Radioprotection 2013 DOI: 10.1051/radiopro/2012050

Article

Assessment of activity and effective dose rate of ^{222}Rn in several dwellings in Bamako, Mali

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(Manuscript received 31 July 2012, accepted 22 November 2012)

ABSTRACT **We used CR-39 detectors to evaluate radon activity concentrations in several habitations of Bamako. The calibration factor of the dosimeters was determined experimentally with known radon activity concentrations inside a radon chamber, and was also simulated with MCNPX. The experimental and simulated calibration factors are, respectively, k_{exp} = 0.119 ± 0.017 and k_{sim} = 0.126 ± 0.007 tr.cm^{-2}.d^{-1}.Bq^{-1}.m^{3}. Indoor radon activity concentrations in Bamako were found to vary from 70 ± 18 to 154 ± 35 Bq.m^{-3}. No significant differences were observed in the mean radon activity concentrations compared with five other African countries. Taking into account an occupancy factor of 0.8 and an equilibrium factor of 0.4 for radon indoors, the effective dose rate ranges from 1.77 to 2.35 mSv.y^{-1}. In all cases the radon activity concentrations measured were below the action limits recommended by the International Commission on Radiological Protection (ICRP) Statement on Radon.**

Keywords: ^{222}Rn measurement / effective dose rate / CR-39 / MCNPX

1. Introduction

Inhaled radon and its daughters can constitute the main source of natural radiological exposure for humans, and it is for health reasons that knowledge of the radon activity concentrations encountered is important. The health risk associated with it is due to lung tissue damage caused by α-particles from the decay of radon and its non-gaseous daughters suspended in the atmosphere. The only radon isotope of consequence is ^{222}Rn, which is formed along the ^{238}U decay chain. Its 3.8-day half-life is long enough for it to collect in habitations situated above uranium-containing terrain or in some cases, inside structures built of radioactive construction materials. Radon can also be brought in from a distance by groundwaters. Its emanation varies with the season, weather conditions, and even time of day. Outdoors it is sufficiently diluted by atmospheric circulation that

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it never reaches a high enough concentration to become an appreciable risk. In all likelihood, any real radon menace will occur in poorly ventilated areas. As a sanitary measure for human health, many countries have developed surveys for radon and its short-lived progeny (^{218}Po and ^{214}Pb) in order to measure their levels in public buildings and habitations (Khan *et al*., 1987; Beozzo *et al*., 1991; Hassib *et al*., 1993; Surinder *et al*., 2004). The ICRP has also recommended that the level for initiating remedial action in dwellings be set in the range of 3-10 mSv for the annual effective dose (Wrixon, 2008). Radon activity concentrations were converted to effective doses, which are different for houses and workplaces largely because of the different number of hours spent in each place. The 3-10 mSv interval corresponds to an activity concentration of radon from 200 to 600 Bq.m^{-3} for houses, and from 500 to 1500 Bq.m^{-3} for workplaces.

However, there exist few measurements for West Africa (Andam, 1992) and in particular, none for Mali. For the first time we introduced passive radon detectors for environmental radon monitoring in Bamako using CR-39 detectors. The detector calibrations were performed experimentally by exposition of detectors to known activity concentrations of radon gas in a closed radon tank and by simulations with MCNPX. We performed measurements in cellars and living areas of six habitations in Bamako and assessed the corresponding effective dose.

2. Simulation

Monte Carlo simulations were carried out with the MCNPX (Monte Carlo N-Particle eXtended) code (Pelowitz, 2008). MCNPX is a general purpose Monte Carlo radiation transport program for modeling the interaction of radiation with matter that has been used in nuclear medicine, nuclear safeguards and accelerator design, among many other applications. The input file of MCNPX contains information about the detection setup: geometry of the device, description of all materials, specification of the cross-sections to use and the types of tallies desired. The irradiation of a CR-39 detector inside the dosimeter housing was modeled as shown in the right panel of Figure 1. The active volume of the dosimeter (76×10^{-6} m^3 at 1 atm of air) was stocked numerically with 10^8 randomly distributed, isotropically directed 5.49 MeV α-emissions. Tallies F1, F8 and F6 together with the WGT card that furnishes the total activity concentration of ^{222}Rn, exposition time and emission rate are read from the input file. The PTRAC option of MCNPX registers the whole history of each particle including position, direction, energy and weight across different cells. A C++ program was written to read the PTRAC output file in order to determine the number of α-particles that enter the CR-39 behind the 9-μm layer removed by etching.

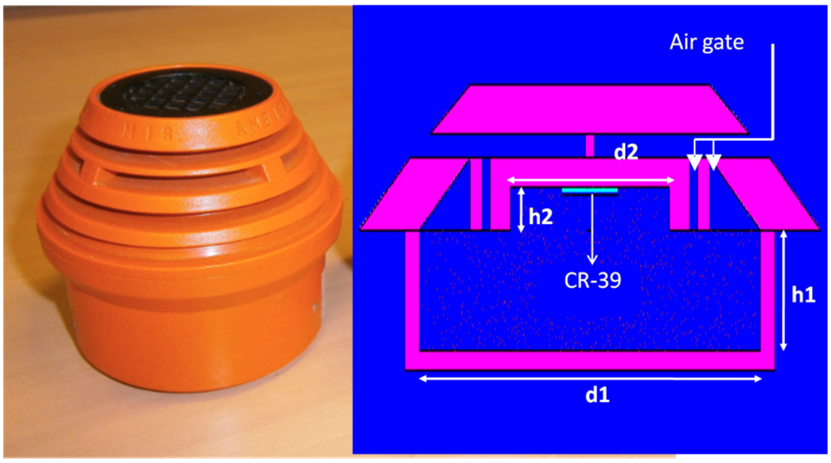

Figure 1 – Radon dosimeter (left) and simulated radon dosimeter (right; $d1$ = 6 cm, $d2$ = 2.8 cm, $h1$ = 2.5 cm, $h2$ = 0.9 cm).

3. Experimental

We used radon dosimeters, one of which is pictured in the left panel of Figure 1. Inside the plastic housing are placed two CR-39 detectors, one for background measurement and one open to the radon-containing atmosphere. The CR-39 was manufactured by the Intercast Company (Parma, Italy) according to specifications set by an ENEA (National Atomic Energy Agency)-University of Bologna-INFN (National Institute for Nuclear Physics) collaboration. Circular samples of 1.4-mm-thick CR39 plates are laser-cut with a 1.6-cm radius (Beozzo *et al.*, 1991).

The device is equipped with an active charcoal filter at the top designed to trap radon daughters. At the end of all the expositions, each CR-39 detector was removed from its dosimeter housing and etched in 6.25 N NaOH at 70 ± 0.5 °C with continuous stirring. Any residual NaOH remaining inside the tracks was neutralized in 0.12 N HCl for 15 min; then the CR-39 was washed with distilled water and dried. The thickness of the detectors measured with an electronic micrometer at five points of each detector before and after the etching showed that a 9-µm layer of CR-39 is removed. Following the etching process, the detectors were read at 10× magnification with an Axioskop microscope linked to a CCD camera piloted by Visilog 5.4 software (Noesis, http://www.noesisvision.com). The track images identified were processed and counted by ImageJ 1.44 software (http://rsbweb.nih.gov/ij/).

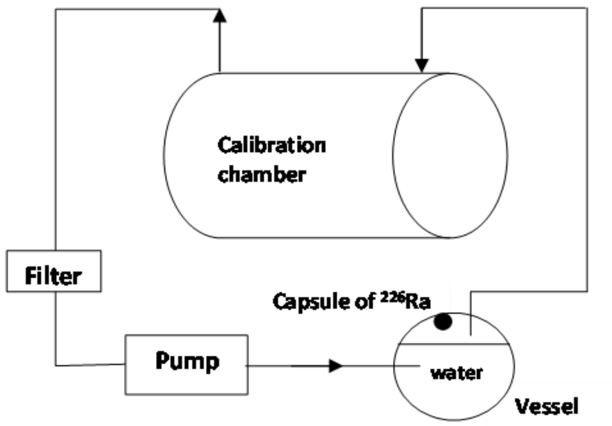

Figure 2 – Schematic diagram of the radon chamber and radon generator.

To evaluate the response of the radon detectors experimentally, they were placed inside a radon chamber, which is a closed cylindrical tank (224 l) into which radon can be injected. The ^{222}Rn is generated by $RaCl_2$ in solution inside a thin glass capsule that allows the radon to diffuse from the capsule to water contained in a closed glass vessel, as shown diagrammatically in Figure 2. This radon generator can be isolated from the radon chamber by a system of stopcocks. The ^{222}Rn is delivered to the tank by circulating the chamber's atmosphere through the radon-containing water for a short time. While at equilibrium this radon generator is certified to deliver 340 ± 11 Bq of ^{222}Rn; our *modus operandi* of exposing the dosimeters required that we monitor the ^{222}Rn activity concentrations inside the chamber with the active AlphaGUARD system (SAPHYMO GmbH, Heerstraße 149, D-60488 Frankfurt a.M., Germany). This sophisticated system registers only ^{222}Rn decays, *i.e.*, suffers no interference from α-emitting daughters of ^{222}Rn.

4. Results and discussion

4.1. Detector response

Three detectors were irradiated separately inside the radon chamber for 24 h, respectively 1, 7 and 11 days after ^{222}Rn was introduced into the chamber. The corresponding ^{222}Rn activity concentrations for each exposition were continuously monitored (Fig. 3) by the AlphaGUARD and the total activity concentration for the

TABLE I
Simulated and experimental responses of CR-39 dosimeters according to the average ^{222}Rn activity concentrations.

Average Rn activity concentrations (Bq.m^{-3})	Simulated response (tr.cm^{-2}.d^{-1})	Experimental response (tr.cm^{-2}.d^{-1})
448	58	58 ± 8
725	88	78 ± 9
1027	132	126 ± 11

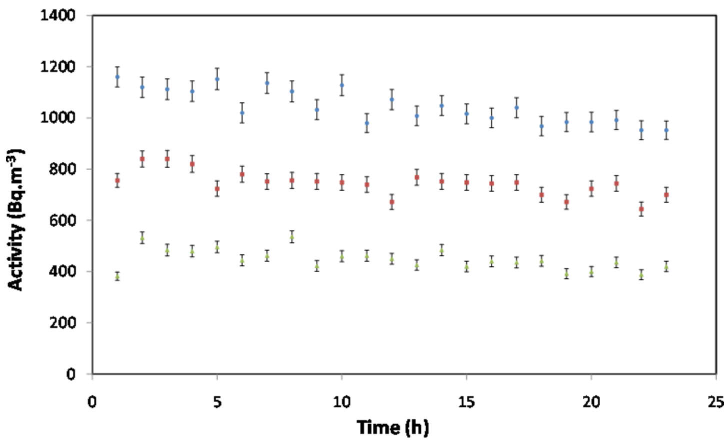

Figure 3 – ^{222}Rn activity concentrations given by the AlphaGUARD device during expositions of the radon detectors.

24 h was computed. In Table I the simulated and experimental responses of the dosimeter for three different average ^{222}Rn activity concentrations are shown.

Both experimental and simulated calibration factors were calculated from the information of Table I using equation $k = \rho/(Ct)$, where k is the calibration factor (tr.cm^{-2}.d^{-1}.Bq^{-1}.m^{3}) ; ρ, the track density (tr.cm^{-2}) ; C, the radon activity concentration delivered by the standard (Bq.m^{-3}) ; and t = exposure time (d). We found values of $k_{exp} = 0.119 \pm 0.017$ and $k_{sim} = 0.126 \pm 0.007$ tr.cm^{-2}.d^{-1}.Bq^{-1}.m^{3}, which agree within the uncertainties. Our experimental calibration factor also agrees with a published value of 0.118 ± 0.011 tr.cm^{-2}.d^{-1}.Bq^{-1}.m^{3} (Jojo *et al.*, 1994).

TABLE II
Radon activity concentrations in different cellars and living areas of Bamako.

Location	Cellar ($Bq.m^{-3}$)	Living area ($Bq.m^{-3}$)
1	154 ± 35	71 ± 16
2	151 ± 33	87 ± 20
3	121 ± 28	93 ± 23
4	125 ± 29	70 ± 18
5	136 ± 31	80 ± 20
6	108 ± 25	74 ± 19

4.2. Radon activity concentrations in Bamako

Bamako is a tropical city, very hot on average all year round. People usually keep their windows open and radon cannot accumulate. Thus, we chose some rare confined areas (cellars and living areas) of habitations for the measurements. Dosimeters were exposed for three months (October-December 2010) in cellars; after changing their internal CR-39 detectors, they were exposed for two months (January-February 2011) in living areas. Table II reports the ^{222}Rn activity concentrations found in Bamako, Mali, in cellars (October-December 2011) and in living areas (January-February 2011). It is seen that radon activity concentrations in the cellars were higher than in dwellings, as expected. However, all of these values are below the action limits recommended by the ICRP.

These measurements can be compared with those of other African countries. Figure 4 shows the variation in radon in the living space of some countries of Africa using the nuclear track technique. Apart from the lowest value observed in Libya (44 ± 6 $Bq.m^{-3}$), there is no significant difference among results obtained from radon surveys in Bamako in Mali, Kumasi in Ghana (Andam, 1992), Beni-Mellal in Morocco (Oufni *et al.*, 2005), Tunisia, and Egypt (Al-Azmi *et al.*, 2011).

For annual radon effective dose rate estimation, the conversion factor (effective dose received by adults per unit ^{222}Rn activity concentration per unit of air volume) given by the UNSCEAR (2009) report was taken into account. The annual effective dose (*ED*) rate was calculated by the following formula:

$$ED\ (\mathrm{mSv.y^{-1}}) = A_C DOF \times 24 \times 365 \times 10^{-6} \qquad (1)$$

where A_C is the measured radon activity concentration in $Bq.m^{-3}$; D is the dose conversion factor (9 $nSv.h^{-1}.Bq^{-1}.m^{3}$); O is the indoor radon occupancy 0.8, and F the radon equilibrium factor indoors 0.4. The results are reported in Table III.

TABLE III
Effective dose rate in different living areas of Bamako.

Location	Living area (Bq.m^{-3})	Radon ED rate for living area (mSv.y^{-1})
1	71 ± 16	1.8
2	87 ± 20	2.2
3	93 ± 23	2.4
4	70 ± 18	1.8
5	80 ± 20	2.0
6	74 ± 19	1.9

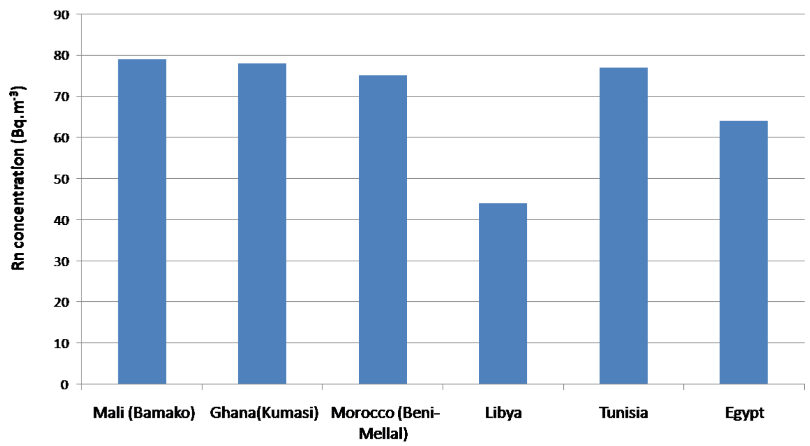

Figure 4 – Average radon activity concentration in some living areas of African countries.

5. Conclusion

MCNPX reproduced the calibration factor of CR-39 quite well. All ^{222}Rn activity concentrations measured are below the action level recommended by the ICRP. It is seen that radon activity concentrations in the cellars were higher than in dwellings, as expected. Indoor radon activity concentrations in five other African countries reported in the literature are not very different from our values for Mali. In all cases of Figure 4 the effective dose rate is below the action levels recommended by the ICRP (3-10 mSv.y^{-1}). Finally, the SSNTD technique has the advantages of not being expensive and being simple to use, while offering an important tool for radon monitoring.

Acknowledgements. *The authors would like to thank Dr. Arthur Pape for his fruitful discussions and the RaMsEs group for their help. Our thanks are also due to INFN Bologna for furnishing the dosimeters.*

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