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Seasonal ^{222}Rn activity in spring water close to rare earth element and uranium mines in North Vietnam

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Abstract

^{222}Rn is among the most important issues for radiation exposure in/near high background radiation areas such as near rare-earth-element (REE) and uranium mines in North Vietnam. Seasonal ^{222}Rn activity concentration in spring water was determined by RAD-7, with average ranges of 1270 ± 60–66,400 ± 2630 Bq m^{-3}, therein the highest value was a REE, and the lowest a uranium mine. The ^{222}Rn activity concentration was higher in the dry season, which could be attributed to ^{222}Rn leaching to spring waters from nearby mines, and lower in the rainy season due to dilution by rain water. The ^{222}Rn annual effective doses were within permissible limits.

Keywords Uranium mines · REEs mines · Spring water · Radon · Seasonal ^{222}Rn activity · Annual effective dose

Introduction

Natural water, including surface water and groundwater contain a variety of beneficial elements and compounds. On the other hand, they carry significant health concerns as well, including the chances of radionuclide and heavy metal contamination. In high radioactive background areas such as those near or within rare earth element (REE) mines, uranium mines or magmatic massifs, the radionuclide activity in groundwater depends on the ability of leaching and dissolving of minerals from aquifer rocks [1, 2]. Tectonic activity, groundwater flow, weathering, natural weather and human/animal activities may lead to the release of significant amounts of radioisotopes into the surrounding environment, especially aquatic environments such as groundwater or spring water. Therefore, local residents using that water for their daily lives could be at risk as a consequence.

Radon with 3.8 days of half-life is a noble gas radionuclide, and for migration purposes it can be considered readily soluble in water [3–6]. As a gas, it has relatively high mobility, and it can move easily through fractures and migrate far from the supply [7]. Previous studies have demonstrated that among all the isotopes of the ^{238}U decay chain, the ^{222}Rn activity was found to be the highest in groundwater [8–11]. In that case, the principal concentration completely dissolves into groundwater without being absorbed and precipitated [10, 11]. In addition, the high radioactivity in the aquifer could have originated during movement through rocks and sediments of potentially radioactive reservoir aquifers such as phosphate, granite and black shale [12–14]. Groundwater or spring water can dissolve uranium and thorium minerals such as coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), (UO_2) and pitchblende (U_3O_8), which then decay to ^{222}Rn and ^{220}Rn. However, because the half-life of ^{220}Rn is very short, usually ^{222}Rn forms the main component of radioactive gas in water or groundwater [15]. Therefore, the radon contamination potential in spring water as well as underground water sources at or close to the high natural radioactive background areas are areas of research interest. It should be mentioned that gross alpha and beta measurements in drinking water are a screening tool in still in favor with many authorities, however such measurement

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have some limitations, so radionuclide specific measurements can be preferred [16].

^{222}Rn can cause undesirable effects on public health directly upon drinking of radon-rich water for a long time or indirectly by increasing the indoor radon concentration. The decay products of radon such as ^{210}Pb and ^{210}Po if inhaled can cause lung cancer and tissue damage [17, 18], being the reason for thousands of cancer deaths each year [19]. Similarly ingesting radon rich water leads to the increase of intestinal cancers [20].

The WHO guidelines of ^{222}Rn concentration in drinking water recommend less than 100 Bq L^{-1} as acceptable [20]. Similarly, European Union recommendation is that concentrations below 100 Bq L^{-1} require no remedial action, while above 1000 Bq L^{-1} action is radiologically warranted. Recent efforts to detect and evaluate the effects of consuming ^{222}Rn containing water in different aquatic environments helped in implementing strategies decreasing their impact on public health [19, 21].

There are multiple REEs and uranium mineral concentrations located in the North–Viet Nam region [22]. Research studies pertaining to the radioactivity in various environmental media were carried out in and surrounding those areas, however there is only limited information on radon in the local water resources available [23–29].

In high mountainous areas, the source of drinking water is mainly rain, well and spring water (the majority is spring water). Spring water in these areas has been identified as close to or flowing past REEs and Uranium mines, which increases the possibility of it harboring high radioactivity concentrations of ^{222}Rn and its parents, ^{226}Ra and ^{238}U. [30]. Therefore, local people may be exposed to high levels of internal radiation when they use that water source for living and drinking. Determining the concentration and radiological hazard assessment for the consumption of ^{222}Rn containing spring water in the high natural radioactive background level areas is an important part of assuring public health in the area. The results will provide a database for radioactive dose assessment and will aid in assessing the impact of mining activities due to the release of ^{222}Rn radionuclides into the surrounding environment. In addition, this present study also presents the seasonal variation of ^{222}Rn activity and emphasizes the influence of climatic factors on the distribution and content of ^{222}Rn in spring water sources in North Vietnam.

Material and method

Study area

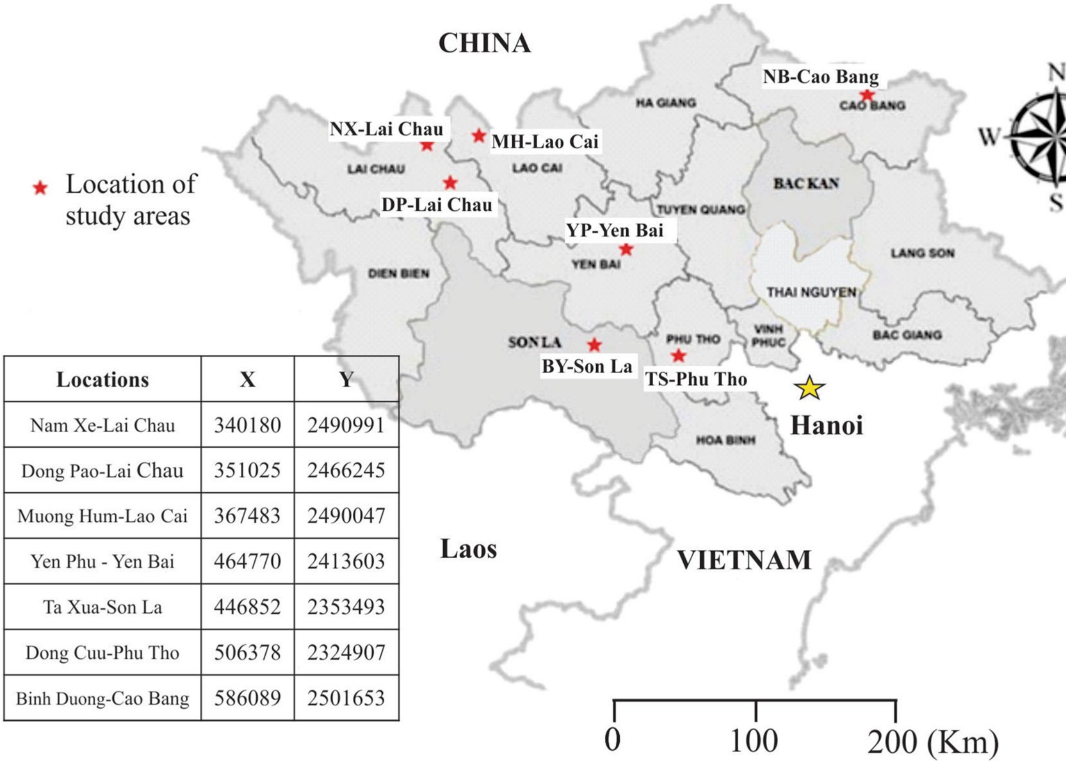
North Vietnam was affected by many tectonic and magmatic events that were sources of ore and natural radionuclide deposits (rare earth elements (REEs) and uranium mines) [31–35]. The REEs mines in North–Vietnam [36] include the Muong Hum—Lao Cai, Nam Xe—Lai Chau, Dong Pao—Lai Chau, and Yen Phu—Yen Bai REE mines, while uranium mines include Ta Xua—Son La, Dong Cuu—Phu Tho and Binh Duong—Cao Bang as presented in (Fig. 1).

The Nam Xe—Lai Chau mine is the largest with about 7.7 million tons of REEs reserve in Vietnam [37]. The U, Th potential of this area is also relatively large, with a reserve of about 76,000 tons of U_3O_8, 59,000 tons of ThO_2 in the north of the mine [36]. The second largest REE mine is Dong Pao- Lai Chau mine with a reserve of 3.7 million tons, where the U and Th concentrations in the ore were reported to be 0.3 and 0.01%, respectively [24]; the Muong Hum—Lao Cai mine has a reserve of about 0.4 million ton of REE, the U_3O_8 and ThO_2 concentrations were recorded as 0.17—0.15% and 0.08—0.03%; the Yen Phu—Yen Bai mine has a REE reserve about 4000 tons, with ThO_2 and U_3O_8 concentrations about 0.001–0.383 and 0.001–0.04%, respectively [1, 38]. The Ta Xua—Son La, Dong Cuu—Phu Tho and Binh Duong—Cao Bang uranium mines have concentrations of U_3O_8 approximately 0.05; 0.05–0.06 and 0.05–0.06%, respectively.

Nam Xe and Dong Pao from Lai Chau are over the Fa Si Pan Granite formation [39], and while Muong Hum from Lao Cai is over a Paleozolic magmatic rock formation, that is partially covered by thin bedded limestone, clayey limestone, clay shale and calcareous sandstone [40]. Yen Phu from Yen Bai lies over a Quaternary sedimentary rock formation, however due to the vicinity of the Red River fault the aquifer includes areas influenced by magmatic activity [39]. Ta Xua from Son La is located over Permian–Triassic sedimentary rocks [39]. Dong Cuu from Phu Tho lies over the Thach Khoan Formation mainly of mica quartz schist, mica schist, staurolite-bearing quartz, disten, sillimanite, and garnet [41]. Finally, Binh Duong from Cao Bang lies over mixed Triassic sedimentary rocks [42].

Method

Monitoring the variation in ^{222}Rn activity in spring water was conducted for both dry and rainy seasons. North Vietnam is characterized by a tropical monsoon climate with high temperature and rainfall in summer (wet or rainy season) and low temperature and rainfall in winter (dry season). The rainy season runs from May to September or October and the dry season runs from October through May. Water samples were evaluated for radon activity at August for the rainy season and in December for the dry season. A total of 126 samples were collected from spring streams flowing from the alpine terrain at seven locations. At each location, the sampling was carried out for 3 consecutive days. Each day the samples were taken at 3 different times including



Locations	X	Y
Nam Xe-Lai Chau	340180	2490991
Dong Pao-Lai Chau	351025	2466245
Muong Hum-Lao Cai	367483	2490047
Yen Phu - Yen Bai	464770	2413603
Ta Xua-Son La	446852	2353493
Dong Cuu-Phu Tho	506378	2324907
Binh Duong-Cao Bang	586089	2501653

Fig. 1 Study areas (modified from Duong et al. [36])

the morning, noon, and evening. We have selected typical sampling sites at locations used by local residents, nearby uranium and rare earth element mining activities. The ^{222}Rn activity concentration was directly measured using a RAD 7 m manufactured by Durridge Company Inc (USA) combined with the RAD H_2O kit, with a measuring range from 0.1 to 200,000 pCi L^{-1} and accuracy of 0.1 pCi L^{-1} (3.7–740 Bq L^{-1} with an accuracy of 3.7 mBq L^{-1}), using a continuous loop aeration system, a technique commonly used in similar studies on drinking water [43], ground water and spring water [44].

To get an accurate performance, the experimental procedure was conducted according to the manufacturer's instructions [45], using the 250 mL and 40 mL plastic vials from the RAD H_2O kit depending on activity concentration. The detection limit using the 250 mL vial was 0.037 Bq L^{-1} (37 Bq m^{-3}) using a 300 min count, while for the 40 mL vial it was 0.259 Bq L^{-1} (259 Bq m^{-3}) using a 300 min count.

Annual effective dose (AED)

The AED to humans contributed by ^{222}Rn from water consumption is determined by the formula below.

The AED from ingestion was determined by formula (1).

$$AED_{Ing} = C_{Rn} \times D_f \times A_i \quad (1)$$

where

- C_{Rn} is the ^{222}Rn activity average in water (Bq L^{-1}).
- D_f is the ^{222}Rn dose conversion factor (mSv Bq^{-1}), the values for adult (> 17 years), child (> 7 to 12 years) and infant (1–2 years) are 3.5×10^{-6}, 5.9×10^{-6}, and 23×10^{-6} mSv Bq^{-1} respectively [46].
- A_i is the annual water consumption (according WHO (2008) the annual water consumption for adults, children and infants is 720, 330 and 230 L, respectively [20]).

The AED from inhalation was determined by formula (2):

$$AED_{Inh} = C_{Rn} \times R \times F \times D_f \times T \quad (2)$$

where

- C_{Rn} is the average ^{222}Rn activity in water sample (Bq L^{-1}),
- R is the ratio between ^{222}Rn in air and water (10^{-4}),
- F is the equilibrium coefficient between ^{222}Rn and its progenies (0.4),
- D_f is the ^{222}Rn dose conversion factor equal to 9×10^{-6} mSv Bq^{-1} h^{-1} $m.^3$ [46]

- T: the average indoor time of each individual (7000 h/year) [46, 47].

Formula 2, while commonly used for evaluating the effects of radon in water for the increase of inhalation dose is, in the current study, an overestimation of the actual risk. The exposure scenario in the formula is that water is piped in the house, where the degassing radon increases indoor radon concentration, leading to the increase of lung cancer risk, assuming people spend approximately 80% of their time indoors. Thus it is only applicable when water is piped inside, if water is collected at the spring, then part of the radon never enters the house, however it could provide a conservative upper estimate.

Result and discussion

^{222}Rn activity concentration

The ^{222}Rn activity concentrations in spring water at different areas are presented by season in Table 1 and Fig. 2. The ^{222}Rn activity concentration in the dry season ranged from 1640 ± 80^{-3} to $89{,}900 \pm 3550$ m^{-3}. The values recorded during the rainy season were significantly lower than in the dry season, where the ^{222}Rn activity concentration in spring water was 900 ± 40–$42{,}900 \pm 1700$ m^{-3}. These values are lower than the recommended international upper limit of 100 Bq L^{-1} (100,000 Bq m^{-3}) [20], so they can be considered safe to drink in regards to radon activity concentration, the influence of the mines, if any, is limited. The ^{222}Rn activity ratio between dry and rainy seasons was calculated to range from 1.5 to 2.7 with an average value of 1.9. This may be useful information for interpreting and comparing literature data in the area. There were significant differences in the yearly average of ^{222}Rn activity concentration in spring water in the different regions as well. The ^{222}Rn activity concentration ranged from 1270 ± 60 m^{-3} (Binh Duong—Cao Bang) located over sedimentary rocks to $66{,}400 \pm 2630$ m^{-3} (Muong Hum-Lao Cai) located over a Paleozolic magmatic rock formation, partially covered by limestone, clay and other sediments. The highest value in the Muong Hum-Lao Cai mine area could be related to the spring activity in the sampling site, where spring water passed through the Muong Hum-Lao Cai REE mine.

The ^{222}Rn activity concentration difference in spring water at different areas can be due to multiple causes, such as differences in aquifer geology [48, 49], regional tectonic and magmatic activities [35, 50–52] or physicochemical properties of water source [46, 53]. Also the nature of the mines in the area might be a factor, REE mines tend to be surface mines, more easily influenced by erosion and weathering than the uranium mines, which tend to be deep mines. Previous studies suggested that the ^{222}Rn activity concentration in the water source was controlled mainly by the concentration of its parent isotope ^{226}Ra [9, 10, 19, 54, 55]. The ^{226}Ra spatial distribution was an important factor [56]. However previous studies with sampling points located in the study area found no statistically significant differences between ^{226}Ra activity concentration in well water and soil

Table 1 The ^{222}Rn activity in spring water in the dry and rainy seasons

Names	Mines type	Value	Activity Concentration of ^{222}Rn (Bq m^{-3})		Dry/Rainy	Average(Bq m^{-3})
			Dry season	Rainy season		
Nam Xe -Lai Chau	REE mine	Range (SD)	3250 ± 140–3530 ± 130	1820 ± 90–1910 ± 90	1.8	2640 ± 120
		Average	3410 ± 140	1860 ± 90		
Dong Pao- Lai Chau	REE mine	Range (SD)	2320 ± 110–2980 ± 150	1720 ± 80–1950 ± 100	1.5	2250 ± 110
		Average	2670 ± 130	1830 ± 90		
Muong Hum—Lao Cai	REE mine	Range (SD)	88,900 ± 3650–91,100 ± 3190	40,900 ± 1510–45,100 ± 2080	2.1	66,400 ± 2630
		Average	89,900 ± 3550	42,900 ± 1700		
Yen Phu—Yen Bai	REE mine	Range (SD)	28,300 ± 1100–33,300 ± 1570	10,300 ± 520–12,100 ± 470	2.7	20,700 ± 890
		Average	30,200 ± 1280	11,200 ± 500		
Ta Xua -Son La	U mine	Range (SD)	2810 ± 130–3190 ± 160	1530 ± 80–1960 ± 80	1.7	2370 ± 110
		Average	2960 ± 150	1780 ± 80		
Dong Cuu—Phu Tho	U mine	Range (SD)	11,300 ± 570–12,300 ± 480	6890 ± 310–7720 ± 320	1.5	9600 ± 430
		Average	11,200 ± 520	7350 ± 330		
Binh Duong—Cao Bang	U mine	Range (SD)	1580 ± 70–1710 ± 90	850 ± 30–950 ± 40	1.8	1270 ± 60
		Average	1640 ± 80	900 ± 40		
Overall range		Minimum	1640 ± 80	900 ± 40	1.5	1270 ± 60
		Maximum	89,900 ± 3550	42,900 ± 1700	2.7	66,400 ± 2630
		Average	20,400 ± 800	9700 ± 400	1.9	15,000 ± 620

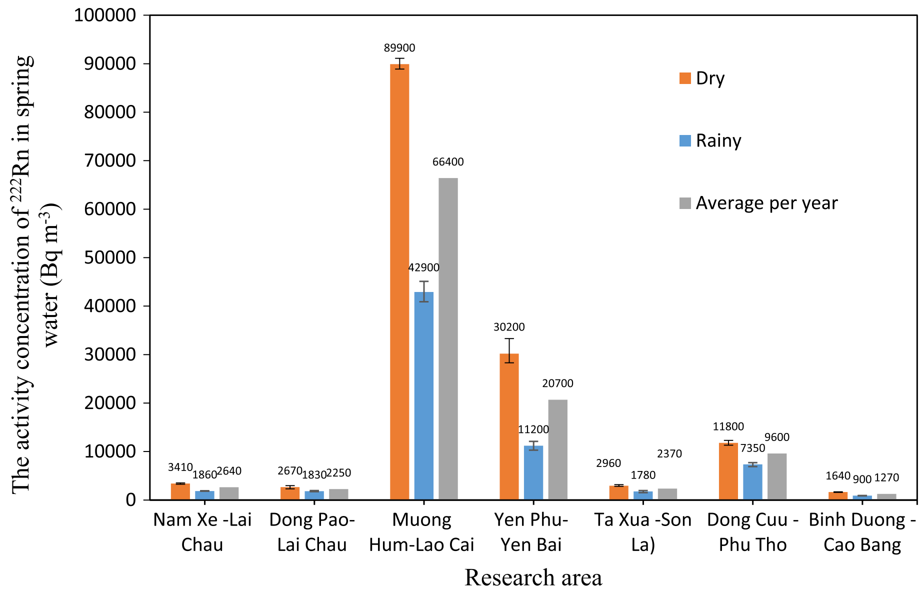


Fig. 2 Distribution of ^{222}Rn activity concentration in spring water in the dry and rainy seasons in the studied areas

samples [25, 26]. On the other hand, the ^{222}Rn concentration in the aquifers or surface water was reported to depend on mainly the leaching and dissolution from the host formation in multiple sources [18, 44, 57]. The presence of ^{222}Rn may be related to physicochemical properties of water source, or tectonic activity. This research gap needs to be further studied to accurately determine the origin and influencing factors on the distribution of ^{222}Rn activity concentration in spring water in the studied areas.

In all of the study areas, the average ^{222}Rn concentration in water was lower than the EU reference value of maximum 100 Bq L^{-1} (100,000 Bq m^{-3}) [58], and can be considered safe to drink in this regard. Previous research by Le Khanh (2015) showed that the ^{222}Rn concentration in the air was determined to be significantly higher than the world average at Nam Xe—Lai Chau mine (reaching 300 Bq L^{-1} or 300,000 Bq m^{-3}) [23]. The ^{222}Rn concentration determined in the air was directly influenced by mining activities leading to the dispersion of radon into the surrounding environment [23]. Since the ratio of ^{222}Rn in air and in water used for calculating the effects of radon in water is 10^{-4} according to Duggal et al. and UNSCEAR [43, 46], our results indicated that there is a limited influence of mining activities on the distribution and dispersion of ^{222}Rn through spring water in study area opposed to the significant influence it had at Nam Xe [23].

Seasonal variation of radon concentration in spring water

The variation of ^{222}Rn concentration in groundwater and surface water over time has been of interest to scientists for a long time [9, 54, 59]. The climate was identified as one of the most important factors affecting the ^{222}Rn concentration distribution in groundwater and surface water [46, 53]. Lower air temperature could significantly reduce water temperatures and increase the solubility of radon [60–62]. The solubility of a gas depends on temperature and could be expressed as C_g related to the pressure of the undissolved gas above the solution through the k proportionality constant, which relation could be distorted if a chemical reaction takes place [62]. The radon solubility in water decreases and it escapes rapidly at higher temperatures [63]. In addition, there was an inverse correlation observed between ^{222}Rn content in water source and precipitation (rainfall) [64, 65], likely caused by dilution due to heavy rainfall. The ^{222}Rn activity concentration in water was reported to increase in winter (dry season) and decrease in summer (rainy season) [9, 54, 59].

Seasonal ^{222}Rn activity concentration monitoring in this study showed that activity concentrations in spring water were comparatively high in the dry season and low in the rainy season. The climate in the North of Vietnam is characterized by a tropical monsoon climate with high temperature and rainfall in summer (rainy season) and low temperature and rainfall in winter (dry season). As it can be seen on Fig. 3, there was strong positive relationship between the ^{222}Rn concentration in spring water in the dry and rainy seasons (with a coefficient of determination $R^2 = 0.99$ and a Pearson correlation coefficient of $R = 0.99$, the data passes the Kolmogorov–Smirnov test of normality, and the strong correlation persist, with an $R = 0.86$ or greater, if we remove any or all of the high concentration values, the good correlation is not falsely caused by outliers, however it must be admitted that the dataset is limited to seven locations, with each dot representing the average value of 3 measurements per day on three consecutive days). This could potentially

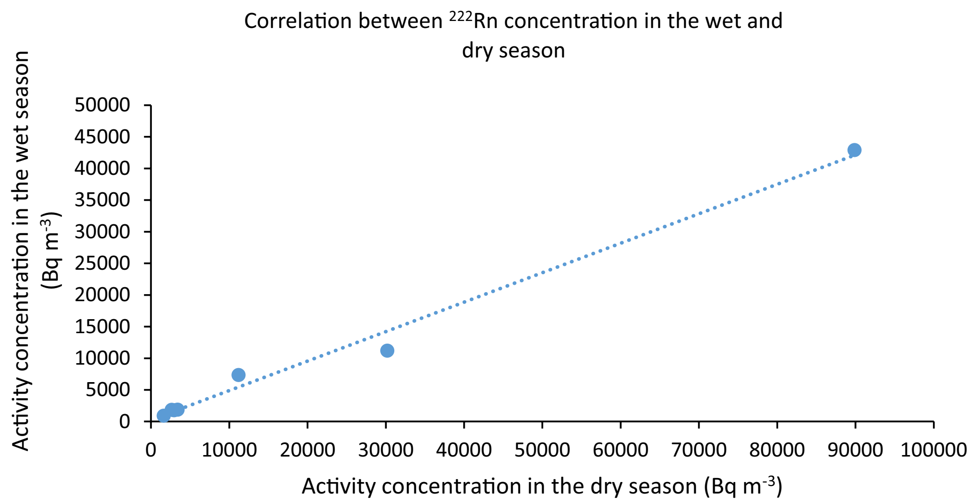


Fig. 3 Correlation between ^{222}Rn activity concentration in spring water in the dry and rainy seasons in the studied areas

make it easier to interpret and compare literature data, and plan monitoring campaigns.

The trend of seasonal ^{222}Rn content variation in spring water in this study seems to be consistent with the results of previous studies [9, 54, 59]. Changes in aquifers can lead to disruption of recharge sources, which might cause corresponding changes in ^{222}Rn activity concentration fluctuations. Geological structures play an important role in radon transport [18]. Tectonic activities can lead to changes in aquifer properties such as porosity and permeability. These properties are among the factors influencing ^{222}Rn migration and dispersal capacity and the recharge rate of water sources [66–68]. Therefore, the application of ^{222}Rn activity concentration monitoring could become a tool for not only radiation hazard studies, but can also be incorporated to analyses and prediction of the recharge rate of water sources, monitoring climate change and geological hazards, in order to solve the environmental issues present in these study areas.

Assessment of the AED

The AED for ^{222}Rn in this study was determined by Formulas 1 and 2 and presented in Table 2 and Table 3.

People who consume water sources containing ^{222}Rn will get internal exposure, which can be estimated by the annual effective dose. Overall, the average AED for adults, children and infants can be considered acceptable, with values ranging from 3.2 to 167.5 and 37.9 μSv y^{-1} on average for adults; from 2.5 to 129.4 and 29.3 μSv y^{-1} on average for children and from 6.7 to 351.4 and 79.6 μSv y^{-1} on average for infants. Despite consuming less water, infants were found to have significantly higher AED than adults, due to the higher dose conversion coefficient. This difference was attributed to a more vigorous metabolism and lower organ mass compared with adults [43, 46]. This value could be an overestimation, since infants generally should not receive untreated water, and boiling the water would reduce the radon concentration in water.

Table 2 AED contributed by ingesting ^{222}Rn from spring water for adults, children and infants

Location	Mine type	AED at dry season (μSv y^{-1})			AED at rainy season (μSv y^{-1})			AED average (μSv y^{-1})		
		Adult	Children	Infant	Adult	Children	Infant	Adult	Children	Infant
NX-LC	REE mine	8.6	6.6	18.0	4.7	3.6	9.8	6.6	5.1	13.9
ĐP-LC	REE mine	6.7	5.2	14.1	4.6	3.6	9.7	5.7	4.4	11.9
MH-LC	REE mine	226.8	175.3	475.8	108.2	83.6	227.0	167.5	129.4	351.4
YP-YB	REE mine	76.2	58.9	159.8	28.3	21.8	59.3	52.2	40.4	109.6
TX-SL	U mine	7.5	5.8	15.7	4.5	3.5	9.4	6.0	4.6	12.5
DC-PT	U mine	29.9	23.1	62.7	18.5	14.3	38.9	24.2	18.7	50.8
BĐ-CB	U mine	4.1	3.2	8.7	2.3	1.8	4.8	3.2	2.5	6.7
Min		4.1	3.2	8.7	2.3	1.8	4.8	3.2	2.5	6.7
Max		226.8	175.3	475.8	108.2	83.6	227.0	167.5	129.4	351.4
Average		51.4	39.7	107.8	24.4	18.9	51.3	37.9	29.3	79.6

Table 3 AED contributed by inhaling ^{222}Rn released from spring water

Location	Mine type	AED dry season (μSv y^{-1})	AED wet season (μSv y^{-1})	AED yearly average (μSv y^{-1})
NX-LC	REE mine	8.6	4.7	6.6
DP-LC	REE mine	6.7	4.6	5.7
MH-LC	REE mine	226.5	108.1	167.3
YP-YB	REE mine	76.1	28.2	52.2
TX-SL	U mine	7.5	4.5	6.0
DC-PT	U mine	28.2	18.5	23.4
BD-CB	U mine	4.1	2.3	3.2
Min		4.1	2.3	3.2
Max		226.5	108.1	167.3
Average		51.1	24.4	37.8

Table 3 shows that the expected excess AED from inhaling ^{222}Rn released from spring water is similar to that of ingestion for adults, however based on the actual conditions in the area, this is an overestimation, actual doses are expected to be less if water is not piped into houses. The arithmetical mean over the whole region is 37.8 μSv y^{-1}. The maximum 167.3 μSv y^{-1} was calculated for the Muong Hum-Lao Cai mine area.

Considering both pathways for radon exposure from spring water the natural sources and the mining activity combined results in radon activity concentrations in spring water that are considered acceptable by international guidelines.

Conclusions

The ^{222}Rn activity concentration in spring water samples close to seven REEs and uranium mines were investigated in North Vietnam. Based on given results, some conclusions were drawn as follows:

The various ^{222}Rn activity concentration levels dissolved in spring water sources were lower than the WHO and EU reference levels for drinking water. The yearly average ^{222}Rn activity concentration was recorded ranging from 1270 ± 60 Bq m^{-3} (Binh Duong—Cao Bang) to 66,400 ± 2630 Bq m^{-3} (Muong Hum—Lao Cai) with an average value of 15,030 ± 620 Bq m^{-3}. Spring water in the vicinity of two rare earth element mines and one uranium mine had radon levels much higher than typical for surface water, however it did not reach 100 Bq L^{-1} (100,000 Bq m^{-3}), so the risk is considered acceptable by most international recommendations, the spring waters are safe to drink in this regard.

The seasonal ^{222}Rn content variation in the spring water sources showed to be higher in the dry season (winter), approximately double, and lower in the rainy season (summer) with the average activity concentration values of 20,400 ± 800 Bq m^{-3} and 9700 ± 400 Bq m^{-3}, respectively. The good correlation might have implications for interpreting literature data and planning monitoring activities, however caution is advised against interpolating based on a limited dataset. The physicochemical factors affecting the ^{222}Rn activity concentrations and distribution in the studied spring water sources need to be further studied in detail.

The AED for local residents who consume the spring water resources is within the acceptable range, with mean values determined to be 37.9 μSv y^{-1} for adults, 29.3 μSv y^{-1} for children and 79.6 μSv y^{-1} for infants, respectively. The dose for infants is probably overestimated, due to boiling water reducing the actual radon concentration in the water intended for consumption. The AED increase from inhaling excess radon degassing from water is probably less than 37.8 μSv y^{-1} on average over the whole region, also within the acceptable range.

The concentration of other radionuclides, such as ^{238}U, ^{226}Ra, ^{228}Ra, ^{210}Pb and ^{210}Po should also be checked in water resources in the area to assure radiological safety. Based on our results, the effect of mining on the concentration ^{222}Rn in spring water in the area and the consequent probable health risk are relatively low, despite previous reports on mining significantly impacting ^{222}Rn activity concentrations in air.

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