Nuclear Engineering and Technology 50 (2018) 950–956

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Radon and thoron concentrations inside ancient Egyptian tombs at Saqqara region: Time-resolved and seasonal variation measurements

E. Salama [a, d, *], M. Ehab [b], W. Rühm [c]

[a] Physics Department, Faculty of Science, Ain Shams University, Cairo, Egypt
[b] Basic Science Department, Faculty of Engineering and Technology, Future University in Egypt (FUE), Cairo, Egypt
[c] Institute of Radiation Protection, German Research Center for Environmental Health, Ingolstädter Landstr. 1, 85764 Neuherberg, Germany
[d] Basic Science Department, Faculty of Engineering, The British University in Egypt (BUE), Egypt

ARTICLE INFO

Article history:
Received 9 September 2017
Received in revised form
23 February 2018
Accepted 25 March 2018
Available online 11 April 2018

Keywords:
Ancient Egyptian Tombs
Radon
Saqqara
Thoron

ABSTRACT

For complete assessment of inhalation doses of radon and its progeny inside the three main ancient Egyptian tombs in Saqqara, seasonal radon concentrations have been measured by using a new electronic device that allows for measurement of real-time–resolved radon concentrations. Measurements were complemented by very fast measurements of thoron concentrations, which turned out to be low. Based on these measurements, annual residence time inside these tombs and the newest International Commission on Radiological Protection–recommended radon dose conversion coefficients or seasonal effective doses were calculated. The results indicate that workers receive highest annual effective doses of up to 140 mSv, which exceeds the annual limit of 20 mSv, whereas lower values up to 15 mSv are received by guides. In contrast, much lower doses were obtained for one-time visitors of the investigated tombs. The obtained results are somewhat different but still consistent with those previously obtained by means of fixed passive dose meters at some of the investigated places. This indicates that reasonable estimates of the effective dose of radon can be also obtained from short-term radon measurements carried out only twice a year (summer and winter season). Increasing the ventilation, minimizing the working times, etc., are highly recommended to reduce the annual effective dose.

1. Introduction

Exposure to ionizing radiation contributes to the overall radiation dose to the public worldwide. In this respect, while radiation exposures from artificial sources such as those from emission of facilities of the nuclear fuel cycle are minor, those from natural sources are of particular interest [1–4]. In fact, it is particularly the radioactive chemical element radon, a natural radioactive noble gas, that is of major importance. The radioisotope ^{222}Rn of this element (in the following called “radon” for simplicity) contributes significantly to the dose of the population from natural sources of ionizing radiation, and about 50% of the public's natural radiation exposure in many countries is due to radon [5,6]. The parent nuclide of radon, ^{238}U, is usually found in the Earth's crust on a concentration level of one or several parts per million (ppm). According to the report of the United Nations Scientific Committee on the Effects of Atomic Radiation in 2013 [7], both low linear energy transfer (LET) radiation and radon have been shown to increase the risk of lung cancer among humans. As for radon and its radioactive daughter nuclides, a significant increase of the risk for lung cancer was shown if their concentrations exceed above 200 Bq/m^3 [8,9]. In contrast, negligible contribution to the effective dose from the isotope thoron (^{220}Rn) was found in the past [10–12]. Because of its short half-life of less than a minute, thoron is unable to penetrate into reasonably airtight buildings. Recently, however, thoron has gained attention because increased concentrations were found in cave dwellings dug into clay soil and in houses with earthen architecture [13–17].

In the present study, radon and thoron measurements were performed in the tombs of the oldest Egyptian ancient cemetery region, 28 km southwest of Cairo, close to Saqqara. Note that the effective doses from radon to individuals who are working at those sites were already estimated in previous studies [18,19] using stationary passive track detectors (CR-39 dosimeters) located inside the tombs to measure radon concentrations in air and assuming a 10 h working day. This approach may include high uncertainty, however, because it does not directly quantify the actual exposure of a person present at those locations. In the present work, we used a portable radon personal exposure meter, which has recently been developed at the German Research Center for Environmental

---

* Corresponding author.
E-mail address: e_elsayed@sci.asu.edu.eg (E. Salama).

https://doi.org/10.1016/j.net.2018.03.017

Health (Helmholtz Zentrum München) and which allows measurement of individual radon exposures for those wearing the device [20]. The device was already successfully used in a pilot study at other Egyptian archeological sites [21]. The results obtained in the present study will be helpful in constructing a suitable ventilation system and developing guidance rules for workers, tourist guides, and visitors to this region.

2. Materials and methods

2.1. Measurement locations

Saqqara is a vast ancient burial ground, located 28 km southwest of Cairo, carved into mountains of limestone and sedimentary rocks (Fig. 1). Visiting these tombs or working inside may result in increased health hazard due to the higher-than-average levels of natural radiation and the low ventilation rates. For example, previously, annual effective doses of about 66 mSv were obtained for safety guards in the Valley of the Kings tombs in Luxor; these doses exceeded the annual dose limit [21]. Some of these tombs are open to visitors, whereas other tombs are closed for renovation work, which affects the ventilation rates and, accordingly, the radon and thoron concentrations in air. The structure of the studied tombs and the locations of measurement are shown in Figs. 2–4.

Four measurement locations were chosen in the Serapeum tombs (Fig. 4), whereas only one location was available for measurement inside the South and Zoser pyramid tombs (Figs. 2 and 3). Selection of the measurement positions and the number of

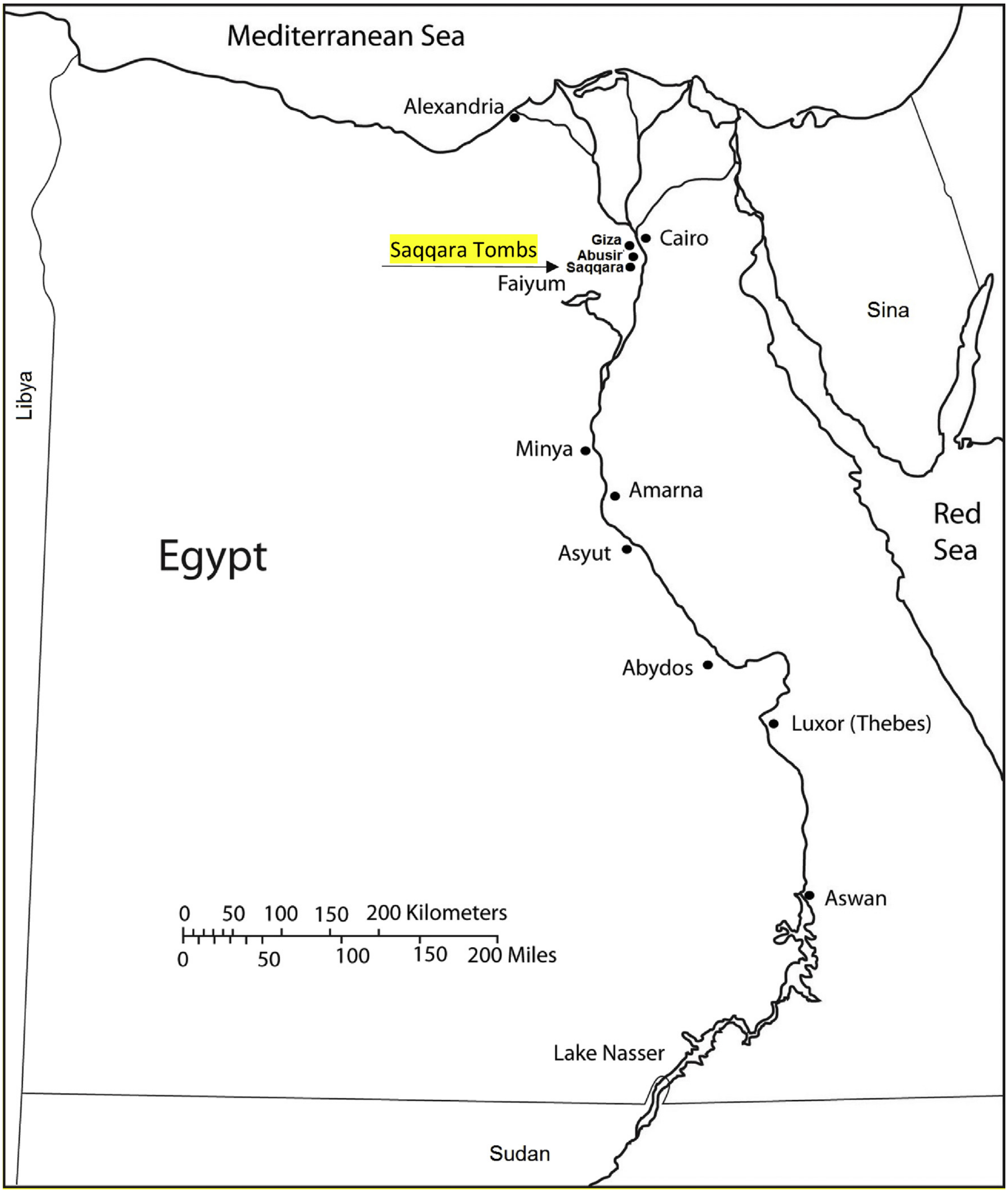

Fig. 1. Location of Saqqara in Egypt.

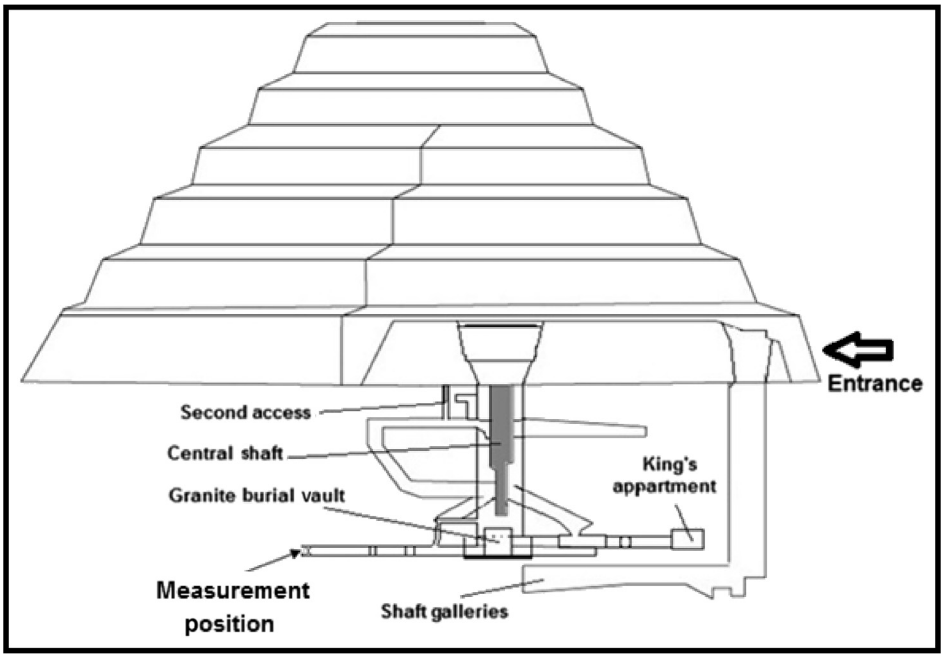

Fig. 2. Substructure and the building stages of Zoser pyramid.

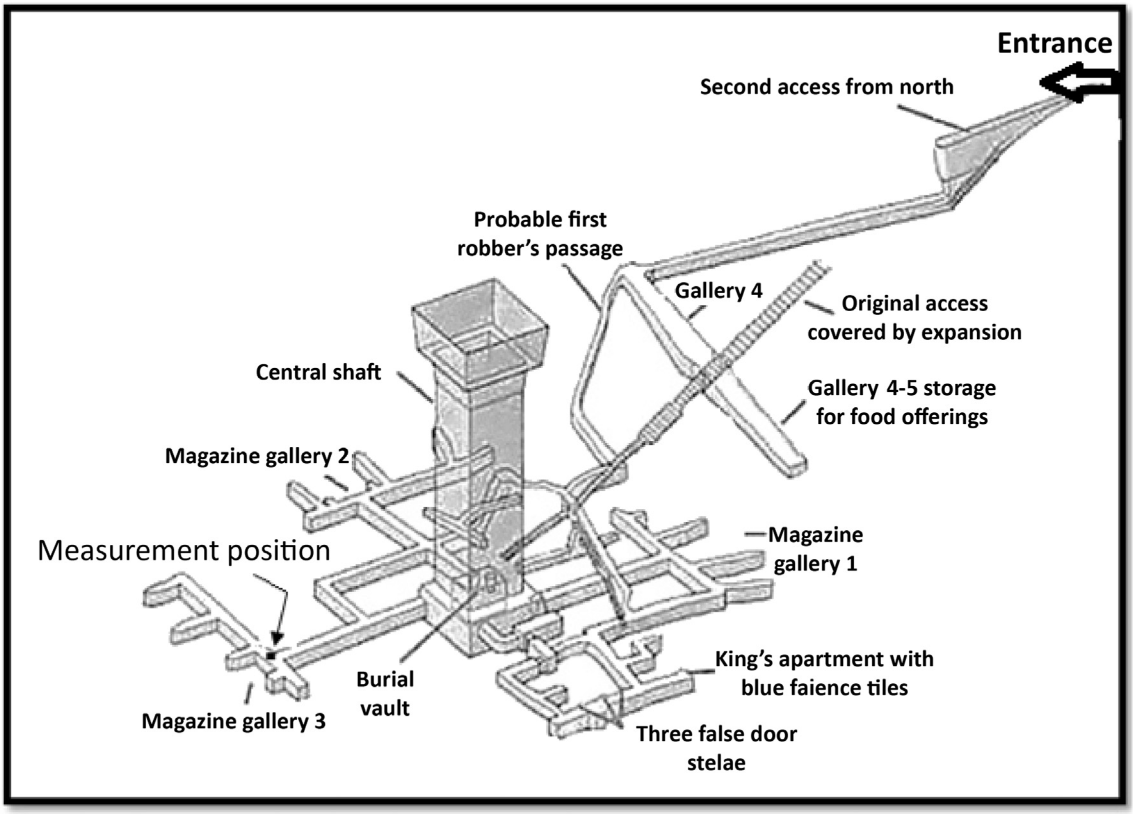

Fig. 3. Substructure of the South tomb of Zoser pyramid.

positions was restricted to the open sites inside each tomb and the available permissions.

2.2. Detectors used for radon and thoron measurements

A recently developed radon exposure meter [20,21] was used for the present study. The housing of the device shows several holes that allow radon gas to diffuse into the chamber. The holes are covered by a filter material to prevent any progeny of radon (and of thoron) in the air to enter the chamber. Inside the chamber, two silicon sensors including electronics and battery are mounted, allowing for the detection of alpha particles emitted by radon and its progeny, which are produced within the chamber due to radon decay. Owing to its characteristics—small size ($11 \times \times 6 \times 3$ cm^3),

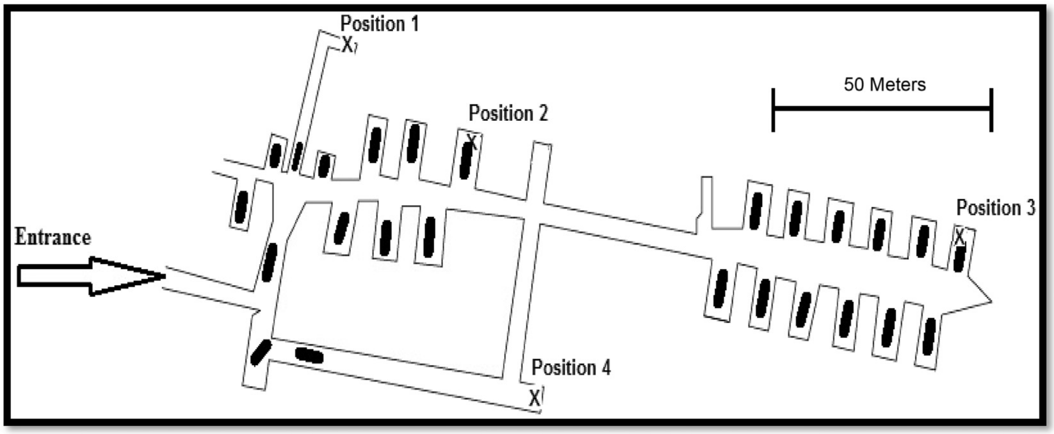

Fig. 4. Map of Saqqara Serapeum.

light mass (150 g), and battery lifetime of more than half a year—the device can easily be worn by an individual and used for assessment of individual radon exposure. This device was, however, not used in the present study, in which the exposure meters were placed at fixed positions. During the measurements, the used exposure meters stored the measured radon concentration every hour, for a total duration of about 3 days. Calibration of these devices was done by comparing their readings with those of a reference device (AlphaGUARD; Saphymo GmbH). The calibration was done inside a stainless steel chamber containing the radon exposure meters, the Alpha Guard device, and a rock sample that served as a natural radon source. Typically, the device provided three counts per hour, in a radon atmosphere of 100 Bq/m^3. Accordingly, for a typical concentration of 2,000 Bq/m^3, the exposure meter yields about 60 counts per hour, with a corresponding statistical uncertainty of about 12%. Details on the device are given in the studies by Karinda et al. and Grubar et al. [20,21].

The thoron concentration in the three aforementioned locations in the Saqqara region was measured at an average distance of 20 cm from the room walls by using the portable thoron monitor RTM 1688-2, SARAD. This device pumps air containing thoron gas with its short lived decay products into the measurement chamber. The direct decay product of thoron, ^{216}Po, is used to calculate the thoron activity concentration. The half-life of ^{216}Po is less than 1 s, and accordingly, equilibrium between thoron and its progeny is immediately achieved. About 150 min is needed for each reading to obtain high accuracy and reproducibility of the measured thoron concentration. The calibration factor for the thoron monitor is 18 counts per hour in a thoron atmosphere of 100 Bq/m^3. Measurements were taken three times for each aforementioned location (i.e., 3 × 150 min), and the mean value was taken. In other words, in contrast to the radon measurements, the thoron measurements were not performed continuously over the whole time of the experiment.

2.3. *Occupational radon and thoron exposures and effective doses*

In its most recent publication on occupational intake of radionuclides, the International Commission on Radiological Protection (ICRP) recommended—for the calculation of effective dose from the inhalation of radon and radon progeny—the use of a dose coefficient of 3 mSv per (mJh/m^3) for underground mines and buildings, whereas for tourist caves and “indoor work involving substantial physical activity,” ICRP recommends a dose coefficient of 6 mSv per (mJh/m^3) [22]. If these values are to be expressed in effective dose per Bq h m^{-3} ^{222}Rn gas exposure, correction for the deviation from radioactive equilibrium of radon gas and radon progeny must be made using the so-called equilibrium factor F.[1] With the standard numerical value for F of 0.4 recommended by ICRP [23], 3 mSv per (mJh/m^3) correspond to 6.7 × 10^{-6} mSv per Bq h m^{-3}, whereas 6 mSv per (mJh/m^3) correspond to 1.3 × 10^{-5} mSv per Bq h m^{-3}.

According to the ICRP, if more detailed site-specific information is available, modified dose coefficients can be used. From discussions with the workers, considering their daily schedules, and referring to our previous work, the typical annual residence times in a tomb were estimated to be about 2400 h and 250 h for workers and tour guides, respectively, and 0.5 h per visit for visitors [21]. Furthermore, values for F were used from previous publications where both radon gas and radon progeny were measured (Table 2). In those cases, the aforementioned dose coefficients translate more generally to 3 mSv per (mJh/m^3), corresponding to F × 1.7 × 10^{-5} mSv per Bq h m^{-3}, whereas the value of 6 mSv per (mJh/m^3) corresponds to F × 3.3 × 10^{-5} mSv per Bq h m^{-3}. Because the F values measured in those sites were close to 1 [19], in most cases, indicating almost complete equilibrium and low ventilation, the fraction of progeny to be attached on aerosol particles was probably high, i.e., the unattached fraction was probably low. In the present work, the dose coefficients for underground areas and mines were used, in the absence of more detailed information.

For thoron, effective doses were not calculated because of the absence of information on thoron progeny concentrations.

3. Results and discussions

3.1. *Measured radon concentrations*

The average radon concentrations as obtained by the real-time exposure meters for the three main different tombs in the Saqqara region are shown in Table 1. The measuring time inside each tomb was 70 h. Winter measurements were made in November, whereas summer measurements were made in May.

As shown in Table 1, there are some variations in the average radon concentration among the three tombs for the same season. In winter and summer, the lowest radon concentrations were measured at position 4 of the Serapeum tomb and on the fifth level of Zoser pyramid, whereas the highest radon concentrations were

---

[1] F is a measure of the disequilibrium between radon gas concentrations and radon progeny concentrations.

Table 1
Radon concentrations measured by means of the real-time exposure meters (uncertainties are given in terms of one standard error of the mean and include a 5% uncertainty due to calibration) (winter measurements were made in November and summer measurements in May).

Tomb		Present work		Previous work (Abo-ElMaged et al., 2006)
		Average concentration (Bq/m^3)		Average concentration (Bq/m^3)
		Winter	Summer	Winter
South tomb		2,866 ± 37	4,077 ± 72	3,220 ± 227
Zoser pyramid (5th level)		1,286 ± 26	2,394 ± 95	204 ± 19
Serapeum	Position 1	1,386 ± 33	4,225 ± 69	—
	Position 2	1,442 ± 31	3,425 ± 53	—
	Position 3	2,387 ± 51	4,592 ± 72	—
	Position 4	1,068 ± 32	3,288 ± 92	—
	Average	1,571 ± 37	3,882 ± 72	1,225 ± 286

Table 2
Equilibrium factors (F) and mean effective dose rates for the studied Saqqara tombs due to the measured radon concentrations in air (see Table 1) (winter measurements were taken in November, and summer measurements were taken in May).

Tomb	F (Abo-ElMaged et al., 2006)		Effective dose rate (μSv/h)	
	Winter	Summer	Winter	Summer
South tomb	0.98 ± 0.01	0.99 ± 0.00	47.7	68.6
Zoser pyramid (5th level)	0.69 ± 0.00	0.98 ± 0.00	15.1	39.9
Serapeum	0.71 ± 0.00	0.94 ± 0.00	19.0	62.0

observed in South tomb at the end of the corridor of the magazine gallery 3 room and at position 3 of the Serapeum tomb (Figs. 3 and 4). The variation of radon concentration observed inside the investigated tombs can be attributed to the fact that, for example, in contrast to the other sites, the South tomb was carved deeply into limestone rocks (Fig. 3) with a complex architecture. Moreover, the South tomb has a very narrow entrance located at the base of a deep well. Serapeum also has a complicated structure (Fig. 4), which makes it completely isolated, and has slight differences in radon concentrations among its measuring positions (Table 1). All these features make these tombs thermally isolated from the surroundings, resulting in low natural air ventilation.

The observed seasonal variation of radon concentration inside these tombs can be attributed to diffusion of radon through the tomb entrance due to the temperature difference between outside and inside. In winter, the temperature inside the tombs is higher than that outdoors, and therefore, the warm air from the tomb escapes to the outside while the outside cold air with low radon concentration flows into the tomb, causing a winter minimum [19,24,25]. In contrast, in summer, the increased temperature inside the tomb increases the thermal energy gained by the rock wall, which increases the radon gas emanation rate and in turn increases the indoor radon concentration [26]; in addition, during daytime, the temperature outside is higher than inside, reducing air exchange between outside and inside.

Compared with the previous winter results obtained using passive accumulating track-edge detectors [19], the present winter results are similar for the South and Serapeum tombs but completely different in case of the Zoser pyramid. This difference can be attributed to the difference in measuring position inside the Zoser pyramid (the previous measurements were done at the entrance, whereas the present measurements were done at the fifth level under the pyramid). The main advantage of the technique used in the present study is that it allows for a fast, accurate, and real-time measurement of radon concentration (see Fig. 5 for an example). The data shown in Fig. 5 suggest that there is only a small diurnal variation during the measurement period. This was also observed at the other measurement locations. This justified the approach of calculating mean radon concentrations and estimating uncertainties from the standard error of the mean.

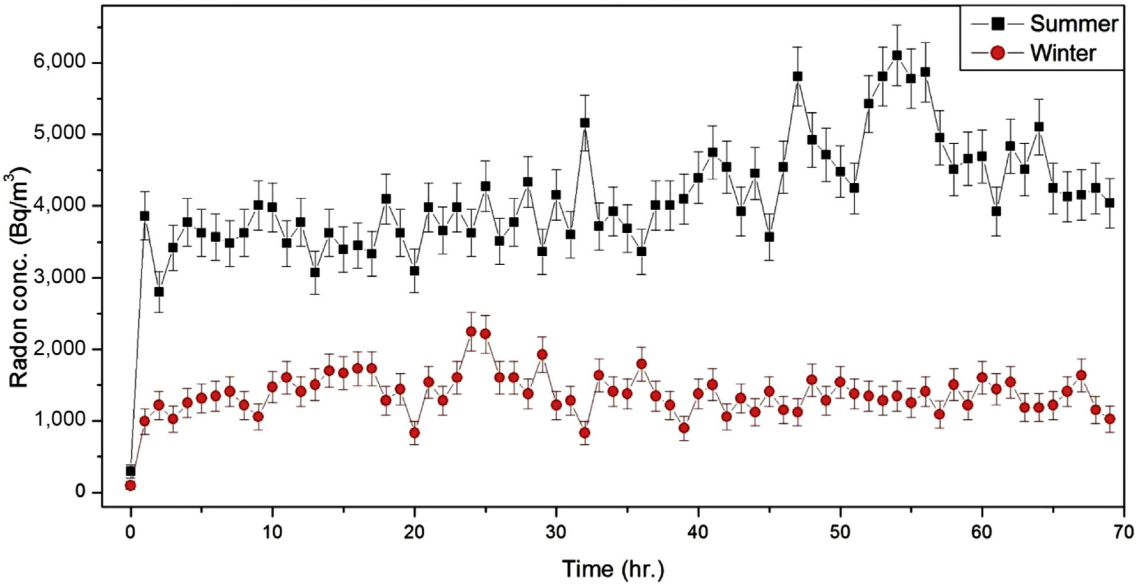

Fig. 5. Seasonal variation of the radon concentration in the Serapeum tomb (Pos.1). Error bars represent one-sigma statistical uncertainties. Winter measurements were made in November, whereas summer measurements were made in May.

Table 3
Seasonal effective dose for workers and tour guides. Doses to visitors are given as per visit (winter measurements were taken in November, and summer measurements were taken in May).

Tomb	Seasonal effective dose (mSv)					
	Workers		Guides		Visitors*	
	Winter	Summer	Winter	Summer	Winter	Summer
South tomb	57.3	82.3	6.0	8.6	0.02	0.03
Zoser pyramid (5th level)	18.0	47.9	1.9	5.0	0.01	0.02
Serapeum	22.8	74.4	2.4	7.8	0.01	0.03

3.2. Annual effective dose due to radon exposure

The individual mean effective dose rates due to exposure to radon and its progeny in the studied tombs are shown in Table 2. These dose rates are directly governed by the mean radon concentrations measured in these tombs (see Table 1). The highest mean individual radon dose rates were obtained in the South tomb, which also showed the highest radon concentrations in air, whereas the lowest individual radon doses were obtained in the Zoser pyramid, where the indoor radon concentrations were low.

Using the aforementioned annual residence time in a tomb for workers, tour guides, and visitors, the seasonal effective doses were calculated and listed in Table 3 assuming 1,200 working hours per season for workers, and 125 working hours per season for guides. For workers, the annual effective dose (sum of winter and summer) ranged from 66 to 140 mSv/y, whereas for tour guides, lower annual effective doses from 7 to 15 mSv/y were obtained. Thus, for workers, the obtained annual effective doses exceed by far the maximum recommended action level for workers (20 mSv/year) [27]. In contrast, levels far below this value were obtained for one-time visitors in all tombs, ranging from 0.01 to 0.03 mSv/visit.

The obtained results demonstrate that the occupational effective dose from radon exposure inside the tombs depends on tomb location, geometry (governing ventilation), and duration of stay inside the tomb. Considerable variations with season were also observed. Compared with the previous winter study [19], lower annual effective dose values were obtained. This can be attributed to the fact that the authors used lower conversion factors at that time and assumed shorter annual working time (1,000 h).

3.3. Measured thoron concentrations

The indoor thoron concentrations for the selected studied tombs in the Saqqara region were also measured. The average thoron concentrations for the studied tombs in the Saqqara region at 20 cm from the wall in summer were low (28 ± 18 and 60 ± 30 Bq/m^3 in the South tomb and the Zoser pyramid, respectively). In contrast, the measured concentrations in all Serapeum's positions were even lower. The uncertainties in thoron measurements of 50–64% were attributed to statistical error. This was expected as the thorium concentrations obtained by the gamma-spectroscopic analysis of the selected studied tomb samples were very low (8.5 Bq/kg) [28]. Because of these low concentrations of thoron, no detailed seasonal investigation was considered necessary.

4. Conclusion

Seasonal radon gas concentrations were measured inside the main three tombs in the Saqqara region, Egypt, and the associated effective dose rates were calculated. Workers received significantly higher annual effective doses than tour guides and visitors, in both winter and summer. Based on typical working hours per year, annual effective doses for workers were found to be significantly above the permissible level of 20 mSv/y.

Because the measured annual effective doses obtained in this pilot study are so high, a more detailed investigation is urgently needed. For example, such an investigation should include repetition of the measurement of the equilibrium factor. Furthermore, the characteristics of the aerosol sizes should be quantified, and the unattached fraction of radon progeny at the measurement sites should be measured. We note that use of the ICRP dose coefficients for tourist caves would have even suggested annual effective doses twice as high as those estimated here.

In the meantime, in an effort to reduce the effective dose due to radon exposure and to keep it within the permissible dose range, it is proposed that time schedules for the workers should be well prepared to control and minimize the individuals' working duration inside these tombs. In addition, an artificial ventilation system should be installed inside these tombs to provide a suitable air exchange rate, which will result in a reduction of the radon concentrations. This must be done, however, without increasing the humidity level, which is an important aspect, because humidity affects the wall decoration and colors of the precious ancient paintings.

In those tombs that were closed at the time when the present study was performed and in which no measurements could be performed, radon measurements should be performed soon because staff members are expected to work in these tombs in the future.

The obtained thoron concentrations in all the studied tombs were low and close to or below the detection limit. Accordingly, thoron contributions to the annual effective doses for workers, tour guides, and visitors are expected to be small compared with the radon contribution. Measurements of thoron progeny concentrations must be made, however, to draw a more reliable conclusion.

Conflicts of interest

The authors declare no conflicts of interest.

References

[1] Gyuseong Cho, Jong Hyun Kim, Tae Soon Park, Kunwoo Cho, Proposing a simple radiation scale for the public: radiation index, Nucl. Eng. Technol. 49 (2017) 598–608.

[2] Mohamed A.E. Abdel-Rahman, Sayed A. El-Mongy, Analysis of radioactivity levels and hazard assessment of black sand samples from Rashid area, Egypt, Nucl. Eng. Technol. 49 (8) (2017) 1752–1757.

[3] Ibrahim F. Al-Hamarnehab, Fahad I. Almasoudcd, A comparative study of different radiometric methodologies for the determination of ^{226}Ra in water, Nucl. Eng. Technol. 50 (1) (2017) 159–164.

[4] Nidal Dwaikat, Anan M. Al-Karmi, Application of CR-39 microfilm for rapid discrimination between alpha-particle sources, Nucl. Eng. Technol. 49 (2017) 881–885.

[5] M.K. Kullab, B.A. Al-Bataina, A.M. Ismail, et al., Seasonal variation of radon-222 concentrations in specific locations in Jordan, Radiat. Meas 34 (2001) 361–364.

[6] WHO, in: Hajo Zeeb, Ferid Shannoun (Eds.), WHO Handbook on Indoor Radon: A Public Health Perspective, 2009.

[7] UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), Annex B, “Effects of Radiation Exposure of Children, vol. II, United Nations, New York, 2013.

[8] W.W. Nazaroff, A.V. Nero Jr., Radon and its Decay Products in Indoor Air vol. 1, John Wiley & Sons. Ltd, Canada, 1988, pp. 6–44.

[9] S. Darby, D. Hill, A. Auvinen, J.M. Barros-Dios, et al., Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 european case-control studies, Br. Med. J. 330 (7485) (2005) 223–227.

[10] E. Stranden, Thoron and radon daughters in different atmospheres, Health Phys. 38 (1980) 777–785.

[11] F. Steinhäusler, Environmental 220Rn: a review, Environ. Int. 22 (1996) 1111–1123.

[12] A. Clouvas, S. Xanthos, M. Antonopoulos-Domis, Radon and thoron progeny measurements in dwellings of northern Greece, Sci. Total Environ. 272 (2001) 249–250.

[13] R.C. Ramola, G.S. Gusain, B.S. Rautela, et al., Levels of thoron and progeny in high background radiation area of southeastern coast of Odisha, India Radiat. Prot. Dosim. 152 (1–3) (2012) 62–65.

[14] R. Mishra, B.K. Sapra, R. Prajith, R.P. Rout, et al., Inhalation exposures due to radon and thoron (222Rn and 220Rn): do they differ in high and normal background radiation areas in India? J. Environ. Radioact 147 (2015) 125–129.

[15] S. Gierl, O. Meisenberg, P. Feistenauer, et al., Thoron and thoron progeny measurements in German clay house, Radiat. Prot. Dosim. 160 (2014) 160–163.

[16] Y. Omori, A. Sorimachi, G. Prasad, et al., Long-term measurements of residential radon, thoron, and thoron progeny concentrations around the Chhatrapur placer deposit, a high background radiation area in Odisha, India J. Environ. Radioact 162–163 (2016) 371–378.

[17] O. Meisenberg, R. Mishra, M. Joshi, et al., Radon and thoron inhalation doses in dwellings with earthen architecture: comparison of measurement methods, Sci. Total Environ. 579 (2017) 1855–1862.

[18] E. Salama, Study of Radon Emanation and Activity Levels of Some Ancient Egyptian Monuments, PhD thesis, Physics Department, Faculty of Science, Ain Shams University, 2006.

[19] M. Abo-Elmagd, S.M. Metwally, S.A. Elmongy, et al., External and internal exposure to natural radiations inside ancient Egyptian tombs in Saqqara, Radiat. Meas. 41 (2006) 197–200.

[20] F. Karinda, B. Haider, W. Rühm, A new electronic personal exposure meter for radon gas, Radiat. Meas. 43 (2008) 1170–1174.

[21] E. Gruber, E. Salama, W. Rühm, Real-time measurement of individual occupational radon exposures in tombs of the valley of the kings, Egypt. Radiat. Prot. Dosim. 144 (2011) 620–626.

[22] ICRP, Occupational Intakes of Radionuclides, Part 3. Publication 137, Ann. ICRP 46 (3/4) (2017). SAGE, London.

[23] ICRP, Protection against Radon-222 at home and at work. ICRP publication 65, Ann. ICRP 23 (2) (1993).

[24] A.F. Hafez, A.S. Hussein, Radon activity concentrations and effective doses in ancient Egyptian tombs of the Valley of the Kings, Appl. Radiat. Isot 55 (2001) 355–362.

[25] A.F. Hafez, M.A. Kotb, G.I. Khalil, Indoor radon and its progeny concentrations in archaeological places in Alexandria, Egypt, Radiat. Meas. 28 (1–6) (1997) 671–674.

[26] S.M. Metwally, M. Abo-Elmagd, E. Salama, Modeling the dependency of radon concentration levels inside ancient egyptian tombs on the ambient temperature variations, Arab J. Nucl. Sci. Appl. (2007) 197–206 (as Special Issue).

[27] ICRP, Lung cancer risk from radon and progeny and statement on radon. ICRP publication 115, Ann. ICRP 40 (1) (2010).

[28] S.U. El-Kameesy, E. Salama, S.A. El-fiki, et al., Radiological safety assessment inside ancient Egyptian tombs in Saqqara, Isotope. Environ. Health Stud. 52 (6) (2016) 567–576.