SUMMARY OF DOCTORAL DISSERTATION

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Entitled: "Changes of ^{222}Rn activity concentration in radon therapeutic water at different stages: from the extraction of radon resources from the deposit to the use of radon material in radon therapy treatments"

prepared under the supervision of
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The aims of the dissertation. The following study goals were formulated: (1) the investigation of changes in the activity concentration of ^{222}Rn in time and health resort during the process of exploitation, transport, and use of radon waters in therapeutic applications, (2) the characterization of the process of radon escape from groundwater (radon therapeutic waters) to the atmosphere, (3) the estimation of ionizing radiation doses from ^{222}Rn and its radioactive daughters during radon therapy treatments for patients, medical personnel, and technical personnel; whereas the overarching aim of the work was (4) to develop guidelines leading to the standardization and optimization of radon therapy treatments.

The achievement of the objectives set out in the doctoral dissertation was possible due to an extensive analysis of literature data, the selection of appropriately located testing areas and measurement points, the selection of adequate research methods, and, finally, the conduct of a number of measurements and analyses. The author obtained permission to perform experiments in the Lower Silesian health resorts of Lądek-Zdrój and Świeradów-Zdrój. These are the only health resorts in Poland using a variety of radon therapy treatments. The therapeutic radon waters exploited by mining plants operating in the aforementioned health resorts are a source of radon (isotope ^{222}Rn) used in radon therapy treatments. The author used the highly sensitive liquid scintillation spectrometry (LSC) method to measure the ^{222}Rn activity concentration in radon therapeutic water samples (considered as mineral, then therapeutic material, and finally effluent). Measurements of the activity concentration of radioactive ^{222}Rn daughters and the concentration of the potential energy of α-radiation in the air were carried out using a RGR-40 mining radiometer. This instrument is equipped with a semiconductor silicon detector and performs the measurement semi-automatically in a Markov measurement cycle. Determinations of ^{222}Rn activity concentrations in air, meanwhile, were carried out with the AlphaGUARD PQ 2000PRO reference instrument in the continuous flow mode with a 10-minute time-lapse using a gas-tight AlphaPUMP pump injecting the air into the instrument's ionization chamber.

Analyses were performed both at the site of the mineral intake, i.e. the therapeutic radon water, i.e. in the reservoir at the intake. Subsequently, in the radon material reservoir (of the therapeutic radon water before it is applied to the procedures, i.e. in the naturopathic facilities) and at different stages of the procedures: individual and group baths (measurements in the bath and pool) and individual and group inhalations (measurements in the emanatorium and in the graduation tower), as well as in the water after the procedures discharged as effluent.

A review of the literature, measurements, and analyses were performed to prove the theses of the paper, which were: (1) changes in the concentration of ^{222}Rn activity in time and health resorts during the process of exploitation, transport and use of radon waters in therapeutic treatments may reach two orders of magnitude, (2) contact of radon groundwater with atmospheric air leads to a rapid decrease in the concentration of ^{222}Rn activity in the therapeutic water, (3) the values of the effective dose of ionizing radiation derived from ^{222}Rn and its daughters in the air of rooms used for radon therapeutic treatments do not exceed the permissible standards for the general population (patients, bathers) as well as for employees working in occupational exposure conditions.

The structure of this dissertation reflects the sequence of procedures pursued in order to achieve the objectives and prove the presented thesis. It is composed of 12 chapters, with the last 3 being lists (literature, tables, and figures).

The first chapter is an introduction to the dissertation, in which the author argues for his motivation to carry out investigations on the chosen topic. The author explains that it results from the to date lack of information regarding the concentration of ^{222}Rn activity in radon materials and the magnitude of effective doses of ionizing radiation from this isotope and its radioactive daughters received by patients, bathers, as well as medical and technical staff during treatments. The current treatments are based on long-standing traditions and do not rely on real-time measurements. In addition, during treatments, the concentration of ^{222}Rn activity in radon materials and the magnitude of radon accumulation in the rooms after treatment are not monitored. The fact that the radon procedures used in health resorts are not standardized may also appear to be a problem. Also, no one is able to determine the effective dose received by patients during treatments, which appears to be a crucial issue in terms of radiological protection.

Chapter two is devoted to radon. Here, the author describes the historical background of the discovery, the initial applications, as well as the periods of growth and decline of scientific interest in this radioactive noble gas. The chapter also includes a characterization of radon and its natural isotopes (description of radioactive series, selected properties). There is a presentation on the manner in which radon is released from the earth's crust and a specification of radon as a component of medicinal waters. In this chapter, the author reviews the available literature describing the effects of radon influence on human health and presents the assumptions of the no-threshold linear hypothesis and the theory of radiation hormesis, citing many articles proving their validity. The chapter concludes with a look at the use of ^{222}Rn in accordance with the law, i.e. a presentation of the permissible effective dose for the general population from ^{222}Rn and its daughters based on the Polish Atomic Law.

The third chapter describes the basic properties of groundwater. The characterization is based on the division of properties into physical and chemical. Within the characterization of physical properties, specific electrolytic conductivity (PEW) and total dissolved mineral content (TDS), temperature (T), and radiosity are outlined. On the other hand, among the chemical properties, those such as oxidation-reduction potential (Eh) and water reaction (pH) are presented.

Chapter four includes the aforementioned objectives set by the author and the formulated main thesis.

The fifth chapter was dedicated to the characteristics of the study areas: Lądek-Zdrój spa and Świeradów-Zdrój spa. The author presents an outline of the geological structure and hydrology of both regions. Moreover, he explains the reasons for the presence of radon groundwater outflows in these areas, which are considered therapeutic waters in the light of Polish law.

Chapter six introduces the scope of work and the applied measurement methodology. The instrumentation and methods used for the determination of basic physico-chemical parameters of water (PEW, T, Eh, pH), for the quantification of ^{222}Rn activity concentrations in water samples and in air, for the analysis of the potential energy of α-radiation and for the activity concentrations of radioactive ^{222}Rn daughters in the air. In the last subsection of Chapter Six, the author presents methods for calculating the effective doses from radon and its daughters and attempts to determine the value of the radioactive equilibrium factor between ^{222}Rn and its daughters. The author also provides a mathematical formula, which is applied in the next chapter, for the estimation of effective doses to which the patients and staff of the two Lower Silesian radon health resorts are exposed.

The seventh chapter is a crucial section of the dissertation. In it, the author presents the results of studies carried out in the Lądek-Zdrój health resort (measurements in radon groundwater resources and exploited air enriched in radon, as well as in radon materials during baths in therapeutic radon-sulfide water and group inhalations of air enriched in ^{222}Rn). Similarly, the results of studies in the Świeradów-Zdrój health resort are also characterized (measurements in the radon groundwater resources, in radon material, during individual and group baths in therapeutic radon-sulfide water, and during individual and group inhalations of air enriched in ^{222}Rn). This chapter presents a detailed analysis of the changes in the activity concentration of ^{222}Rn in water from the intake of the radon groundwater resource through its use to its discharge into wastewater. The author also analyzes the changes in ^{222}Rn activity concentration in the air during the treatments carried out in the health resorts. The author also determines the limits of ^{222}Rn activity concentrations due, on the one hand, to the permissible dose limit for people in the general population (1 mSv/year) and, on the other hand, to the radiological requirements that radon therapeutic water must comply with (the ^{222}Rn activity concentration in radon therapeutic water must be above 74 Bq/dm^3).

Chapter Eight summarizes the conducted studies. The analyses determined the mean value of activity concentration of ^{222}Rn in the radon groundwater resource in the Lądek-Zdrój health resort (it ranged from 1136 ± 29 Bq/dm^3 to 1291 ± 44 Bq/dm^3) and in the radon groundwater resource in the Świeradów-Zdrój health resort (it ranged from 988 ± 31 Bq/dm3 to 1084 ± 30 Bq/dm^3). The mean activity concentration of ^{222}Rn in radon water contained in a radon material reservoir is also presented (ranging from 901 ± 22 Bq/dm^3 to 1021 ± 31 Bq/dm^3). In the Lądek-Zdrój health resort, changes in ^{222}Rn activity concentration between the radon resource and the radon material prior to treatment with individual radon baths ranged from 500 Bq/dm^3 (44.0%) to 683 Bq/dm^3 (53.2%). In contrast, changes in the concentration of ^{222}Rn activity in radon water between radon material and effluent oscillated between 27 Bq/dm^3 (4.1%) and 44 Bq/dm^3 (7.0%). The total mean change in ^{222}Rn activity concentration during individual bath treatments was 616 Bq/dm^3 (51.0%). The estimated effective dose possibly received by the bather during a single individual bath treatment ranged from 1.2 to 48 nSv (average for all measurements carried out from 17 to 24 nSv), and during inhalation from 0 nSv to 366 nSv (average for all measurements carried out from 95 to 119 nSv). Employees operating personal bathing treatments are exposed to a maximum effective dose of 0.28 mSv/year, while those handling radon inhalations receive a dose of 0.95 mSv/year.

The average change in ^{222}Rn activity concentration at the Lądek-Zdrój health resort between the radon groundwater resources in the reservoir and the radon material prepared for the individual bath treatment is 48.1%. In contrast, the difference between the ^{222}Rn activity concentration in the radon groundwater resources and the water after the treatment (effluent) is 51.0%. The mean change in activity concentration of ^{222}Rn in the Świeradów-Zdrój health resort from the radon groundwater resources to the radon material reservoir is 6.3%. During individual bath treatments, the mean change in ^{222}Rn activity concentration between the water concerned as radon resources and the water concerned as a radon material prior to the treatment was 25.2%, while between the radon resources and the water after the treatment (effluent) was 37.0%. During the group inhalation treatments (graduation tower), the average change in ^{222}Rn activity concentration in the radon therapeutic water at the transfer stage from the radon groundwater resources (in the intake) to the radon material before its release in the graduation tower was 93.8%, while from the radon resources to the water after its release (before the intake in the effluent tank) was 99.8%.

In the health resort Świeradów-Zdrój the estimated effective dose possibly received by a patient during a single treatment is for individual baths from 7 to 44 nSv (the average for all measurements made from 17 to 24 nSv), for pool baths from 1129 to 1674 nSv (the average for all measurements made from 1324 to 1485 nSv), for individual inhalation from 27 022 to 35 499 nSv (average for all measurements carried out 29 579 to 33 212 nSv), and inhalation in a radon-saline graduation tower from 4 nSv to 82 nSv (average for all measurements carried out 26 to 37 nSv).

The estimated maximum effective dose potentially obtained by resort staff is: 0.18 mSv/a when operating group inhalations (graduation tower), 0.29 mSv/a operating individual baths, and 11.88 mSv/a operating group baths (swimming pool). In the latter case, it should be noted that the health resort's pool was closed due to technical reasons. As a kindness of the health resort, it was possible to take measurements, however, these were carried out with only cold water and without the participation of the bather. These factors may have significantly influenced the estimated dose values obtained.

Reaching or exceeding the upper limit of activity concentration of ^{222}Rn, estimated due to the dose limit for persons in the general population defined in the Atomic Law Act, for treatments in Lądek-Zdrój and Świeradów-Zdrój for the majority of treatments is realistically unattainable (such a high activity concentration of ^{222}Rn does not occur in nature). The only treatment for which it could possibly be achieved was the individual inhalation treatment in Świeradów-Zdrój. Assuming an intake of 14 treatments, it was 2135 Bq/dm^3, and with 25 treatments, it amounted to 1198 Bq/dm^3. It would therefore be advisable to pay particular attention to the concentration of ^{222}Rn activity in the radon resources when planning individual inhalation treatments.

The lower limit of the ^{222}Rn activity concentration in the radon groundwater resources (radon therapeutic water) to maintain radon levels above 74 Bq/dm^3 during bathing is 700 Bq/dm^3 for the Lądek-Zdrój health resort and 464 Bq/dm^3 for the Świeradów-Zdrój health resort.

The ninth chapter contains the conclusions formulated by the author based on the conducted research. These have been grouped into: concerning changes in ^{222}Rn activity concentration, dose limits, ^{222}Rn activity concentration limits, and standardization and optimization of radon therapy treatments. Based on these, the author declares that all the objectives of the work have been fulfilled and the thesis statements have been proven.