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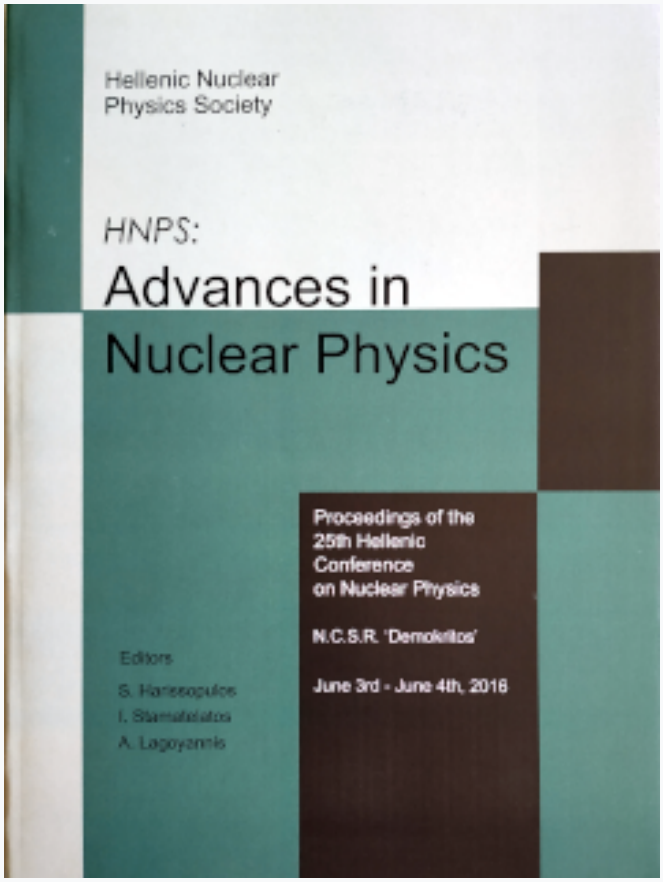

Limitations in the assessment of radon dose: the role of activity measurements in the human body

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Limitations in the assessment of radon dose: the role of activity measurements in the human body

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Abstract

Radon-222 is classified in the Group I of the human carcinogens. The *in situ* decay of inhaled ^{222}Rn and its short-lived decay products ($T_{1/2}$ <30 min) is the main source of radiation burden to the general population of natural origin. The corresponding effective dose is routinely calculated as the product of the ^{222}Rn concentration in air, a predetermined dosimetric constant and a factor that depends on the space type (e.g. residential or public building, cave, mine, etc). However, in practice, there are large spatial and temporal variations in the activity ratio of each progeny to ^{222}Rn in air, the characteristics of the progeny carrying particles and the metabolism of each progeny depending on air quality, as well as differences in the anatomic and physiological characteristics between individuals, that vary substantially even with time. Therefore, the currently employed dosimetric approach may introduce large uncertainties.

In the hypothetical case of acute deposition and full retention in the human body of equal activities of all ^{222}Rn progeny, about 93% of the effective dose is due to the decaying ^{214}Po. The ^{214}Po activity can be assessed by measurement of its γ-emitting precursor, ^{214}Bi, which is in full equilibrium with ^{214}Po in the human body. The ^{214}Bi activity can be measured using a high-sensitivity whole-body counter with high counting uniformity, such as the one in use at the Ioannina University Medical Physics Department. Its detection efficiency and its dependence on body shape and size were assessed by Monte Carlo simulations. Measurements carried out in healthy adult volunteers residing at a short distance from the counter, indicated a mean total body ^{214}Bi activity (TBBi) of ~100 Bq during the cold season of the year and lower during the hot one. Higher mean TBBi levels were found in male than in female adults. Therefore, TBBi measurements may allow for accurate radon-related risk assessment on individual base.

Key words: ^{214}Bi, Radiation protection, Radon, Metabolism, Whole body counting

Introduction

The annual exposure to ionizing radiation of the average non-occupationally exposed adult Greek is almost 5 mSv. Among the sources of natural origin the inhaled ^{222}Rn and its short-lived progeny are the dominant dose contributors with ~1.7 mSv. More specifically, ^{222}Rn undergoes successive decays to rapidly decaying nuclei ($T_{1/2}$ <30 min) up to ^{210}Pb ($T_{1/2}$ = 22.2 y), liberating 19.54 MeV as total kinetic of energy of the α-particles and 2.69 MeV either as β^- particle or photon energy per decay [1]. Most of the first formed long-lived radionuclide, ^{210}Pb, is biologically eliminated from the human body before decay; thus ^{210}Pb and its progeny are of limited interest in radiological protection.

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Radon is a naturally occurring inert gas that emanates mainly from the earth's crust and the building materials to the indoor air spaces. Due to its chemical characteristics, the radon retention in the human body is limited, e.g. only ~5 Bq in case of adults men or women, present over few days in an environment with 60 Bq m^{-3} of ^{222}Rn in its air. Most of the radon-related exposure is due to the inhalation of its four airborne short-lived progeny and not of the ^{222}Rn itself. Among them, two are α-emitters, ^{218}Po and ^{214}Po ($T_{1/2}$ = 3.10 min and 0.16 ms, respectively) and two β-γ emitters, ^{214}Pb and ^{214}Bi ($T_{1/2}$ = 26.8 and 19.9 min, respectively). Their activities in the human body are usually one to two orders of magnitude higher than that of ^{222}Rn. However, the effective dose is routinely calculated as the product of three quantities, i.e. the ^{222}Rn concentration in the inhaled air, a dosimetric constant and a factor (F), which depends on the assumed of degree equilibrium of ^{222}Rn with its progeny in air. This factor, which refers only to the energy liberated as kinetic energy of the α-particles, is usually assumed to be ~0.4 and ~0.7 inside and outside the buildings, respectively.

The average indoor ^{222}Rn concentration in the indoor air, for example in domestic dwellings, is usually one to two orders of magnitude higher than that in the outdoor air and its mean value varies between the 74 regional units of Greece up to one order of magnitude. In addition, there are large variations in ^{222}Rn concentration between the buildings in each regional unit, rooms at different floors at the same building, rooms at the same floor, as well as temporal variations in each room according to the meteorological conditions, the season of the year, the day and even the time of the day. For example, the ^{222}Rn concentration in domestic dwellings is usually higher during winter and night than summer and daytimes. In addition, some human activities, such as room ventilation and heating, smoking and cooking, further modify the ^{222}Rn concentration as well as the activity ratios of the progenies to that of ^{222}Rn. Therefore, the currently widely employed approaches for the assessment of the effective dose of an individual are prone to substantial uncertainties, calling for alternative approaches.

Radon and radon progeny metabolism

In general, radionuclides which enter in the human body (e.g. by ingestion and inhalation) can be localized in tissues and organs until either their decay or their biological elimination (e.g. via urine). The activity and the bio-distribution of inhaled radon progenies depend among other things on the size and shape distributions, the electric charge and the hygroscopicity of their carriers, the humidity in air, a number of anatomical factors of the exposed person, his current and recent breathing patters (i.e., rate of inhaled volume and partition between nasal and mouth breathing) and other time-varying physiological factors. For example, the rate of the inhaled air volume by men during heavy exercise is often considered to be ~6.5 higher than that during rest (a 8.5 factor is often considered in women) [2]. In addition, digestion and a number of diseases and conditions, such as pregnancy, modify the metabolic rate. Thus many factors influence the uptake, retention, redistribution between organs and tissues and the elimination patterns from the body, that compete with the in situ decay.

Most of the ^{222}Rn in the human body under equilibrium conditions is located at the fat-rich tissues (e.g. adipose tissue, yellow bone marrow, female breast). On the contrary, most of short-lived radon progeny are deposited on the lining of the respiratory track; smaller quantities are deposited on the gastrointestinal track lining, and some can be found in a variety of tissues or organs following blood uptake, such as in kidneys and liver. The radon-related radiation burden is attributed mainly to the three α-emitters, ^{222}Rn, ^{218}Po and ^{214}Po, which practically do not emit γ-rays, thus they cannot to be

detected at some distance from the human body. However, in the hypothetical case of full equilibrium between ^{222}Rn and its progeny in air (F=1.00) and full progeny retention, about 90% of the radon-related effective energy is due to the decaying ^{214}Po nuclei (lower percentage if F<1.00).

Direct ^{214}Po activity measurements are not possible due to lack of γ- emissions with abundance higher than 1%. However, due to its μs decay rate, ^{214}Po is always in radio-active equilibrium with its precursor, ^{214}Bi, emiting γ-rays of abundance above 10% of 609 keV (45.5%), 1120 keV (14.9%), and 1764 keV (15.3%), with a half-life of almost 20 min. Therefore, the ^{214}Bi activity in the human body (TBBi) can be directly measured as a ^{214}Po surrogate using a high-sensitivity whole-body counter (WBC) with a response relatively invariant with respect both the source bio-distribution and the size of the counted subject, such as the one at the University of Ioannina Medical Physics Department (UIMPL) [3].

The whole body counting facility

The UIMPL WBC design was based on preconstruction MC simulations aiming to provide high detection efficiency and sensitivity in the energy region 0.1 to 1.85 MeV, coupled with almost invariance of the efficiency from body morphology and radionuclide bio-distribution. It is a shadow-shield-type counter with a bed moving in a 2.0 m - long tunnel made of low activity 10 cm-thick Pb bricks. A 60.0 cm x 48.4 cm opening through the bricks allows for the patient positioned in the supine position on a couch to pass with constant velocity through the tunnel. The counter is equipped with sixteen cylindrical NaI(Tl) at fixed symmetrical positions at the central region of the tunnel. Seven detectors with nominal dimensions 15.7 cm × 5.0 cm are located below the human body and seven of the same type above, at a 58.5 cm face-to-face distance between opposing detectors. The remaining two detectors, 29.2 cm × 10.2 cm in nominal size, are located on the sides of the scanned subject, at a 60 cm face-to-face distance. The detectors are also surrounded by 10 cm –thick lead bricks of high purity, except for the side which faces the human body as it passes close to the detectors. The signal from each detector is driven to a MCB920E ORTEC multi-channel buffer unit and analyzed individually using the emulation software Maestro 32® also by ORTEC.

The counting rate registered by each detector during background measurements in each nuclide-specific region of interest (ROI) around the corresponding peak maximum, such the 1691-1837 in case of ^{214}Bi measurements, was subtracted from that during the subject measurement (both 2100 s long). The background signal was obtained by scanning a blank phantom of appropriate size and shape for the subject to be counted with a time interval between the two measurements up to 45 min. The phantoms consist of sets plastic bottles filled with either 1.0 or 2.0 liters of de-ionized water. Similar phantoms containing radioactive solutions of known activity were used to test the accuracy of the detection efficiency and its dependence on body shape assessed by Monte Carlo simulations using the MCNPX5 code.

The counting room is separated by 70 cm-thick concrete walls from the two auxiliary rooms, one used for long-term storage of phantoms and cloth changing, and the other for irradiations with (α, n) sources. The room is separated from a similar complex of rooms at the first floor by a 30 cm-thick concrete plaque. In an attempt to keep airborne radioactivity at low and almost stable levels, the counting room that is located at the

ground floor of the UIMPL building (there is no basement below), is constantly ventilated. More specifically, fresh air from the outdoor space is forced to enter in the counting room by two fans installed close to the openings of the shielding tunnel at 3 m height above the ground level [4]. Temperature regulation of the room is carried out by two air-conditioning units augmented by a central heating system during the cold season of the year. Thus a 2.95% coefficient of variation of total body ^{40}K measurements in adult subjects of both sexes was obtained [3- 5]).

Total body ^{214}Bi activity in healthy adults

Sequential TBBi measurements carried out at IUMPL on a subject exposed over a short time-period to high radon and radon progeny levels indicated a reduction rate of his extra ^{214}Bi body activity with an effective half-life of about 40 min, a value slightly lower than the 50 min-long half-life of the cascade between the decay of the ^{222}Rn nuclei and the formation of the corresponding long-lived ^{210}Pb nucleus [5]. In addition, successive measurements in a group of volunteers during the cold period of the year, indicated TBBi levels during the second measurement carried out about 1 h after the first one were ~20% lower than in the first one, initiated no more than 20 min after the subjects' entrance to the room. These findings are attributed to the reduced in air activity in at the counting room [4, 5]. Our the observed TBBi changes due to transient changes in the inhaled air quality are in accordance to the hypothesis that the volume and quality of the recently inhaled air is more important TBBi contributors than the "long-lived" radon inhaled at much earlier times and stored in the human body before its gradual decay to ^{214}Bi. It is pointed out that the temporal changes of the progeny activity distribution in the human body had minor influence on measurement uncertainty, due to the characteristics of the employed counter.

Taking into account the fast temporal TBBi changes in case of varying environmental conditions, the remaining measurements presented in this study were divided in two groups, those on subjects that entered the counting room less than 20 min before counting and those on subjects after an at least 2.5 h-long presence in it. The first group reflects in large the quality of the inhaled air before entrance to the counting room, while the second the metabolic differences among individuals exposed to the more or less stable air quality at the WBC room (~40 Bq m^{-3} during the cold season of the year, i.e. about half of the geometric average in buildings at the city of Ioannina [4]).

Measurements of the first type carried out during the cold season of the year (15 October to 15 April) on seventy adult healthy volunteers residing at a distance less than 5 km from the UIMPL, that neither smoked, made intensive physical exercise, or consumed a heavy meal during the previous few hours, indicated a large spread in the TBBi values. In general, higher TBBi values were found in men (108 $\pm$ 53 Bq) than in women (87 $\pm$ 68 Bq), a difference attributed in-large to gender differences in body mass (85$\pm$ 12 kg and 64 $\pm$ 13 kg, respectively). The large coefficient of variation of the TBBi values in each gender, reflect mainly differences in the quality of air that they were exposed before their arrival to the counting room and not measurement uncertainties.

Measurements of the first type were also carried out on 22 young female volunteers during the period May 15 and June 30, indicated lower mean TBBi (54 $\pm$ 34 Bq) relative to that in the female volunteers measured during the cold season of the year. A similar effect was also observed in male volunteers. In addition, double measurements in a group of 14 volunteers carried out in early April and in early June, indicated lower mean

TBBi values during in June (p=0.01) [5]. Therefore, it is concluded that there is a substantial seasonal variation in TBBi, which is attributed to variations in the progeny levels, thus the radon radiation burden is elevated during the cold season of the year.

Poisson counting statistics contributed an uncertainly (68%) of 22 Bq to the uncertainty of TBBi measurements carried out in June, i.e. during a time-period with low outdoor ^{222}Rn levels and no need for artificial modification of the counting room temperature. This value was comparable with the standard deviation of 21 Bq found experimentally by counting twenty times a young women with a mean TBBi of 52 Bq during the same month (five daily measurements with 1.5 h long time interval between them).

A male volunteer was measured twice immediately after his arrival at the counting room from open-air at the University of Ioannina University Campus in June. A 20 min-long heavy physical exercise in open-air before the second measurement resulted in a TBBi increase from 68 to 153 Bq, a change attributed to the increased volume of inhaled air per min during exercise.

Discussion - Conclusion

Radon, a member of the ^{238}U decay series, is the immediate daughter of ^{226}Ra and belongs in a Group I of the human carcinogen. Epidemiological studies on domestic and occupational exposure have shown strong evidence of lung cancer risk and suggestive evidence of an association with other types of cancer, (e.g. cancers of the exathoracic airways and leukemia) [6]. Therefore, the employed strategies to achieve risk reduction by prevention and mitigation in new and existing closed spaces, respectively, must rely on accurate assessments of the anticipated effective dose.

Direct TBBi measurements reflect recent exposures and allow the assessment of radon-related radiological burden in a way much more accurate than the conventional methods, which are based on measured or assumed ^{222}Rn activity concentration in the inhaled air. However, such measurements are by far technically simpler and cheaper than the direct measuring of TBBi levels.

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References

[1] ICRP 2008 *Nuclear decay data for dosimetric calculations.* ICRP107, Annals of ICRP 38(3)

[2] ICRP 2002 *Basic anatomical and physiological data for use in radiological protection.* ICRP publication 89 Annals of the ICRP 32(3-4)

[3] JA Kalef-Ezra, ST Valakis, TA Soupsanas 2011 *High sensitivity multi-detector whole body-counter*. Radiat Prot Dosim 144 415-418

[4] ST Valakis, S Pallada, JA Kalef-Ezra 2014 *Measurement uncertainties in whole body counting and radon progeny*. Health Phys. 107 36-46

[5] J Kalef-Ezra, S Valakis 2016 *Direct total body ^{214}Bi measurements and their implications on radon dose assessment*. J. Radiol. Prot. 36 518-531

[6] ICRP 2010 *Lung cancer risk from radon and progeny Statement on radon*. ICRP1115, Annals of ICRP 40(1)