scientific reports

OPEN

Radon measurement and age-independent effective dose attributed to ingestion of bottled water in Iran: sensitivity analysis

Mina Pourshabanian[1,2], Simin Nasseri[1,2], Ramin Nabizadeh Nodehi[1,2], Sara Sadat Hosseini[1] & Amir Hossein Mahvi[1,2]✉

A comprehensive study was made to measure the radon concentration in bottled water available in Iran market. The 222Rn concentration in 70 bottled water samples were measured by the sniffing mode technique and RTM 1688-2 (SARAD, Germany) in immediate sampling time and 3 months later for determination of radon decay. The measured radon concentration ranged from 0.003 to 0.618 Bq L^{-1} in bottled water samples, which were much lower than the recommended value for radon in drinking water by WHO (100 Bq L^{-1}) and United states environmental protection agency (USEPA) (11.1 Bq L^{-1}). The annual effective dose of 222Rn due to ingestion bottled water was also evaluated in this research. The mean annual effective dose due to ingestion of radon in bottled water for adults, children, and infants were estimated to vary from 5.30×10^{-4} mSv^{-1}, 4.90×10^{-4} mSv^{-1}, and 2.15×10^{-4} mSv^{-1}, respectively. Overall, this study indicated that the Iranian people receive no significant radiological risk due to exposure to radon concentration in bottled water brands common consumed in Iranian market.

The environmental sources, especially groundwater drawn from granitic and metamorphic rocks are considered as the primary source of radioactivity[1,2]. Radioactive materials are commonly introduced into the environment via naturally occurring sources and man-made or artificial radionuclide fallouts[3,4]. The naturally occurring sources include the 238U and its daughter's 226Ra and 222Rn, commonly observed in water resources, rocks and soil[4,5]. However, artificial radionuclide fallouts caused by accidents and nuclear explosion can contaminate the water resources and environment which human live[6,7]. Radon (222Rn), as the heaviest noble gas, which is produced via alpha decay of 238U is naturally ubiquitous in the environments; 222Rn alone comprises 50% of total natural radiation[8,9]. Radon gas is derived from soil, rock, and sediments and commonly observed in the groundwater due to high solubility (510 cm^3 L^{-1}) and density (9.73 g L^{-1})[10–13]. 222Rn is recognized as the colorless, tasteless, and odorless radioactive gas with half-life of 3.82 days[14,15]. Radon is characterized with long-term half-life and capability of alpha particle emission, causing lung, blood and gastrointestinal cancer in humans during long term exposure[5,16]. The inhalation and ingestion are the main pathways of exposure to 222Rn; the occurrence of high levels of this carcinogenic agent in indoor air and groundwater resources give rise to human internal exposure[16–19]. 222Rn exposure, as the second risk factor for lung cancer can also damage DNA, penetrate the stomach and move through the human body via the bloodstream[5,8]. World health organization (WHO) and United states environmental protection agency (USEPA) have recommended the values of 100 BqL^{-1} and 11.1 BqL^{-1}, respectively, as the maximum contamination level in water resources[20,21]. Furthermore, 0.1 mSv^{-1} has been recommended by WHO as annual effective dose induced by exposure to 222Rn in drinking water[22,23]. The quantification of radioactivity in drinking water is vital for public health risk and exposure level of population and annual effective radiation doses[12,24]. Bottled water is considered as the major source of drinking water over the world, particularly in countries with hot and dry climates[3]. In recent year, bottled water contained in polyethylene in polyethylene terephthalate (PET) have drawn great attention and countries continue to produce

[1]Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran. [2]Center for Solid Waste Research, Institute for Environmental Research, Tehran University of Medical Science, Tehran, Iran. ✉email: ahmahvi@yahoo.com

bottled water in a large-scale application[25]. For instance, according to world water report, the average annual consumption of United Arab Emirates (UAE) has increased 260 L per person in 2006 Worldwater.org (http://www.worldwater.org/). Due to the fact that consumption of bottled water have increased worldwide, continuous monitoring of radon concentration in bottled water can facilitate the issues and concerns about the water supply. Recently, several studies have focused on radon levels in various drinking water such as bottled water, groundwater and surface water over the world[26–30]. In case of Iran, some studies have been focused on radon concentration in water resources including spring, wells, Qanat and tap water[5]. However, to best of our knowledge, no information are available on radon concentration in Bottled water. This study could be regarded as the first attempt to comprehensively monitor the radon concentration in Iran and estimate the annual effective dose by Monte Carlo stimulation technique.

Materials and methods

Sampling. This cross-sectional study was performed in 2019 to comprehensively monitor radon concentration in bottled water in the Iranian market. A total of 70 different bottled water brands mostly consumed by Iranian people were collected from different provincial areas of Iran. The bottled waters were transferred to the laboratory, each bottle of water had specific code. The radon measurements were performed twice; immediately after collection of bottled water and three months later in order to determine radon decay after production. Special care was taken to avoid the exposure of water samples in bottled water with air and kept at 25 °C.

Measurement of radon concentration in water. The concentration of 222Rn in the bottled water was measured by the slow-mode technique and RTM 1688-2 (SARAD, Germany) using radon gas extraction from the solution[31]. A brief description of radon measurement procedure is described here. Generally, the Radon (222Rn) gas concentration is determined by the short living daughter products, generated by the Radon decay inside a measurement chamber. In addition, the measurement of radon activity concentration in the water sample is based on the equilibrium state between the Radon air and water activity concentrations which takes place within a sealed system after a certain time (1 h). The bubbling flask containing 500 mL of bottled water at 25 °C was connected to RTM 1688-2 device. The bubbling Flask enables release of radon gas form the water sample, which is directed to a closed loop. The released volume air circulates the loop by the internal pump of Radon monitor. Immediately after the radon decay, the remaining Po-218 nuclei becomes charged positively for a short period; some shell electrons are scattered away by the emitted alpha particle. At the same time, the semiconductor detector shows the ions collected by the electrical field force; the numbers of collected Po-218 ions is proportional to the Radon gas concentration inside the chamber. Generally, the total radon activity within the system is calculated as a constant over the measurement period and the relationship can be stated as per the formula[31]:

$$\mathrm{A(Water)} = \mathrm{A1(Water)} + \mathrm{A\ (Air)}, \tag{1}$$

with: A(Water) = Total activity of the water sample before the de-gassing, A1 (Water) = Remaining activity of the water sample after the de-gassing, A(Air) = activity in the air volume.

In addition, the radon concentrations were reported with 95% confidence interval and $\mathrm{BqL^{-1}}$. The pH, and conductivity were measured for different bottled brands.

Estimation of annual effective doses (AED). The exposure to radon concentration in drinking water in long-term period contribute to increased radiation dose exposure on stomach[9]. The average annual effective dose (Ed, $\mathrm{mSvy^{-1}}$) due to exposure of radon following ingestion the bottled water rich in Radon was estimated using the procedure and equation recommended by UNSCEAR[5,12]:

$$E_d = A_c \times q \times C_f \times T, \tag{2}$$

where, A_c refers to radon activity concentration in bottled water samples ($\mathrm{BqL^{-1}}$), q represents the daily consumption rate ($\mathrm{Lday^{-1}}$), Cf is the dose coefficient ($\mathrm{mSvBq^{-1}}$) for different groups of ages, and T is ingestion period (365 days).

It is important to note that there is no valid and official data on consumption rate of bottled drinking water for Iran, therefore, we have adopted data reported United Nations Scientific Committee on the Effects of Atomic Radiation[16] for different group: infants (150 $\mathrm{Lyr^{-1}}$), children (350 $\mathrm{Lyr^{-1}}$), and adults (730 $\mathrm{Lyr^{-1}}$). The dose coefficient (Cf) for each age group was obtained from "International Basic Safety Standards for Protection against Ionizing Radiation and for Safety of Radiation Sources"[32]: Adults (18×10^{-6} $\mathrm{mSv/Bq^{-1}}$) and Children (35×10^{-6} $\mathrm{mSvBq^{-1}}$).

Monte Carlo simulation technique. The uncertainty and variability of the parameters considered in the equation of risk index were calculated with Monte-Carlo simulation technique and 10,000 iterations in the Oracle® Crystal Ball software (1.1.2.4.850 version). This technique selects the values of the parameters in the specified range proportional to the distribution of each variable, and then calculates the risk level. This process is repeated several times and calculates the average, minimum, maximum, standard deviation, different percentile values, and some other statistical indices as the final result. These repetitions remove the uncertainty and variability of the parameter values. Therefore, the results are more reliable and more valuable than the obtained results with constant values of input parameters. In order to determine the contribution of input variables in the predicted value of the risk index, sensitivity analysis was conducted. On the other hand, the sensitivity analysis indicated how much influential factors can change the response variable, annual effective dose for different groups of ages.

Results and discussion

Radon activity concentration in bottled water. A total of 70 bottled water brands that were commercially available in Iran market and different provinces were collected and analyzed for 222Ra concentration (BqL^{-1}). Table 1 presents the mean radon concentration in bottled water samples immediately collected from Iran market and its concentration after 3 months storage in 25 °C. As seen in Table 1, the radon concentration varies from 0.003 to 0.618 BqL^{-1}. The highest and lowest 222Rn concentration value were observed in Codes 35 and 49, respectively. In addition, the mean value of radon measurement in the initial stage was calculated to be 0.040 BqL^{-1}, which is much lower the recommended values of 222Rn in drinking water USEPA (11.1 BqL^{-1}) and WHO (10 BqL^{-1})[33,34]. The decay of 222Rn concentration in bottled water samples storage at environment temperature within 3 months were calculated to be 0.001 to 0.593 BqL^{-1}. Generally, the 222Rn concentrations in all bottled water samples were measured to be lower than the recommended level and are acceptable for drinking water in Iran. Abojassim et al. surveyed the radon concentration in bottled water in Iraq market. They reported that the mean radon concentration in drinking bottled water were 0.11256 BqL^{-1} (0.0354–0.248 BqL^{-1})[35]. In addition, Turhan et al. reported that the average gross alpha and beta radioactivity concentrations in bottled water in Turkey were 21 ± 5 m BqL^{-1} and 59 ± 12 $mBqL^{-1}$, respectively[2]. In a systematic review made in Iran, Keramati et al. reported that radon concentration in drinking waters were lower the guideline value except springs[5], which are in consistent with our study. The less solubility and short-lived period of radon leads to release of this radioactive gas to atmosphere from surface water. That is the most likely explanation of lower observed radon concentration in tap water compared to water taken from depths[36]. In addition, Table S1 lists the pH and EC of bottled water samples in initial stage and measurement after three months.

Code	Initial Ra-22 concentration (BqL^{-1})	Decay Ra-22 concentration (BqL^{-1})	Code	Initial Ra-22 concentration (BqL^{-1})	Decay Ra-22 concentration (BqL^{-1})
1	0.008 ± 0.001	0.005	36	0.008 ± 0.001	0.004
2	0.003 ± 0.001	0.002	37	0.003 ± 0.001	0.001
3	0.006 ± 0.001	0.004	38	0.008 ± 0.001	0.006
4	0.008 ± 0.001	0.003	39	0.278 ± 0.011	0.039
5	0.003 ± 0.001	0.002	40	0.017 ± 0.005	0.006
6	0.014 ± 0.002	0.011	41	0.302 ± 0.004	0.041
7	0.007 ± 0.002	0.005	42	0.092 ± 0.010	0.023
8	0.005 ± 0.001	0.002	43	0.003 ± 0.001	0.001
9	0.006 ± 0.002	0.004	44	0.003 ± 0.001	0.002
10	0.038 ± 0.004	0.021	45	0.011 ± 0.001	0.005
11	0.003 ± 0.001	0.001	46	0.003 ± 0.001	0.002
12	0.006 ± 0.001	0.004	47	0.038 ± 0.008	0.015
13	0.003 ± 0.001	0.002	48	0.023 ± 0.004	0.014
14	0.008 ± 0.001	0.005	49	0.003 ± 0.001	0.002
15	0.005 ± 0.001	0.002	50	0.01 ± 0.001	0.006
16	0.385 ± 0.006	0.015	51	0.006 ± 0.001	0.002
17	0.003 ± 0.001	0.002	52	0.014 ± 0.002	0.005
18	0.309 ± 0.009	0.006	53	0.008 ± 0.002	0.004
19	0.015 ± 0.003	0.008	54	0.011 ± 0.001	0.005
20	0.008 ± 0.001	0.006	55	0.016 ± 0.001	0.006
21	0.176 ± 0.003	0.032	56	0.008 ± 0.001	0.005
22	0.02 ± 0.006	0.012	57	0.006 ± 0.002	0.002
23	0.008 ± 0.001	0.06	58	0.005 ± 0.002	0.002
24	0.003 ± 0.001	0.001	59	0.009 ± 0.001	0.005
25	0.032 ± 0.002	0.017	60	0.015 ± 0.003	0.008
26	0.003 ± 0.001	0.001	61	0.005 ± 0.001	0.001
27	0.085 ± 0.004	0.014	62	0.015 ± 0.001	0.006
28	0.003 ± 0.001	0.002	63	0.007 ± 0.001	0.003
29	0.009 ± 0.001	0.007	64	0.015 ± 0.001	0.009
30	0.008 ± 0.001	0.004	65	0.019 ± 0.004	0.005
31	0.017 ± 0.003	0.012	66	0.009 ± 0.001	0.006
32	0.02 ± 0.004	0.011	67	0.008 ± 0.001	0.003
33	0.005 ± 0.001	0.004	68	0.005 ± 0.001	0.002
34	0.006 ± 0.001	0.002	69	0.017 ± 0.001	0.008
35	0.618 ± 0.001	0.025	70	0.012 ± 0.002	0.005

Table 1. Radon concentration in different bottled water samples available in Iran market at start and after three months.

Parameter	Age group (years)			Distribution	Refs.
	Infants	Children	Adults		
Water ingestion (Ld^{-1})	0.45 ± 0.12	1.12 ± 0.27	1.23 ± 0.27	Log normal	[38]
Radon concentration (BqL^{-1})	Initial: 0.03 ± 0.09; storaged: 0.01 ± 0.01			Log normal	This study
Dose coefficient ($mSvBq^{-1}$)	35×10^{-6}		18×10^{-6}	–	[12]
Exposure frequency (day)	0–365	0–365	0–365	Uniform	This study

Table 2. Parameters used in calculating annual effective doses of radon in bottled water samples.

Associated age specific annual effective dose estimation. The calculation of annual effective dose can provide good interpretation of health risks in exposure to pollutant[37]. The annual effective doses of radon in bottled water samples due to ingestion were calculated for different groups of ages (viz., infant, child and adult) using the parameters presented in Table 2. Figure 1a,b reveals the annual mean effective doses of radon in bottled water consumed by Iranian people for different groups of ages. Figure 1a shows the corresponding annual effective dose of radon in the bottled water samples in the immediate and initial stage. For infants, the Ed value varies from 1.57×10^{-5} to 3.20×10^{-3} $mSvy^{-1}$ with average value of 2.15×10^{-4} $mSvy^{-1}$. In case of children group of ages, the Ed were calculated to be in range of 3.64×10^{-5}–7.50×10^{-3} $mSvy^{-1}$ with average value of 4.90×10^{-4} $mSvy^{-1}$. As for adults group, the annual effective dose was estimated to be between 3.94×10^{-5} and 8.10×10^{-3} $mSvy^{-1}$ with average value of 5.30×10^{-4} mSv^{-1}. Based on these results, the Ed for adults groups was found to be the highest followed by infants and children. Therefore, the adults are considered to be the most critical population group for consuming bottled water in Iran. As the dose conversion coefficient in infants and children are twice that of adults group, the annual consumption rate of bottled water is most likely influencing parameter on higher Ed in adults group. According to result obtained from the measurement of radon in bottled water brands studied in the present research, we found that all annual effective dose of radon in different groups of ages is much lower the maximum annual reference dose recommended by WHO and UNSCEAR (0.1 $mSvy^{-1}$)[22,23]. The similar results with Ed lower than the normal limits of the world (i.e. 1 mSv^{-1}) were previously reported in studies focused on radon in water resources[3,8,35].

In addition, the annual effective doses of radon in bottled water samples stored at 25 °C for three months are shown in Fig. 1b. As shown in Fig. 1b, the Ed for adults group of age were calculated to be in range of 1.31×10^{-6}–7.88×10^{-5} $mSvy^{-1}$ with average value of 1.07×10^{-5} $mSvy^{-1}$. In case of children group, the Ed values varies from 1.21×10^{-5} to 7.28×10^{-4} $mSvy^{-1}$ with average value of 9.93×10^{-5} $mSvy^{-1}$. As for infants, this value was estimated to be between 5.24×10^{-6} and 3.14×10^{-4} $mSvy^{-1}$ with average value of 4.28×10^{-5} $mSvy^{-1}$. Generally, the Ed estimated for radon concentration in storage bottled water samples are significantly lower than those of initial samples. Overall, for the investigated radon concentration in bottled water, it can be concluded that the Iranian people receive no significant radiological risk due to exposure to radon concentration in bottled water brands commonly observed.

Sensitivity analysis. Sensitivity analysis using Monte-Carlo simulation was performed to investigate how variability of the outputs can be apportioned quantitatively to different sources of variability in the inputs. In addition, the Monte-Carlo simulation technique and sensitivity analysis aid the authorities to understand which influential factors affect more on annual effective dose.

The results for risk assessment through ingestion of bottled water with radon show that in both measurements (initial and after storage), radon concentration has the highest contribution to variation of this index (see Fig. 2). As seen from Fig. 2, the contribution of radon concentrations in initial stage ranged from 75.8 to 77.0%; these values were estimated to be 50.0 to 50.9% for bottled water samples storaged at temperature 25 °C.

This highlights the importance of radon concentration in exposure to bottled water and water sources rich in radon. Therefore, this parameter should be monitored continuously by the authorities and preventive measurements are suggested to take radon concentration in water sources as priority.

Conclusion

The present study represents one of first attempt to comprehensively monitor the radon activity concentration in bottled water available in Iran market. Our conclusions are based on radon concentration in 70 bottled water brand common consumed by Iranian people: (1) the measured radon concentration in bottled water sample (0.003–0.618 BqL^{-1}) were much lower than the values recommended by WHO and UNCERP. (2) The annual effective doses of radon in bottled water were estimated to be lower than the valued recommended by WHO. (3) Overall, it can be concluded that the Iranian people receive no significant radiological risk due to exposure to radon concentration in bottled water brands commonly observed. However, the continuous monitoring of radon concentrations in different sources can aid authorities to provide mitigation action in order to minimize the health risk. In addition, the limitation of present study can be described such that there is no official consumption rate for bottled water in Iran, therefore, the authorities are suggested to measure this value to aid the definite annual effective doses of radon in bottled water.

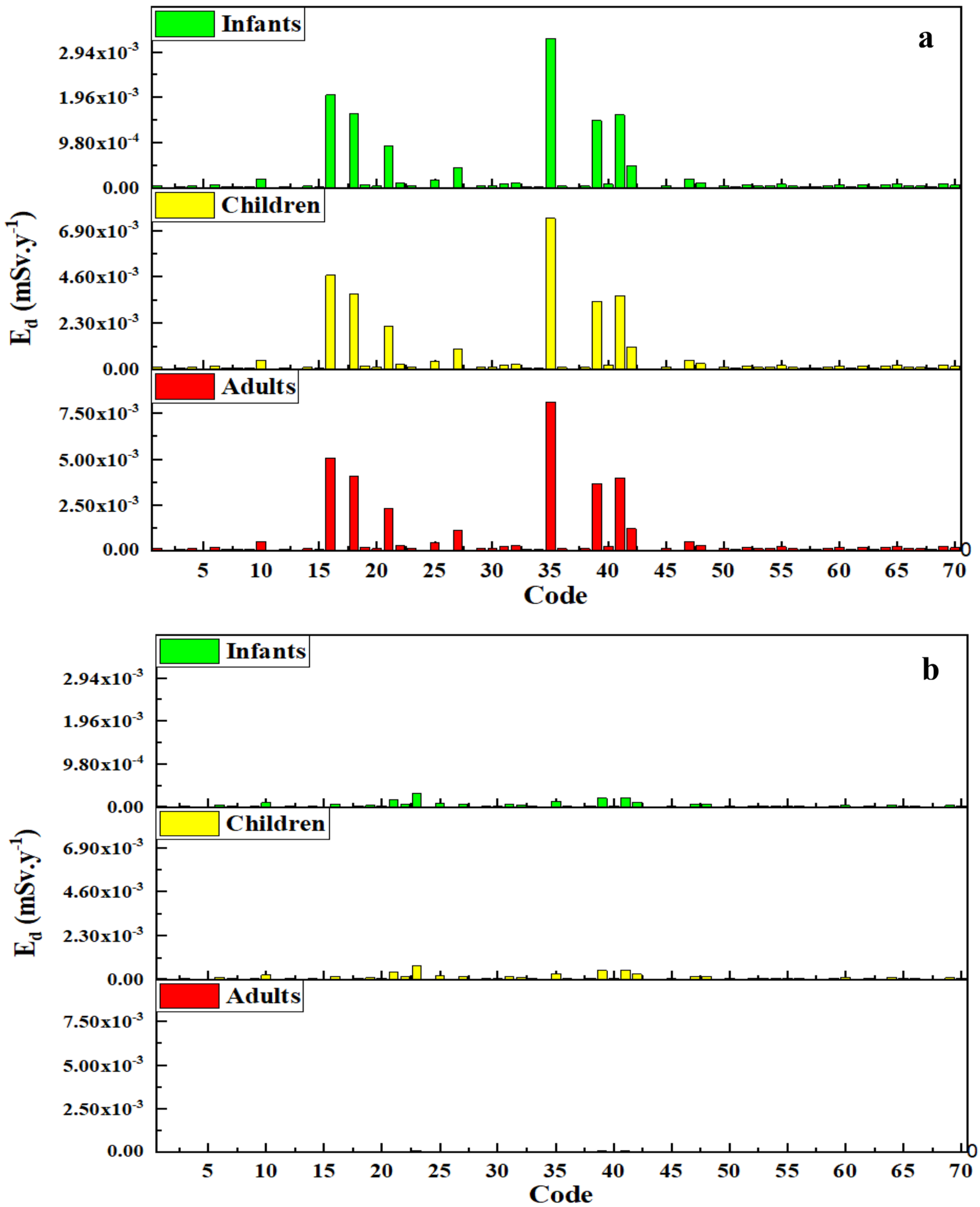

Figure 1. The calculated annual effective doses of radon in bottled water samples in initial stage (**a**), and stored at 25 °C for 3 months (**b**).

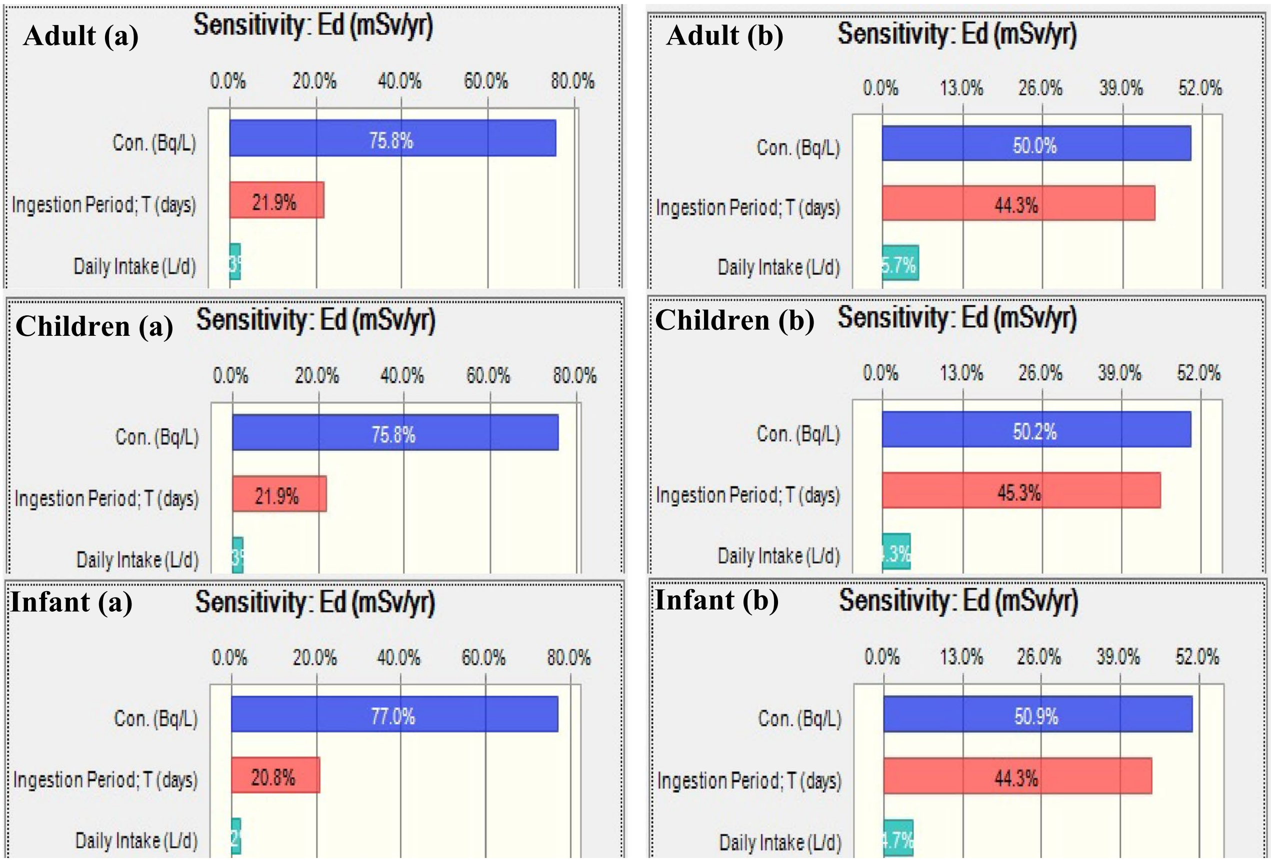

Figure 2. Sensitivity analysis and the contribution of influencing parameters on annual effective doses of radon in bottled water. (**a**) (Initial), (**b**) (storaged).

Data availability

The datasets generated and analyzed during the current study available from the corresponding author on reasonable request.

Received: 19 May 2023; Accepted: 28 July 2023
Published online: 05 August 2023

References

1. de Oliveira Lucas, F. & Ribeiro, F. B. Radon content in groundwaters drawn from the metamorphic basement, eastern São Paulo State, Brazil. *Radiat. Meas.* **42**, 1703–1714 (2007).
2. Turhan, S. *et al.* Radiochemical analysis of bottled drinking waters consumed in Turkey and a risk assessment study. *Microchem. J.* **149**, 104047 (2019).
3. Semerjian, L. *et al.* Age-dependent effective ingestion dose estimations and lifetime risk assessment for selected radionuclides (40K and 3H) in bottled waters marketed in United Arab Emirates. *Chemosphere* **249**, 126114 (2020).
4. Dueñas, C., Fernández, M. C., Liger, E. & Carretero, J. Natural radioactivity levels in bottled water in Spain. *Water Res.* **31**, 1919–1924 (1997).
5. Keramati, H. *et al.* Radon 222 in drinking water resources of Iran: A systematic review, meta-analysis and probabilistic risk assessment (Monte Carlo simulation). *Food Chem. Toxicol.* **115**, 460–469 (2018).
6. Dinh Chau, N. *et al.* Natural radioactivity in groundwater—A review. *Isot. Environ. Health Stud.* **47**, 415–437 (2011).
7. Gigantesco, A. & Giuliani, M. Quality of life in mental health services with a focus on psychiatric rehabilitation practice. *Ann. Ist. Super Sanità* **47**, 363–372 (2011).
8. Tan, W. *et al.* Distribution of radon and risk assessment of its radiation dose in groundwater drinking for village people nearby the W-polymetallic metallogenic district at Dongpo in southern Hunan province, China. *Appl. Radiat. Isot.* **151**, 39–45 (2019).
9. Inácio, M., Soares, S. & Almeida, P. Radon concentration assessment in water sources of public drinking of Covilhã's county, Portugal. *J. Radiat. Res. Appl. Sci.* **10**, 135–139 (2017).
10. Fakhri, Y. *et al.* Assessment of concentration of radon 222 and effective dose; Bandar Abbas city (Iran) citizens exposed through drinking tap water. *Int. J. Pharm. Technol.* **8**, 10782–10793 (2016).
11. Oner, F., Yalim, H. A., Akkurt, A. & Orbay, M. The measurements of radon concentrations in drinking water and the Yeşilirmak River water in the area of Amasya in Turkey. *Radiat. Prot. Dosimetry* **133**, 223–226 (2009).
12. Bello, S., Nasiru, R., Garba, N. N. & Adeyemo, D. J. Annual effective dose associated with radon, gross alpha and gross beta radioactivity in drinking water from gold mining areas of Shanono and Bagwai, Kano state, Nigeria. *Microchem. J.* **154**, 104551 (2020).
13. Fouladi-Fard, R. *et al.* Radon concentration and effective dose in drinking groundwater and its relationship with soil type. *J. Radioanal. Nucl. Chem.* https://doi.org/10.1007/s10967-020-07424-x (2020).
14. Duggal, V., Sharma, S. & Mehra, R. Risk assessment of radon in drinking water in Khetri Copper Belt of Rajasthan, India. *Chemosphere* **239**, 124782 (2020).

15. Sharma, S., Duggal, V., Srivastava, A. K. & Mehra, R. Assessment of radiation dose from exposure to radon in drinking water from western Haryana, India. *Int. J. Environ. Res.* **11**, 141–147 (2017).
16. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). *Sources and Effects of Ionizing Radiation—Annex C, D and E* (United Nations Publication, 2008).
17. WHO. *Guidelines for Drinking-Water Quality Fourth Edition WHO Library Cataloguing-in-Publication Data* (WHO, 2011).
18. ICRP. Lung cancer risk from radon and progeny and statement on radon—ICRP publication 115. *Ann. ICRP* **40**, 1–64. https://doi.org/10.1016/j.icrp.2011.08.011 (2010).
19. Vogeltanz-Holm, N. & Schwartz, G. G. Radon and lung cancer: What does the public really know? *J. Environ. Radioact.* https://doi.org/10.1016/j.jenvrad.2018.05.017 (2018).
20. World Health Organization. *Guidelines for Drinking-Water Quality: Third Edition, Incorporating the First and Second Addenda, Volume 1-Recommendations* (World Health Organization, 2008).
21. USEPA (United States Environmental Protection). *Office of Groundwater and Drinking Water Rule: Technical Fact Sheet EPA 815-F-99-006* (USEPA, 1997).
22. Gorchev, H. G. & Ozolins, G. *Guidelines for Drinking-Water Quality* 3rd edn, 564 (World Health Organisation, 2004).
23. World Health Organization. *Guidelines for Drinking-Water Quality* (WHO, 2011).
24. Burghele, B. *et al.* The FIRST large-scale mapping of radon concentration in soil gas and water in Romania. *Sci. Total Environ.* **669**, 887–892 (2019).
25. Lucchetti, C., De Simone, G., Galli, G. & Tuccimei, P. Evaluating radon loss from water during storage in standard PET, bio-based PET, and PLA bottles. *Radiat. Meas.* **84**, 1–8 (2016).
26. Kaur, M., Tripathi, P., Choudary, I., Mehra, R. & Kumar, A. Assessment of annual effective dose due to inhalation and ingestion of radon in water samples from some regions of Punjab, India. *Int. J. Pure Appl. Phys.* **13**, 193–200 (2017).
27. Fakhri, Y. *et al.* Effective dose of radon 222 bottled water in different age groups humans: Bandar Abbas City, Iran. *Glob. J. Health Sci.* **8**, 64–71 (2015).
28. Giri, S., Singh, G., Jha, V. N. & Tripathi, R. M. Risk assessment due to ingestion of natural radionuclides and heavy metals in the milk samples: A case study from a proposed uranium mining area, Jharkhand. *Environ. Monit. Assess.* **175**, 157–166 (2011).
29. Al-Alawy, I. T., Mohammed, R. S., Fadhil, H. R. & Hasan, A. A. Determination of radioactivity levels, hazard, cancer risk and radon concentrations of water and sediment samples in Al-Husseiniya River (Karbala, Iraq). *J. Phys. Conf. Ser.* **1032**, 012012 (2018).
30. Ravikumar, P. & Somashekar, R. K. Determination of the radiation dose due to radon ingestion and inhalation. *Int. J. Environ. Sci. Technol.* **11**, 493–508 (2014).
31. An, A. N., June, V. & Oswald-coefficient, T. *Measurement of the Radon Concentration of Water Samples, Sampling Set-up*, Vol. 1, 4–8. www.sarad.de (SARAD GmbH, 2007).
32. IAEA. *Categories in the IAEA Safety Series* Vol. 48 (IAEA, 1996).
33. WHO. *Guidelines for Drinking Water Quality* 4th edn. (World Health Organisation, 2011).
34. USEPA. *Assessment of Risks from Radon in Homes: Indoor Air Division (EPA 402R03003)* (2003).
35. Abojassim, A. A., Kadhim, S. H., Mraity, H. A. A. & Munim, R. R. Radon levels in different types of bottled drinking water and carbonated drinks in Iraqi markets. *Water Sci. Technol. Water Supply* **17**, 206–211 (2017).
36. Mittal, S., Rani, A. & Mehra, R. Radon levels in drinking water and soil samples of Jodhpur and Nagaur districts of Rajasthan, India. *Appl. Radiat. Isot.* **113**, 53–59 (2016).
37. Ghaffari, H. R. *et al.* Gamma radiation in the mineral hot springs of Ardabil, Iran: Assessment of environmental dose rate and health risk for swimmers. *Environ. Monit. Assess.* **192**, 2 (2020).
38. Ghaffari, H. R. *et al.* Assessment of hydrogeochemical characteristics and quality of groundwater resources in relation to risk of gastric cancer: Comparative analysis of high- and low-risk areas in Iran. *Environ. Geochem. Health* **43**, 1 (2020).

Acknowledgements

The authors gratefully acknowledge the financial support given by Deputy of Research, Tehran University of Medical Sciences, Tehran, Iran, as Grant Number 35747. The authors would like to thanks the laboratory staff of School of Public Health.

Author contributions

M.P.: Writing, Methodology, Investigation. S.N.: Methodology. R.N.N.: Investigation, Analysis, S.S.H.; Experimental analysis, A.H.M.: Conceptualization, Supervision.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-023-39679-1.

Correspondence and requests for materials should be addressed to A.H.M.

Reprints and permissions information is available at www.nature.com/reprints.