Assessment of radiation dose hazards caused by radon and its progenies in tap water by the human dosimetric model

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ABSTRACT

Radon is readily soluble in water, and radon exposure caused by household water consumption may pose a threat to public health. In this study, the radon concentration in the tap water of residential buildings was measured, and the average value was 543.33 mBq L⁻¹, which was in line with the radon concentration limit recommended by USEPA (11.11 Bq L⁻¹) and EURATOM (100 Bq L⁻¹), and also within the range of the results of radon concentration measurements in tap water in other countries or regions. Through water bath heating at different temperatures, the radon retention curves of multiple groups of samples at different temperatures were fitted and analyzed. The results showed that the radon retention continued to decrease between 25 and 70 °C, remained stable between 70 and 85 °C, and then continued to decline slowly. Combined with the measurement results, the effective doses of α- and β-particles emitted by 222Rn and its progenies to residents respiratory and alimentary tissues and organs were calculated using the computational model provided by ICRP under two typical water scenarios of shower and drinking water, and the results show that radon exposure caused by normal water consumption will not pose a serious threat to public health.

Key words: human dosimetric model, radon concentration, radon retention rate, tap water

HIGHLIGHTS

- The radon concentration of domestic tap water in Urumqi, Xinjiang was measured.
- The variation trend of radon concentration in tap water with temperature was analyzed.
- The radiation dose contributed by radon exposure to residents under different water-use scenarios was calculated based on the actual water temperature.
- The radiation doses to human organs from the α and β decay progenies of radon were calculated.

1. INTRODUCTION

Radon, a colorless, odorless inert radioactive gas, has four radioactive isotopes (218Rn, 219Rn, 220Rn, and 222Rn) in nature. 222Rn has received extensive attention because its parent nucleus 226Ra is abundant in soil and rock and has the longest half-life (3.82 days) (ICRP 2007). The decay of 222Rn emits α-particles and produces a series of short-lived progenies such as 218Po, 214Pb, 214Bi, and 214Po (UNSCEAR 2000). Considering the soluble readily in water, 222Rn can easy to diffuse from solid materials into the water and be transported when various types of water resources in nature come into contact with soil and rocks (Zhuo et al. 2001; Yasouka et al. 2008; Jantsikene et al. 2014; Mehra et al. 2016).

Water is an important factor affecting public health (WHO 2009). The major source of domestic water for urban residents is tap water supplied through the urban water supply network. 222Rn dissolved in tap water can be transported to residential buildings far away from water supply plants in a short period through the pipe network, and then degassed from water to indoor environment in the process of domestic water use, or be ingested by residents along with drinking water or food (UNSCEAR 2000; Vinson et al. 2008). The 222Rn and progenies which enter the respiratory system of the human body through respiration cannot be completely filtered, in breathing, the inhaled 222Rn is almost exhaled again, but the progenies of decay can attach to air particles and have a certain probability in the respiratory tract tissue surface adhesion and
deposition (Vinson et al. 2008; Oner et al. 2009), α- or β-particles emitted by the decay of these short-lived progenies cause genetic damage to the cells on the surface of the deposited organ or tissue and can also penetrate the mucous membrane on the surface of the tissue or organ, causing damage to stem cells deep inside those tissues or organs (Zhuo et al. 2001; Kendall & Smith 2002; Darby et al. 2005; Alghami & Aleissa 2014). Meanwhile, some progenies are transferred to the body fluids through which they are transported to organs other than the respiratory organs, causing radiation damage to those organs. The ingestion of tap water with a higher $^{222}\text{Rn}$ concentration was also associated with an increased risk of visceral disease, especially the incidence of gastric cancer and gastrointestinal cancer. Besides causing radiation damage to surface cells in the lining of digestive organs, $^{222}\text{Rn}$ can also be absorbed by the gastrointestinal tract into body fluids and cause damage to other radiation-sensitive tissues or organs in the body. Therefore, the measurement and dose assessment of $^{222}\text{Rn}$ and its progenies in tap water are of great significance in preventing random biological effects and improving public health (Kulali et al. 2019).

Many previous studies have calculated the effective inhaled or ingested dose of radon exposure due to domestic water (Binesh et al. 2012; Nita et al. 2013; Sharma et al. 2019). Nevertheless, the dose calculation of α- and β-particles to specific organs and tissues in the respiratory tract and alimentary tract is rarely involved, and the effect of temperature on radon concentration in water was not considered. In the present study, $^{222}\text{Rn}$ concentrations in different tap water samples were measured, and the variation trend of $^{222}\text{Rn}$ concentrations in tap water at different temperatures was analyzed. Based on the measurement results, the effective doses of α- and β-particles to the public were estimated using the human respiratory and alimentary tract model the human digestive tract model provided by ICRP.

### 2. MATERIALS AND METHODS

#### 2.1. Sample collection and determination of radon concentration

Urumqi River is the water source of Urumqi City in Xinjiang. The water supply plants in the city carry out centralized filtration and purification treatment for the river water and then transport it to the residents. In the study, 400 mL glass sampling bottles were used to collect indoor tap water from six residential areas in Urumqi. After the collection, the samples were sealed and brought back to the laboratory for radon concentration measurement under a constant temperature environment. Meanwhile, the collected water samples were heated to 25, 40, 55, 70, 85, and 100 °C in a constant temperature water bath with the same water bath time, and the radon concentration in the samples was measured at different water bath temperatures. All the measurements are completed on the same day of sampling.

The concentration of radon in the sample was measured by FD216, an environmental radon measurement instrument based on the scintillation chamber method, and its principle and structure are shown in Figure 1. Detailed experimental methods and procedures are described in the previous work (Yong et al. 2020).

#### 2.2. Estimation of radon and its progenies in the air

The transfer coefficient of radon in tap water diffusing into the air is calculated as follows:

\[
C_a = f \cdot C_w
\]  

(1)

![Figure 1](http://iwaponline.com/jwh/article-pdf/doi/10.2166/wh.2021.113/957507/jwh2021113.pdf) | Structure and principle of FD216 environmental radon concentration measuring instrument.
where $C_a$ is the concentration of radon in indoor air produced by water (Bq m$^{-3}$), $f$ is the transfer factor, $C_w$ is the concentration of radon in tap water (Bq m$^{-3}$) (Nazaroff et al. 1987):

$$f = (W \cdot e)/(\lambda \cdot V)$$  

(2)

where $W$ is the per capita water consumption of residents (m$^3$ h$^{-1}$), $e$ is the release rate of radon from tap water into the air, with a value of 0.55, the ventilation rate of the dwelling $\lambda$ is 0.68 h$^{-1}$, and $V$ is the volume of the dwelling (m$^3$) (Nazaroff et al. 1987).

The concentration of partial short-lived progenies of $^{222}$Rn diffused into the air using Equations (3) and (4):

$$c_{j+1} = c_j$$  

(3)

$$d_j = \lambda_{j+1} / [\lambda_{j+1} + L + h_{j+1} \cdot q_a + (1 - h_{j+1}) \cdot q_u]$$  

(4)

where $j = 0, 1, 2, 3, 4$, $c_{j=0}$ is the concentration of $^{222}$Rn in air (Bq m$^{-3}$), and $c_j$ is the concentration of $^{222}$Rn’s $j$th progeny in air (Bq m$^{-3}$), $\lambda_{j+1}$ is the disintegration constant of the $j + 1$th progeny, $L$ is the ventilation rate of the dwelling (h$^{-1}$), $h_{j+1}$ is the ratio of the concentration of the attached $j + 1$th progeny on aerosols to the total concentration of the attached and unattached radon progenies, $h_1 = 0.9$ and $h_2 = h_3 = h_4 = 1$, $q_a$ and $q_u$ are the deposition rates of the attached and unattached progenies, $q_a = 7.5 \times 10^{-5}$ (s$^{-1}$), and $q_u = 8.33 \times 10^{-3}$ (s$^{-1}$) (Planinić et al. 1997; Misdaq et al. 2012).

2.3. Estimation of the committed effective dose of radon and its progenies

According to the human respiratory tract model and the partial human alimentary tract model provided by ICRP Publication (ICRP 2015), as shown in Figure 2.

Compartment ET$_1$: retention of material deposited in the anterior nose (region ET$_1$); compartment ET$_{seq}$: long-term retention in airway tissue of a small fraction of particles deposited in the nasal passages (region ET$_2$); compartment ET$'_2$: short-term retention of the material deposited in the posterior nasal passage, larynx, and pharynx (ET$_2$ region); compartment BB$'$: retention of particles in the bronchial (region BB), with particle transport to ET$'_2$; compartment bb$'$: retention of particles in the bronchiole (region bb), with particle transport to BB$'$; compartment BB$\text{seq}$: long-term retention in airway walls of a small fraction of the particles deposited in the bronchiole (region bb); compartment bb$\text{seq}$: long-term retention in airway walls of a small fraction of the particles deposited in the bronchiole (region bb); compartment ALV: retention of particles deposited in the alveoli. INT: long-term retention of the particles deposited in the alveoli that penetrate to the interstitium: the particles are removed slowly to the lymph nodes (ICRP 2015).

**Figure 2** | Compartment model representing time-dependent particle transport from each region. The transport rates shown alongside arrows are reference values in units of d$^{-1}$, the combined model of the human respiratory tract and alimentary tract refers to ICRP Publication 130 (ICRP 2015).
The rate of change of the jth decay progeny of 222Rn in the ith compartment of the respiratory tract is given by the following equation:

$$\frac{dA_i^j(t)}{dt} = \frac{F_d(t)}{I(j)} \cdot I(j) + \sum \lambda_{n,i} \cdot A_i^j(t) - \left( \sum \lambda_{n,i} + \lambda_i \right) \cdot A_i^j(t) \quad (5)$$

where $A_i^j(t)$ is the radioactive activity of the jth decay progeny of 222Rn in the ith compartment of the respiratory tract, $F_d(t)$ is the fractional deposition in the compartment i of the respiratory tract of different members of the public, $I(j) = B \cdot A_C(j)$. B is the average breathing rate for different members of the public (m$^3$h$^{-1}$). $A_C(j)$ is the radioactive activity of the jth decay progeny (Bq m$^{-3}$). $\lambda_{n,i} = m_{n,i}$, where $m_{n,i}$ is the clearance rate from regions n to i due to particle transport. $\lambda_{i,n} = m_{i,n} + f_r \cdot S_r + (1 - f_r) \cdot S_t$, where $m_{i,n}$ is the clearance rate from regions i to n due to particle transport, $f_r$ is the fraction dissolved into the blood relatively rapidly, at a rate $S_r$ (d$^{-1}$), $(1 - f_r)$ is the fraction dissolved into the blood relatively slowly, at a rate $S_t$ (d$^{-1}$). Except for the anterior nasal passage (ET1), the deposit from other regions of the respiratory tract is absorbed into the blood at a certain rate, and the dissolution rates of different radon progenies are different, in the process of 214Pb dissolving into the blood, a certain proportion of particles will first transform into `bound' state. $\lambda_i$ is the radioactive constant of the jth decay progeny of 222Rn (ICRP 2002a, 2015; Misdag & Flata 2003).

The rate of change of the jth decay progeny of 222Rn in the ith compartment of the alimentary tract is given by the following equation:

$$\frac{dA_i^j(t)}{dt} = \sum m_{n,i} \cdot A_i^j(t) - \left( \sum \lambda_{n,i} + \lambda_i \right) \cdot A_i^j(t) \quad (6)$$

where $\lambda_{n,i} = m_{i,n} + \lambda_{i,b}$, $m_{i,n}$ is the transport rate from regions i to n, and $\lambda_{i,b}$ is the rate of blood absorption in organ or tissue i, for material cleared from the respiratory tract to the alimentary tract, the fractional absorption in the alimentary tract is the product of $f_r$ and $f_A$, where $f_A$ is the fractional absorption in the alimentary tract for relatively soluble forms of the element (ICRP 2015).

Then the committed equivalent doses of the jth decay progeny of 222Rn in the target region T are given by the following equations:

$$H_T(j)(\tau) = \frac{\int_0^{\tau} \dot{H}_T(j)(t) dt(t)}{0} \quad (7)$$

$$\dot{H}_T(j)(t) = k \cdot A_i^j(t) \cdot wR \cdot Y_i \cdot E_j \cdot SAF \quad (8)$$

where $\dot{H}_T(j)(t)$ is the equivalent dose rate of the jth decay progeny of 222Rn, $A_i^j(t)$ is the radioactive activity of the jth decay progeny of 222Rn in the target region T of the respiratory tract (Bq), $w_R$ is the radiation-weighting factor, $\alpha$-particle is 20, $\beta$-particle is 1. $k = 1.6 \times 10^{-13}$ (J MeV$^{-1}$) is the joule to electron volt conversion factor, $Y_i$ is the yield of the jth decay progeny of 222Rn (Bq s$^{-1}$), $E_j$ is the energy of the jth decay progeny of 222Rn (MeV), SAF is the specific absorbed fraction (kg$^{-1}$), $\tau$ is the exposure time of the target region T (ICRP 2016).

Equations (9) and (10) are used to calculate the committed equivalent dose of the extrathoracic region and the thoracic region, respectively. Equation (11) is used to calculate the committed equivalent dose of the colon region:

$$H_{ET}(j)(\tau) = H_{ET1}(j)(\tau) \cdot A_{ET1} + H_{ET2}(j)(\tau) \cdot A_{ET2} + H_{EN}(j)(\tau) \cdot A_{EN} \quad (9)$$

$$H_{TH1}(j)(\tau) = H_{BB}(j)(\tau) \cdot A_{BB} + H_{bb}(j)(\tau) \cdot A_{bb} + H_{AI}(j)(\tau) \cdot A_{AI} + H_{LN}(j)(\tau) \cdot A_{LN} \quad (10)$$

$$H_{col}(j)(\tau) = H_{RC}(j)(\tau) \cdot A_{RC} + H_{LC}(j)(\tau) \cdot A_{LC} + H_{RS}(j)(\tau) \cdot A_{RS} \quad (11)$$

where $H_{ET1}(j)(\tau)$ is the committed equivalent dose of the jth decay progeny of 222Rn in the ET1 region, $A_{ET1}$ represents the ET1 region’s estimated radiosensitivity relative to that of the whole organ, $A_{ET2} = A_{EN} = 0.001$, $A_{ET1} = 0.998$, $A_{BB} = A_{bb} = A_{AI} = 0.333$, $A_{LN} = 0.001$, $A_{RC} = A_{LC} = 0.4$, and $A_{RS} = 0.2$ (ICRP 1994, 2002a).
The committed effective dose of the \( j \)th decay progeny of \(^{222}\text{Rn} \) is given by the following equation:

\[
E(j)(\tau) = \sum_T \omega_T \cdot H_T(j)(\tau)
\]  

(12)

where the tissue-weighting factor \( \omega_T \) for \( H_{ET}(j)(\tau) \) is 0.025, the tissue-weighting factor \( \omega_T \) for \( H_{HT}(j)(\tau) \) is 0.12, for organs of the alimentary tract other than the esophagus, the tissue-weighting factor \( \omega_T \) is 0.12, while the tissue-weighting factor of the esophagus is 0.04 (ICRP 2002a).

According to the gastrointestinal system provided by ICRP Publication (ICRP 1979), as shown in Figure 3, the whole gastrointestinal system comprises five regions: stomach, small intestine, upper large intestine, lower large intestine, and blood.

The rate of change of \(^{222}\text{Rn} \) in the \( i \)th compartment of the alimentary tract is given by the following equation:

\[
dA_i^{(222\text{Rn})}/dt = \sum_n m_{n,i} \cdot A_n^{(222\text{Rn})} - \left( \sum_n \lambda_{i,n} + \lambda_{i,b} \right) \cdot A_i^{(222\text{Rn})}
\]  

(13)

where \( A_i^{(222\text{Rn})} \) is the activity of \(^{222}\text{Rn} \) in the \( i \)th compartment of the alimentary tract, \( m_{n,i} \) is the transport rate from regions \( n \) to \( i \), \( \lambda_{i,n} = m_{i,n} + \lambda_{i,b} \), \( m_{n,i} \) is the transport rate from regions \( i \) to \( n \) and \( \lambda_{i,b} \) is the rate of blood absorption in the organ or tissue \( i \), and \( \lambda \) is the radioactive constant of the \(^{222}\text{Rn} \) (ICRP 2015).

The committed equivalent doses of \(^{222}\text{Rn} \) in the tissue \( T \) of the alimentary tract are given by the following equations:

\[
H_T^{(222\text{Rn})}(\tau) = \int_0^\tau H_T^{(222\text{Rn})}(t)dt
\]  

(14)

\[
H_T^{(222\text{Rn})}(\tau) = 0.01 \cdot A_T^{(222\text{Rn})}(\tau) \cdot \omega_R \cdot k \cdot K_j \cdot S_j \cdot R_j / m_T
\]  

(15)

where \( H_T^{(222\text{Rn})}(\tau) \) is the equivalent dose rate of \(^{222}\text{Rn} \), 0.01 is assuming that only 1% of the contents of \( \alpha \)-particle will cause a dose to any of the walls of the gastrointestinal tract, \( A_T^{(222\text{Rn})}(\tau) \) is the radioactive activity of \(^{222}\text{Rn} \) in the tissue \( T \) of the respiratory tract (Bq), \( \omega_R \) is the radiation-weighting factor, \( k = 1.6 \times 10^{-13} \text{J MeV}^{-1} \) is the electron volt to joule conversion factor, \( K_j \) is the branching ratio for \(^{222}\text{Rn} \) disintegration, \( S_j \) is the stopping power of the tissue \( T \) for the \( \alpha \)-particles emitted by \(^{222}\text{Rn} \) (MeV cm\(^2\) g\(^{-1}\)), \( R_j \) is the range of the \( \alpha \)-particles emitted by \(^{222}\text{Rn} \) in the tissue of the target organ (g cm\(^{-2}\)), \( m_T \) is the mass of tissue \( T \) (kg), and \( \tau \) is the exposure time of the tissue \( T \) (ICRP 2002b).

\[ \text{Figure 3} \] Structure of the gastrointestinal system. The model refers to ICRP Publication 30 (ICRP 1979).
The committed effective dose of the $j$th decay progeny of $^{222}$Rn is given by the following equation:

$$ E(^{222}Rn)(\tau) = \sum_T w_T \cdot H_T(^{222}Rn)(\tau) $$

(16)

3. RESULT AND DISCUSSIONS

3.1. Radon concentration in residential tap water

The radon concentrations of tap water in residential buildings at different temperatures are shown in Table 1. The radon concentration of residential tap water ranges from 280 to 750 mBq L$^{-1}$, with an average value of 548.16 mBq L$^{-1}$, among them, the radon concentration of tap water sample L5 is the highest, and that of L6 is the lowest, which is 738 $\pm$ 20.2 and 288 $\pm$ 7.6 mBq L$^{-1}$, respectively. Radon concentrations in all tap water samples were consistent with the USEPA’s maximum contaminant level of 11.11 Bq L$^{-1}$ and the drinking water radon parameter (100 Bq L$^{-1}$) set by the EURATOM Drinking-Water Directive (USEPA 1999; Council Directive 2013/51/Euratom 2013). Radon concentrations in tap water in some countries and regions are shown in Table 2, and it is obvious that the measurement results of this study are within the range of those measured in these countries and regions (Sarrou & Pashalidis 2003; Marques et al. 2004; Rusconi et al. 2004; Pagava et al. 2008; Nita et al. 2013; Ahmad et al. 2015; Erdogan et al. 2015; Fakhri et al. 2015; Le et al. 2015).

3.2. Variation of radon concentration in tap water at different temperatures

In this study, tap water samples from different residential buildings will be gradually heated to 25, 40, 55, 70, 85, and 100 °C by water bath heating. Radon concentrations at different temperatures are shown in Table 3. The radon concentration in the

| Sample code | Temperature (°C) | Radon concentration (mBq L$^{-1}$) |
|-------------|------------------|-----------------------------------|
| L1          | 24.5             | 376 $\pm$ 23.6                    |
| L2          | 24.3             | 456 $\pm$ 15.0                    |
| L3          | 24.8             | 720 $\pm$ 85.4                    |
| L4          | 24.0             | 710 $\pm$ 17.3                    |
| L5          | 24.4             | 738 $\pm$ 20.2                    |
| L6          | 24.1             | 288 $\pm$ 7.6                     |
| Average     |                  | 548.16                            |

| Location                | Radon concentration (mBq L$^{-1}$) | References            |
|-------------------------|-----------------------------------|-----------------------|
| Konya, Turkey           | 870–18,340                        | Erdogan et al. (2015) |
| Minab, Iran             | 200–1,710                         | Fakhri et al. (2015)  |
| Ho Chi Minh, Vietnam    | 30–205                            | Le et al. (2015)      |
| Sungai Petani, Kedah, Malaysia | 2,390–8,010               | Ahmad et al. (2015)   |
| Cyprus                  | 100–2,000                         | Sarrou & Pashalidis (2003) |
| Brazil                  | 340–510                           | Marques et al. (2004) |
| Transylvania, Romania   | 1,200–4,500                       | Nita et al. (2013)    |
| Milano, Italy           | 390–690                           | Rusconi et al. (2004) |
| Tbilisi, Georgia        | 3,000–5,000                       | Pagava et al. (2008)  |
| Urumqi, China           | 280–750                           | Present study         |
six groups of tap water samples showed an obvious downward trend on the whole with the increase of the water bath temperature. The average radon concentration at 25 °C was 543.33 mBq L⁻¹, and it decreased to 116.11 mBq L⁻¹ at 100 °C. The variation of the radon retention rate (radon concentration at a certain water bath temperature/initial radon concentration × 100%) in tap water at different water bath temperatures is shown in Figure 4, radon retention decreases with the gradual increase of temperature too, when the temperature reaches 100 °C, the average radon retention rate in the sample group is only 21.99%. The results indicate that heating tap water can effectively reduce the concentration of radon in water and reduce the harm of radon intake to public health.

Despite there were two different trends, the concentration of radon in the samples decreased after water bath heating. Due to the low initial radon concentration (the average value is 368.89 mBq L⁻¹), the radon retention rates of samples L1, L2, and L6 decrease continuously from 40 to 70 °C and then change gently. However, the radon retention rate of samples L3, L4, and L5 (with an average radon concentration of 717.78 mBq L⁻¹) with a high initial radon concentration decreased rapidly.
between 25 and 40 °C, and then the change was flat. The radon concentration and retention rate of the six sample groups increased slightly from 70 to 85 °C. Statistical analysis showed that there was no significant difference in the radon concentration value and the radon retention rate between 70 and 85 °C (p < 0.05).

The radon retention rates of all samples at different temperatures were fitted by the method of locally weighted regression (LOESS), as shown in Figure 5. When the water bath heating temperature changes from 25 to 70 °C, with the increase in temperature, radon retention decreases continuously, dropping to only about 30%. With the increase of water bath temperature, radon retention decreases continuously, dropping to only about 30%.

![Figure 5](image)

**Figure 5**: (a) Fitting curve of the change of radon retention rate of tap water samples at different temperatures. (b) Boxplot of radon retention rates at different temperatures.

### Table 4

| Sample code | Decay progenies of 222Rn | Annual committed equivalent dose (µSv a⁻¹) |
|-------------|-------------------------|------------------------------------------|
|             | ET₁ | ET₂ | LN₆₇ | BB  | bb  | Al  | LNT₂ |
| L1          | 218Po | 125.65 | 1.21 | 1.84 × 10⁻⁸ | 0.26 | 2.19 | 9.86 × 10⁻⁸ | 0.83 × 10⁻⁸ |
|             | 214Pb | 0.98 | 5.48 × 10⁻² | 2.53 × 10⁻⁴ | 3.59 × 10⁻³ | 1.94 × 10⁻³ | 5.88 × 10⁻⁴ | 2.63 × 10⁻⁵ |
|             | 214Bi | 0.48 | 2.34 × 10⁻² | 6.88 × 10⁻⁴ | 2.14 × 10⁻³ | 1.34 × 10⁻³ | 7.77 × 10⁻⁴ | 1.08 × 10⁻⁴ |
|             | 214Po | 2.68 × 10⁻⁴ | 2.51 × 10⁻⁶ | 1.13 × 10⁻²⁰ | 7.19 × 10⁻⁷ | 1.02 × 10⁻⁶ | 5.61 × 10⁻⁸ | 5.14 × 10⁻⁷ |
| L2          | 218Po | 160.56 | 1.55 | 2.35 × 10⁻⁸ | 0.34 | 2.80 | 1.26 × 10⁻¹ | 1.06 × 10⁻⁸ |
|             | 214Pb | 1.25 | 7.01 × 10⁻² | 3.23 × 10⁻⁴ | 4.59 × 10⁻³ | 2.48 × 10⁻³ | 7.51 × 10⁻⁴ | 3.36 × 10⁻⁵ |
|             | 214Bi | 0.61 | 2.99 × 10⁻² | 8.79 × 10⁻⁴ | 2.73 × 10⁻³ | 1.72 × 10⁻³ | 9.93 × 10⁻⁴ | 1.38 × 10⁻⁴ |
|             | 214Po | 3.42 × 10⁻⁴ | 3.21 × 10⁻⁶ | 1.45 × 10⁻²⁰ | 9.19 × 10⁻⁷ | 1.31 × 10⁻⁶ | 7.17 × 10⁻⁸ | 6.57 × 10⁻⁷ |
| L3          | 218Po | 157.87 | 1.53 | 2.02 × 10⁻⁸ | 0.29 | 2.41 | 1.08 × 10⁻¹ | 0.91 × 10⁻⁸ |
|             | 214Pb | 1.08 | 6.02 × 10⁻² | 2.78 × 10⁻⁴ | 3.94 × 10⁻³ | 2.13 × 10⁻³ | 6.45 × 10⁻⁴ | 2.89 × 10⁻⁵ |
|             | 214Bi | 0.52 | 2.57 × 10⁻² | 7.54 × 10⁻⁴ | 2.35 × 10⁻³ | 1.47 × 10⁻³ | 8.52 × 10⁻⁴ | 1.18 × 10⁻⁴ |
|             | 214Po | 2.94 × 10⁻⁴ | 2.76 × 10⁻⁶ | 1.24 × 10⁻²⁰ | 7.89 × 10⁻⁷ | 1.12 × 10⁻⁶ | 6.16 × 10⁻⁸ | 5.64 × 10⁻⁷ |
| L4          | 218Po | 150.09 | 1.45 | 2.20 × 10⁻⁸ | 0.32 | 2.62 | 1.17 × 10⁻¹ | 0.99 × 10⁻⁸ |
|             | 214Pb | 1.17 | 6.55 × 10⁻² | 3.02 × 10⁻⁴ | 4.29 × 10⁻³ | 2.32 × 10⁻³ | 7.02 × 10⁻⁴ | 3.14 × 10⁻⁵ |
|             | 214Bi | 0.57 | 2.80 × 10⁻² | 8.21 × 10⁻⁴ | 2.55 × 10⁻³ | 1.61 × 10⁻³ | 9.28 × 10⁻⁴ | 1.29 × 10⁻⁴ |
|             | 214Po | 5.20 × 10⁻⁴ | 3.00 × 10⁻⁶ | 1.35 × 10⁻²⁰ | 8.59 × 10⁻⁷ | 1.22 × 10⁻⁶ | 6.71 × 10⁻⁸ | 6.14 × 10⁻⁷ |
| L5          | 218Po | 123.91 | 1.19 | 1.81 × 10⁻⁸ | 0.26 | 2.16 | 0.97 × 10⁻¹ | 0.82 × 10⁻⁸ |
|             | 214Pb | 0.97 | 5.41 × 10⁻² | 2.49 × 10⁻⁴ | 3.54 × 10⁻³ | 1.91 × 10⁻³ | 5.80 × 10⁻⁴ | 2.60 × 10⁻⁵ |
|             | 214Bi | 0.47 | 2.31 × 10⁻² | 6.78 × 10⁻⁴ | 2.11 × 10⁻³ | 1.32 × 10⁻³ | 7.66 × 10⁻⁴ | 1.06 × 10⁻⁴ |
|             | 214Po | 2.64 × 10⁻⁴ | 2.48 × 10⁻⁶ | 1.12 × 10⁻²⁰ | 7.09 × 10⁻⁷ | 1.01 × 10⁻⁶ | 5.53 × 10⁻⁸ | 5.07 × 10⁻⁷ |
| L6          | 218Po | 99.47 | 0.96 | 1.46 × 10⁻⁸ | 0.21 | 1.73 | 0.78 × 10⁻¹ | 0.66 × 10⁻⁸ |
|             | 214Pb | 0.78 | 4.34 × 10⁻² | 2.01 × 10⁻⁴ | 2.84 × 10⁻³ | 1.53 × 10⁻³ | 4.65 × 10⁻⁴ | 2.08 × 10⁻⁵ |
|             | 214Bi | 0.38 | 1.85 × 10⁻² | 5.44 × 10⁻⁴ | 1.69 × 10⁻³ | 1.06 × 10⁻³ | 6.15 × 10⁻⁴ | 0.85 × 10⁻⁴ |
|             | 214Po | 2.12 × 10⁻⁴ | 1.99 × 10⁻⁶ | 0.89 × 10⁻²⁰ | 5.69 × 10⁻⁷ | 0.81 × 10⁻⁶ | 4.44 × 10⁻⁸ | 4.07 × 10⁻⁷ |
temperature, the declining trend of radon retention is gentle, and the fitting curve is flat between 70 and 85 °C, followed by a slow decline between 85 and 100 °C, which possibly because blisters appeared in the heated samples as the water bath temperature increased, accelerating radon degassing in the water.

3.3. Estimation of the committed equivalent and effective dose of residential tap water

The annual committed equivalent dose and effective dose of radon and its progenies in tap water to respiratory and alimentary tract organs or tissues were estimated.

According to the actual situation of resident residence, bathroom space is about 14 m³. Meanwhile, according to the actual water consumption habits of residents, the temperature of shower water is assumed to be 40 °C, 30 min of shower three times a week, the water consumption is about 0.36 m³ h⁻¹, and the decay progenies of radon released into the air during the shower are attached to the particles with an activity median aerodynamic diameter (AMAD) of 1 μm. The annual drinking water quantity of adult residents is 500 L, and the tap water will be boiled and cooled for drinking, ignoring the part of the indoor air radon dissolves into the tap water during cooling, the study assumes that all the radon concentrations taken in are the values at 100 °C and appear in the stomach (UNSCEAR 2000; ICRP 2002a).

The committed equivalent dose of inhalation of α decay short-lived progenies (²¹⁸Po and ²¹⁴Po) and β decay short-lived progenies (²¹⁴Pb and ²¹⁴Bi) to the respiratory tract and alimentary tract target tissues during a shower is shown in Tables 4-6. The committed equivalent dose contribution of α-particles to ET₁, ET₂, BB, bb, and AI in the respiratory tissue regions was higher than that of β-particles. The committed equivalent doses of β-particles to the target tissues of the respiratory tract are close to each other in order of magnitude, and the committed equivalent dose to LNₑₑₑₑ and LNₚₚₚₚ regions is higher than that of the α-particles. In the alimentary tract, the committed equivalent dose of ²¹⁴Pb to the target tissues of the esophagus was higher than that of ²¹⁴Bi, while that to other organs of the alimentary tract was lower than ²¹⁴Bi.

Due to different respiratory rates (0.54 m³ h⁻¹ for adult males and 0.39 m³ h⁻¹ for adult females) and SAF, the committed equivalent dose contribution of short-lived progenies to all tissue regions of the adult male respiratory tract (except region

### Table 5 | Annual committed equivalent dose due to inhalation of radon decay progenies ²¹⁸Po, ²¹⁴Pb, ²¹⁴Bi, and ²¹⁴Po during the bath to adult female respiratory tract target tissues

| Sample code | Decay progenies of ²²²Rn | ET₁ | ET₂ | LNₑₑₑₑ | BB | bb | AI | LNₚₚₚₚ |
|-------------|--------------------------|-----|-----|--------|----|----|----|--------|
| L1 ²¹⁸Po    | 80.83                    | 0.71| 1.86×10⁻⁸| 0.17  | 1.96| 7.49×10⁻²| 0.85×10⁻⁸|
| ²¹⁴Pb       | 0.82                     | 4.64×10⁻²| 4.55×10⁻⁵| 2.89×10⁻³| 1.61×10⁻³| 4.75×10⁻⁴| 1.16×10⁻⁴|
| ²¹⁴Bi       | 0.40                     | 1.96×10⁻⁵| 1.36×10⁻⁴| 1.71×10⁻³| 1.02×10⁻³| 6.30×10⁻⁴| 4.41×10⁻⁴|
| ²¹⁴Po       | 2.24×10⁻⁴                | 2.34×10⁻⁶| 1.14×10⁻¹₀| 5.54×10⁻⁷| 9.07×10⁻⁷| 4.27×10⁻⁸| 5.25×10⁻⁸|
| L2 ²¹⁸Po    | 103.14                   | 0.90| 2.38×10⁻⁸| 0.22  | 2.51| 9.58×10⁻²| 1.00×10⁻⁸|
| ²¹⁴Pb       | 1.05                     | 5.93×10⁻²| 5.82×10⁻⁵| 3.70×10⁻³| 2.06×10⁻³| 6.07×10⁻⁴| 1.48×10⁻⁴|
| ²¹⁴Bi       | 0.52                     | 2.51×10⁻⁵| 1.74×10⁻⁴| 2.19×10⁻³| 1.31×10⁻³| 8.05×10⁻⁴| 5.63×10⁻⁴|
| ²¹⁴Po       | 2.86×10⁻⁴                | 2.98×10⁻⁶| 1.46×10⁻²⁰| 7.08×10⁻⁷| 1.15×10⁻⁶| 5.45×10⁻⁸| 6.72×10⁻¹⁰|
| L3 ²¹⁸Po    | 88.57                    | 0.77| 2.04×10⁻⁸| 0.18  | 2.15| 8.22×10⁻²| 0.93×10⁻⁸|
| ²¹⁴Pb       | 0.90                     | 5.09×10⁻²| 4.99×10⁻⁵| 3.17×10⁻³| 1.76×10⁻³| 5.21×10⁻⁴| 1.27×10⁻⁴|
| ²¹⁴Bi       | 0.45                     | 2.16×10⁻²| 1.49×10⁻⁴| 1.88×10⁻³| 1.12×10⁻³| 6.91×10⁻⁴| 4.83×10⁻⁴|
| ²¹⁴Po       | 2.45×10⁻⁴                | 2.56×10⁻⁶| 1.25×10⁻²⁰| 6.07×10⁻⁷| 9.95×10⁻⁷| 4.68×10⁻⁸| 5.77×10⁻²¹|
| L4 ²¹⁸Po    | 96.42                    | 0.84| 2.22×10⁻⁸| 0.20  | 2.34| 8.95×10⁻²| 1.02×10⁻⁸|
| ²¹⁴Pb       | 0.98                     | 5.54×10⁻²| 5.45×10⁻⁵| 3.46×10⁻³| 1.92×10⁻³| 5.67×10⁻⁴| 1.38×10⁻⁴|
| ²¹⁴Bi       | 0.41                     | 2.35×10⁻²| 1.63×10⁻⁴| 2.04×10⁻³| 1.22×10⁻³| 7.53×10⁻⁴| 5.26×10⁻⁴|
| ²¹⁴Po       | 2.67×10⁻⁴                | 2.79×10⁻⁶| 1.36×10⁻³⁰| 6.61×10⁻⁷| 1.08×10⁻⁶| 5.10×10⁻⁸| 6.28×10⁻⁸|
| L5 ²¹⁸Po    | 79.60                    | 0.69| 1.83×10⁻⁸| 0.16  | 1.93| 7.39×10⁻²| 0.84×10⁻⁸|
| ²¹⁴Pb       | 0.81                     | 4.57×10⁻²| 4.50×10⁻⁵| 2.85×10⁻³| 1.59×10⁻³| 4.68×10⁻⁴| 1.14×10⁻⁴|
| ²¹⁴Bi       | 0.39                     | 1.94×10⁻²| 1.34×10⁻⁴| 1.69×10⁻³| 1.01×10⁻³| 6.21×10⁻⁴| 4.34×10⁻⁴|
| ²¹⁴Po       | 2.21×10⁻⁴                | 2.31×10⁻⁶| 1.13×10⁻³⁰| 5.46×10⁻⁷| 8.94×10⁻⁷| 4.21×10⁻⁸| 5.18×10⁻⁸|
| L6 ²¹⁸Po    | 63.91                    | 0.55| 1.47×10⁻⁸| 0.13  | 1.55| 5.93×10⁻²| 0.67×10⁻⁸|
| ²¹⁴Pb       | 0.65                     | 3.67×10⁻²| 3.61×10⁻⁵| 2.29×10⁻³| 1.27×10⁻³| 3.76×10⁻⁴| 0.92×10⁻⁴|
| ²¹⁴Bi       | 0.31                     | 1.55×10⁻²| 1.08×10⁻⁴| 1.35×10⁻³| 0.81×10⁻³| 4.99×10⁻⁴| 3.49×10⁻⁴|
| ²¹⁴Po       | 1.77×10⁻⁴                | 1.85×10⁻⁵| 0.91×10⁻²⁰| 4.38×10⁻⁷| 7.18×10⁻⁷| 3.38×10⁻⁸| 4.16×10⁻²¹|
The average annual cumulative effective dose of the respiratory tract and digestive tract in males was 0.125 and 6.97 × 10^{-4} μSv a^{-1}, respectively, and that of females was 0.104 and 5.43 × 10^{-4} μSv a^{-1}. The average total annual committed effective dose was 0.126 μSv a^{-1} for adult male and 0.105 μSv a^{-1} for an adult female (as shown in Table 7), the annual committed effective dose due to inhalation of radon decay progenies (218Po, 214Pb, 214Bi, and 214Po) during the bath.
effective contribution of sample group L2 to residents was the highest, and that of adult male and an adult female was 0.152 and 0.127 μSv a⁻¹, respectively, and the annual committed effective dose of sample group L6 was the lowest, 0.094 and 0.078 μSv a⁻¹, respectively, which were all lower than the upper reference value of about 10 mSv a⁻¹ set by ICRP (ICRP 2014).

Table 8 shows the annual committed effective dose and annual committed equivalent dose caused by ²²²Rn in tap water entering the residents’ gastrointestinal tract. The annual committed effective dose of sample group L3 is the highest, and that of sample group L6 is the lowest, which is 0.2722 and 0.0514 μSv a⁻¹, respectively. Among all the regions of the gastrointestinal tract, the lower large intestine region had the highest average annual committed equivalent dose (1.4606 μSv a⁻¹), followed by the upper large intestine region (1.1502 μSv a⁻¹), and the small intestine region was the lowest (0.1438 μSv a⁻¹).

4. CONCLUSION

In this study, the radon concentration in the tap water of six residential areas was measured, and the average radon concentration was 548.16 mBq L⁻¹. All samples were under the radon concentration limits recommended by USEPA and EURATOM (11.11 Bq L⁻¹ and 100 Bq L⁻¹). Compared with the radon concentration in the tap water of other countries or regions, the radon concentration in this study is within the range of other measurement results. At the same time, the radon concentration and the retention rate under different temperatures were obtained by heating tap water in the water bath, and the radon concentration generally showed a downward trend with the increase in temperature. Finally, the dose calculation model provided by ICRP was used to estimate the dose of radon exposure in some water-use scenarios. In the process of the shower, the annual committed effective dose of radon progenies to the male respiratory tract and the alimentary tract is higher than that of female, and in the respiratory tract, the committed equivalent dose caused by α activities to the respiratory tract target tissue is higher than that of β activities, while the average annual committed effective dose of radon from drinking water ingestion to the resident gastrointestinal tract is 0.1789 μSv a⁻¹. Urban water supply plants, therefore, can reduce the concentration of radon in the water source by centralized aeration, while residents can reduce the concentration of radon in the water by heating and degassing to avoid further increase of public exposure to radon.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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