             | Basement          | 1130±20 – 3320±40          | 3 mth     |
| Karpniki [30]             | Basement          | 1750±30                    | 3 mth     |
| Janowice Wielkie [30]     | Ground floor      | 640±20 – 1030±20           | 3 mth     |
| Przesieka [30]            | Ground floor      | 680±20 – 3440±40           | 3 mth     |
| Piechowice [30]           | Basement          | 912.9±8 – 3440±40          | 24-96 h   |
| Świdnicy Zdrój [31]       | Ground floor      | 189.3±8 – 3440±40          | 24-96 h   |
| Czerniawa Zdrój [31]      | Basement          | 981.1±8 – 3440±40          | 24-96 h   |
| Suwałki [32]              | Inhabited part    | 40±8 – 3440±40             | 48 h      |
| Olsztyn [33]              | Basement          | 33.3±2.7 – 96.6±7.8        | 24-96 h   |
| Olsztyn [32]              | Inhabited part    | 15.5±1.1 – 42.4±3.3        | 24-96 h   |
| Białystok [32]            | Basement          | 52±8 – 3440±40             | 48 h      |
| Białystok [32]            | Inhabited part    | 22±8 – 3440±40             | 48 h      |
| Białystok [32]            | Basement          | 81±8 – 3440±40             | 48 h      |
| Białystok [32]            | Inhabited part    | 24±8 – 3440±40             | 48 h      |
| Łódź [34]                 | Inhabited part    | 56 – 115                  | Annual average |
| Ciechanów [32]            | Basement          | 55±8 – 3440±40             | 48 h      |
| Siedlce [32]              | Inhabited part    | 18±8 – 3440±40             | 48 h      |
| Ostrołęka [32]            | Basement          | 50±8 – 3440±40             | 48 h      |
| Łomża [32]                | Inhabited part    | 21±8 – 3440±40             | 48 h      |
| Łomża [32]                | Basement          | 49±8 – 3440±40             | 48 h      |
| Rybnik [35]               | Basement          | 20±10 – 740±50             | no data   |
| Rybnik [35]               | Ground floor      | 10±10 – 390±40             | no data   |
| Ostrów Wielkopolski [36]  | Kindergartens and schools | 5 – 216.8 | 48 h      |
3.2. Radon in spas – advantages and disadvantages considerations
Radon is a radioactive gas, in Poland commonly occurring in Lower Silesia. This region of Poland is rich in radon due to its geological structure - crystalline rocks rich in isotopes $^{238}$U and $^{226}$Ra, which produce $^{222}$Rn due to their radioactive decay. Water reach in $^{222}$Rn is the most common radon source in many spas in the world as well as in Poland. These waters are used in the treatments of many diseases on the theory of radiation hormesis. According to this theory, small doses of ionizing radiation can have a beneficial (therapeutic) effect on the human body. Unfortunately, in many spas, including polish ones, the values of $^{222}$Rn activity concentrations, which should be safely used in therapeutic procedures, have not been specified so far. Moreover, there is no current information on $^{222}$Rn activity concentration during the treatment in a therapeutic material such as radon water, as well as radon-enriched air, which seems to be a crucial for workers employed in such spas (due to potentially big effective dose). There is also a lack of information on $^{222}$Rn activity concentrations changes between consecutive treatments on one day and on subsequent days, including a series of treatments prescribed during the entire stay of the patient in the spa. Radon treatments are often carried out based on methods of applying radon materials, developed and practiced over the decades, but without doses calculations.

4. Radon detectors in the air
The presence of radon in the air is of interest to many scientists. The methods used to measure its activity concentration in the air are based on recording the radiation emitted by them. The most useful methods is based on scintillation, ionization chambers or traces detectors.

4.1. Lucas’ chambers
Lucas chambers are used for both continuous and temporary measurements. It is a system of scintillation chambers (most often with a volume of about 0.2 dm$^3$) with a photomultiplier tube and a pulse counter. The inner walls are covered with silver-activated zinc sulfide. The scintillation light falls on the photomultiplier tube through the light-transmissive bottom. The chambers are made of glass, plastic or metal. Momentary measurements consist in pumping the air out of the chamber, then filling it with the tested air, which passes through the filter that cuts off derivatives. After three hours, i.e. the time after which the radioactive equilibrium of radon with derivatives is formed, the pulses per time unit are counted. The photomultiplier processes the electric pulses incident on the walls covered with the scintillator, which amplified are counted by the pulse counter [37].

4.2. Activated carbon detectors
Activated carbon detectors require an exposure of two to four days due to the carbon absorption capacity. Then, they are analyzed by measuring the $\gamma$ radiation (emitted by radon decay products) or by licking $\alpha$ and $\beta$ particles (emitted by radon and its derivatives) [37].

The disadvantage of carbon-based methods is the influence of air temperature and relative humidity on the carbon absorption capacity. Temperature is inversely proportional to the absorption capacity and correcting its effect is simpler than relative humidity, where it is necessary to shorten the exposure time and mix the carbon with the silica gel. As a result, water vapor is readily absorbed by the silica gel, but the radon is also partially absorbed [37].

4.3. Trace detectors
Trace detectors are used to obtain an average result over the exposure time from three to 12 months. They look like a small plastic container. In this case, it is a diffusion chamber. Aerosols and radon decay products are cut off from the air by a filter. At the bottom of the container there is a foil of

---

Kalisz [35]  Kindergartens and schools  5 – 194.4  48 h

* Arithmetic average.
polycarbonate allyl diglycol - PADC. It bears the trade name CR-39. When passing through the foil, α particles damage it and create a latent path. Due to its etching with 40% sodium base at 70-80°C, it can be observed under a microscope. The density of the traces is proportional to the exposure time and the radon concentration in the tested air. Thanks to the possibility of using them for up to one year, these detectors provide the basis for assessing the risk of radon to health [37].

4.4. Electret ionization chambers (electrets)
Electrets are polytetrafluoroethylene discs with permanent positive potential. It is located at the bottom of a container made of conductive plastic. There is also a filter whose task is to cut off aerosols and decay products of radon from diffusing air into the container. Due to the ionization of the air by the α radiation emitted by radon and its newly formed derivatives, negative ions are formed. In the chamber, they are attracted to the positively charged disk by an electrostatic field. This results in a drop in potential on the disk. It is proportional to the exposure time and the radon concentration [37].

5. Summary
222Rn as a colorless and odorless noble gas with radioactive properties. On the one hand, it may be a therapeutic component of water or air, and a toxic component on the other. There has been a dispute for years between supporters and opponents of the theory of hormesis. There are even studies showing that there is no scientific evidence linking radon exposure to lung cancer [38, 39].

It is an element that contributes to over 30% of the annual component of radiation dose received by a statistical inhabitant of Poland [26].

Its activity concentration in water and air depends mainly on the mineralogical, petrological and geochemical characteristics of the reservoir rocks. One of the sources of radon in human environment is water. When groundwater flows out on the surface, all of its components, including radon, flows out with this water on the surface. Groundwaters can have different properties due to different chemical composition – it is important to control their clearness and properties if they are used as tap water or medicinal water. It is important to remember, that radon could have beneficial impact on human body – according to the hypothesis of radioactive hormesis it is used in balneotherapy (as radon water or radon enriched air) – as well as dangerous impact on health because of its radioactivity. In Poland, there are legal provisions regulating the concentration of 222Rn activity in water – in the case of waters intended for human consumption (less than 100 Bq/L) and medicinal waters (above 74 Bq/L). Every consumer should be aware of this fact. Radon also occurs in human environment as indoor radon. In the case of its activity concentration in the air, 300 Bq/m³ was set as the upper limit in buildings intended for human habitation. However, there are no regulations governing the upper and lower limits when air is used as a radon material for radon therapy. Nowadays, there are many scientific methods to determination of radon in the air and in water used for many purposes.

References
[1] Collé R 1995 Radioactivity & Radiochemistry 6 16–29
[2] Collé R 1995 Radioactivity & Radiochemistry 6 30–40
[3] Przylibski T A 2000 Archives of Environmental Protection 26 55–71
[4] Przylibski T A 2002 Wiadomości Chemiczne 56 1003–33; in Polish
[5] Ministry of Maritime Economy and Inland Navigation 2018 Economic use of waters Water resources management in Poland 2018 Report 80-3; in Polish
[6] Law of 7 June 2001 on collective water supply and collective sewage disposal J. Laws 2020, Item 2028; in Polish
[7] Regulation by the Minister of Health of 7 December 2017 on the quality of water intended for human consumption J. Laws 2017, Item 2294; in Polish
[8] Regulation of the Minister of Maritime Economy and Inland Navigation of 29 August 2019 on the requirements for surface waters used to supply the population with water intended for human consumption J. Laws 2019, Item 1747; in Polish
[9] Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast)

[10] Council Directive 2013/51/Euratom of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption

[11] Council Directive 98/83/WE of 3 November 1998 on the quality of water intended for human consumption

[12] Commission Directive (EU) 2015/1781 of 6 December 2015 amending Annexes II and III to Council Directive 98/83/EC on the quality of water intended for human consumption

[13] Biliska I 2016 Medycyna Środowiskowa - Environmental Medicine 19 51-6

[14] Law of 9 June 2011: Geological and mining law J. Laws 2020, Item 1064; in Polish

[15] Vaupotić J, Kobal I 2001 Radon exposure in Slovenian spas Radiation Protection Dosimetry 97 265-270

[16] Radolić V, Vuković B, Šmit G, Stanić D and Planinić J 2005 Journal of Environmental Radioactivity 83 191-8

[17] Horváth Á, Bohus L O, Urbani F, Marx G, Piróth A and Greaves E D 2000 Journal of Environmental Radioactivity 47 127-133

[18] Soto J, Fernández P L, Quindós L S and Gómez-Arozamena J 1995 The Science of the Total Environment 162 187-192

[19] Przylibski T A and Żebrowski A 1999 Journal of Environmental Radioactivity 46 121-9

[20] Danali-Cotsaki S and Margomenou-Leonidopoulou G 1998 Demokritos National Research Center for Physical Sciences (Greece: Thessaloniki)

[21] Kozłowska B, Walencik A, Dorda J and Zipper W 2010 Applied Radiation and Isotopes: Including Data, Instrumentation and Methods for Use in Agriculture, Industry and Medicine 68 854-7

[22] Przylibski T A 1998 Przegląd Geologiczny 46 365-370; in Polish

[23] Przylibski T A, Mroczkowski K, Żebrowski A and Filbier P 2001 Environmental Geology 40 429-439

[24] Przylibski T A 2005 (Wrocław: Publishing House of the Wrocław University of Science and Technology); in Polish

[25] Strupeczewski A 2009 Thermal and Professional Energy 6 5-10; in Polish

[26] Radiological protection of the population and employees in Poland 2019 Annual Report Activities of the President of the National Atomic Energy Agency and the assessment of nuclear safety and radiological protection in Poland in 2019 51-65; in Polish

[27] Law of 29 November 2000: Atomic law. J. Laws 2018, Item 792; in Polish

[28] National plan in the case of long-term risks from exposure to radon in buildings intended for human residence and workplaces 2021; in Polish

[29] Website: https://www.remap.jrc.ec.europa.eu/ [date of collection: 01.06.2021.]

[30] Kozak K, Mazur J, Kochowska E, Grządziel D, Hovhannisyan H, Haber R and Zdziarski T 2008 Institute of Nuclear Physics, Polish Academy of Sciences Report No. 2017/AP (Kraków: Instytut Fizyki Jądrowej im. Henryka Niewodniczańskiego Polskiej Akademii Nauk)

[31] Pachocki K A, Gorzowski B, Różycki Z, Wilejczyk E and Smoter J 2000 Roczn. PZH 51 291-298

[32] Zalewski M, Karpińska M, Mnich Z and Kapała J 1998 J. Environ. Radioactivity 40 147-154

[33] Gorzowski B, Pachocki K, Różycki Z, Majle T and Krześlak A 1998 Roczn. Panstw. Zakl. Hig. 49 199-206; in Polish

[34] Olszewski J and Skubalski J 2011 Medycyna Pracy 62 31-6

[35] Rubin J A, Wysocka M and Chmielewska I 2015 The 2nd International Conf. Radon in the Environment 2015 (Kraków)
[36] Bem H, Bem E M, Krawczyk J, Plotek M, Janiak S and Mazurek D 2013 Journal Radioanal Nucl. Chem. 295 2229–2232

[37] Mamont-Cieśla K Radon – a radioactive gas in a human environment, Central Laboratory for Radiological Protection; unpublished

[38] Fornalski K W and Dobrzyński L 2012 Problemy Techniki Jądrowej 57(3) 21-28; in Polish

[39] Dobrzyński L and Formalski K W 2015 International Journal of Low Radiation 10(2) 143-154