Estimation of the annual effective doses from direct ingestion of $^{226}\text{Ra}$ and $^{228}\text{Ra}$ in the Disi groundwater for different age groups

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Abstract. The total annual effective doses (TAED) from ingestion of naturally occurring radionuclides (NOR) in Disi groundwater for infants, children, and adults have been calculated. The ranges of the estimated annual effective dose reported in this study from direct ingestion of radium ($^{226}\text{Ra}$ and $^{228}\text{Ra}$) were found to be from 0.085±0.021 to 0.532±0.205 mSv y$^{-1}$, with a mean value of 0.322 ± 0.095 mSv y$^{-1}$ for infants, from 0.144±0.011 to 0.828±0.203 mSv y$^{-1}$, with a mean value of 0.519 ± 0.102 mSv y$^{-1}$ for children and from 0.087±0.024 to 0.383±0.130 mSv y$^{-1}$, with a mean value of 0.252 ± 0.067 mSv y$^{-1}$ for adults. The present results of this study were compared with the minimum recommended limits (MRL) reported by the World Health Organization (WHO, 2008) and the International Commission on Radiological Protection (ICRP, 2000), and the previously published data in different countries. The mean annual effective dose from direct consumption of Disi groundwater for infants and adults found to be about three times higher than the MRL of 0.1 mSv/y suggested by WHO, 2008. The average TAED for children found to be five times higher than that recommended limits by WHO, 2008.

Keywords: Total annual effective dose; Direct ingestion of $^{226}\text{Ra}$ and $^{228}\text{Ra}$ in the groundwater; Disi groundwater; Age groups; Radiological quality of the drinking water;

1. Introduction

Natural background radiation originates from cosmic rays, terrestrial radiation, and internal radiation in the body (WHO, 2008 [1]; ICRP, 2000 [2]; WHO, 2000 [3]; UNSCEAR, 2000 [4] and IAEA, 2002 [5]). Naturally occurring radionuclides (NOR) are found in soil, phosphate (Al-Bedri et al., 2014 [6], Santawamaire et al., 2014 [7]), rocks (El-Gamal et al., 2019 [8]), food (Lauria, et al., 2012 [9]) and air (Haque and Ferdous 2017 [10]). Usually, drinking water and groundwater contains different types of NORs such as uranium and thorium series and their decay products (WHO, 2000 [3]; UNSCEAR, 2000 [4]; IAEA, 2002 [5]; Lauria, et al., 2012 [9]; Haque and Ferdous 2017 [10], Al-Bedri et al., 2020 [11] and Pintilie–Nicolov et al., 2021 [12]).

$^{226}\text{Ra}$ isotope in uranium-series ($^{238}\text{U}$) decay to produce radon-222 gas ($^{222}\text{Rn}$) with a short half-life of 3.82 day and emitting alpha particles with 4.87 MeV energy, while $^{226}\text{Ra}$ in thorium series ($^{232}\text{Th}$) decay to produce a radon-220 gas ($^{220}\text{Rn}$) with a short half-life of 56 second and emitting alpha particles with 5.789 MeV energy (WHO, 2008 [1]; UNSCEAR, 2000 [4]; IAEA, 2002 [5]). Generally, both $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are dissolved in groundwater [3] and may expose the internal organs and soft tissues in the body (Reisz et al., 2016 [13]) from the ingestion of
contaminated groundwater with NOR. Some of the radon gas ($^{220}$Rn and $^{222}$Rn) escape from the groundwater to the environmental air causing an increase in a dose to the lung and other organs in the body from the inhalation of contaminated air with radon gas.

The radiological quality of the drinking water is useful especially for the environmental studies for the health of the general public caused by internal radiation hazard from the NOR in groundwater WHO, 2008 [1]; ICRP, 2000 [2], and IAEA, 2002 [5]). The internal radiation hazard due to the alpha particles emitted from radium and radon isotopes may damage the deoxyribonucleic acid (DNA) and the living cells in the body, may lead to loss of cell functions, prevent or loss of cell division, or may produce late effects of radiation appear as cancer (WHO, 2008 [1]; UNSCEAR, 2000 [4]; IAEA, 2002 [5] and Reisz et al., 2016 [13]).

The activity of $^{226}$Ra and $^{228}$Ra were measured by Al-Bedri et al., 2020 [11] in nine different groundwater wells in Jordan, and were analyzed using hyper-pure germanium (HPGe) detector spectrometry system. The previous data of the activity of $^{226}$Ra and $^{228}$Ra [11] were found to agree with the MRL [1, 14].

The present work aims to calculate the TAED for different groups from the analysis of the combined ingestion of $^{226}$Ra and $^{228}$Ra activity in groundwater based on the data reported in table 1 by Al-Bedri, et al., 2020 paper [11].

In the present study, the ranges and mean values of the AED from direct ingestion of combined $^{226}$Ra and $^{228}$Ra activity in groundwater for different age groups have been calculated. Comparisons have been made between the present results and the MRL by WHO, 2008 [1], ICRP, 2000 [2] and European Union (EU), 1998 [14]). The estimated TAED of this study for different age groups were compared with previously published data from different countries such as (Brazil, 2004 [15]; China, 2019 [16]; Egypt, 2019 [17]; Finland, 2007 [18]; India, 2016 [19]; Jordan, 2009 [20, 21 ]; Nigeria, 2017 [22]; Palestine, 2012 [23]; Romania, 2021 [12], 2019 [24]; Saudi Arabia, 2016 [25]; Spain, 2004 [26]; Sweden, 2002 [27]; Thailand, 2018 [28]; UK, 1993 [29]; USA, 2006 [30] and Yemen, 2015 [31]).

2. Calculation of annual effective dose (AED)

WHO, 2008 [1] has estimated that the consumption of drinking water is an average of 2 liters per day for adults, giving an annual consumption of 730 liters per year. The AED from the consumption of drinking water for an adult is 0.1 mSv per year recommended by WHO, 2008 [1] and IAEA, 2002 [5]. The following formula reported by WHO, 2008 [1] have been used to calculate the AED from the ingestion of $^{226}$Ra and $^{228}$Ra in water samples as follows:

$$AED = D_f \times W_i \times A_c$$

Where $AED = TAED$ (mSv/y) to the public from the ingestion of NOR in the drinking water $D_f =$ effective dose conversion factor due to ingestion of NOR in drinking water (mSv/Bq) see Table 1 $W_i =$ annual water rate consumption of 730 L/y for adults ($\geq 17$ years), 330 L/y for children (1 to 10 y) and 150 L/y for infants ($< 1$ y), according to the WHO, 2000 [3], and UNSCEAR, 2000 [4] $A_c =$ the activity of NOR in drinking water samples (Bq/L).

The ingested dose conversion factors ($D_f$) for different age groups provided by ICRP, 1996 [32] from consumption of radium in drinking water are shown in table 1.

Table 1. The dose conversion factors ($D_f$) of $^{226}$Ra and $^{228}$Ra for different age groups reported by (ICRP, 1996 [32]).

| Age Groups  | $^{226}$Ra (mSv/Bq) | $^{228}$Ra (mSv/Bq) |
|-------------|---------------------|---------------------|
| Adults ($\geq 17$ y) | $2.8 \times 10^{-4}$ | $6.9 \times 10^{-4}$ |
| Children (1-10 y) | $8 \times 10^{-4}$ | $3.9 \times 10^{-3}$ |
| Infants ($< 1$ y) | $9.6 \times 10^{-4}$ | $5.7 \times 10^{-3}$ |
Usually, drinking water contains different types of radionuclides; therefore, the doses arising from each type of radionuclides must be added to each other to get the TAED.

ICRP, 2000 [2] recommended that the acceptable AED for the radioactive materials in drinking water is approximately 1 mSv per year, while the AED from the consumption of drinking water for an adult is 0.1 mSv per year recommended by WHO, 2008 [1] and IAEA, 2002 [5]. Below the MRL of 0.1 mSv per year as reported by WHO, 2008 [1] for the drinking water, the water is considered to be acceptable and safe for human consumption and it is not necessary to take any action to reduce the level of NOR in the drinking water (WHO-2008 [1]).

3. Results and discussion

The activity of $^{226}$Ra and $^{228}$Ra reported in table 1 of Al-Bedri et al., 2020 [11] paper were used in the present study for further analysis to calculate the AED for different age groups (see table 2).

### Table 2. The activity of radium in the groundwater based on data in table 1 of Al-Bedri et al., 2020, compared with the reference limits.

| Disi well number | Activity of radium ± SD (Bq/L) | $^{226}$Ra ± SD | $^{228}$Ra ± SD |
|------------------|---------------------------------|-----------------|-----------------|
| DW 28            | 0.606±0.090                    | 0.429±0.093     |
| DW 29            | 0.510±0.006                    | 0.401±0.104     |
| DW 31            | 0.557±0.041                    | 0.474±0.010     |
| DW 35            | 0.302±0.085                    | 0.300±0.017     |
| DW 40            | 0.370±0.102                    | 0.240±0.047     |
| DW 41            | 0.580±0.064                    | 0.525±0.138     |
| DW 42            | 0.723±0.207                    | 0.440±0.153     |
| DW 43            | 0.442±0.078                    | 0.307±0.020     |
| DW 46            | 0.540±0.024                    | 0.188±0.099     |
| Range ± SD       | 0.302±0.085                    | 0.474±0.010 to 0.525 ± 0.138 |
| Mean ± SD        | 0.723 ± 0.207                  | 0.287 ± 0.091   |

SD = Standard Deviation

WHO 2008 [1], recommended that the reference AED level of 0.1 mSv per year is equal to 10% of the AED limit for public recommended by ICRP, 2000 [2] and IAEA, 1996 [32]. Table 3 shows the calculated TAED for infants (< 1 y), children (1–10 y), and adults (≥ 17 y) from direct consumption of activity of $^{226}$Ra and $^{228}$Ra in groundwater in Jordan [11].

### Table 3. The calculated AED for different age groups compared with the international reference limits (WHO 2008 [1] and ICRP 2000 [2]).

| Disi well number | Annual effective dose ± SD (mSv/y) |
|------------------|-----------------------------------|
|                  | Infants               | Children            | Adults               |
| DW 28            | 0.453±0.195            | 0.712±0.143         |
| DW 29            | 0.415±0.152            | 0.650±0.106         | 0.306±0.056         |
| DW 31            | 0.119±0.062            | 0.205±0.056         | 0.138±0.084         |
| DW 35            | 0.085±0.052            | 0.144±0.011         | 0.087±0.024         |
| DW 40            | 0.258±0.081            | 0.406±0.145         | 0.196±0.054         |
| DW 41            | 0.532±0.205            | 0.828±0.203         | 0.383±0.130         |
In this study, the ranges of calculated TAED from directly consumption groundwater found to be from 0.085±0.021 to 0.532±0.205 mSv/y, with a mean value of 0.322±0.095 mSv/y for infants, from 0.144±0.011 to 0.828±0.203 mSv/y, with a mean value of 0.519±0.102 mSv/y for children, and from 0.087±0.024 to 0.383±0.130 mSv/y, with a mean value of 0.252±0.067 mSv/y for adults. The TAED from direct consumption of $^{226}$Ra and $^{228}$Ra in groundwater for infants, children, and adults were below the MRL of 1 mSv/y as reported by ICRP, 2000 [2]. The TAED for infants and adults was about three times higher than that reported by WHO 2008 of 0.1 mSv/y, while for children from the consumption of 330 L/y Disi water was found to be five times higher than that suggested by WHO, 2008 [1]. The results of TAED in table 3 show that mean AED received by children to be higher than the TAED received by infants and adults; these are in agreement with the results obtained by El-Gamal et al., 2019 [11] (Palestine); Ademola et al., 2017 [22] (Nigeria) [16] and Saleh et al., 2015 [31] (Yemen).

In this study, the higher TAED values for different age groups from direct ingestion of groundwater may be caused by high concentrations of radium [7, 27] in the groundwater of Jordan.

Table 4 shows the comparison between the present values of the calculated TAED for different age groups from direct consumption of $^{226}$Ra and $^{228}$Ra in the groundwater with previously published results in different countries. This results of the ranges and mean values of the TAED received by adults from the consumption of $^{226}$Ra and $^{228}$Ra in the groundwater were found to be below the published data in some countries such as Brazil [15]; Finland [17]; India [19]; Jordan [20, 21]; Nigeria [28]; Palestine [29]; Saudi Arabia [25]; Spain [26]; Sweden [27]; UK [29]; Yemen [31], except the published results in China [16] Egypt [17]; Romania [24]; Thailand [28] and USA [30]. Most of the published results from other countries in table 4 were calculated as the TAED from natural mineral water, surface water, bottled water, and groundwater for adults only.

Table 4. The estimated AED in mSv per year from the ingestion of $^{226}$Ra and $^{228}$Ra activity in the Disi water of present study for different age groups compared with previously published data from other countries.

| Country      | Water Type       | Age Group | Min ± SD | Max ± SD | Mean AED (mSv/y) |
|--------------|------------------|-----------|----------|----------|------------------|
| Brazil, 2004 | Groundwater      | Adults    | –        | –        | 0.80             |
| China, 2019  | Groundwater      | Adults    | 0.002    | 0.055    | –                |
|              |                   | Children  | 0.005    | 0.11     | –                |
|              |                   | Infants   | 0.008    | 0.188    | –                |
| Egypt, 2019  | Surface and      | Adults    | 0.0139   | 0.127    | 0.058            |
|              | Groundwater      | Children  | 0.0143   | 0.1466   | 0.068            |
|              |                   | Infants   | 0.0082   | 0.0837   | 0.0386           |
| Finland, 2007| Groundwater      | Adults    | 0.020    | –        | 0.41             |
| India, 2016  | Drinking water   | Adults    | 0.360    | 7.91     | 3.92             |
A previous study in Jordan by Ismail et al., 2009 [20] and Vengosh et al., 2009 [21] show that the AED from ingestion of bottled water and Disi groundwater, respectively were nineteen times higher than the MRL (WHO, 2008). In the present study, the estimations of the TAED for adults were found to be seven times lower than the results published by Ismail et al., 2009 [20] and Vengosh et al., 2009 [21].

From the present investigations, groundwater from Disi wells must be blended in Dabouk and Abu Alanda reservoirs with natural water resources with a ratio of 5:1 of natural resources water to Disi groundwater to bring the drinking water to be acceptable and safe for human consumption (WHO, 2008).

### 4. Conclusion

The mean AED from the direct ingestion of $^{226}$Ra and $^{228}$Ra in groundwater for children were found higher than that for infants and adults; this is in agreement with the previously published results from other countries.

The TAED from direct consumption of $^{226}$Ra and $^{228}$Ra in groundwater for different age groups were below the MRL of 1 mSv/y as reported by ICRP, 2000. The TAED from direct consumption of radium in groundwater for infants and adults were found to be about three times higher than that reported by WHO 2008 of 0.1 mSv per year, while for children from the consumption of groundwater was found to be five times higher than that suggested by WHO, 2008.

From the present study, groundwater from Disi wells must be blended in Dabouk and Abu Alanda reservoirs with natural water resources with a ratio of 5:1 of natural resources water to

| Country | Source | Age Group | Adults | Children | Infants |
|---------|--------|-----------|--------|----------|---------|
| Jordan, 2009 [20] | Bottled water | Adults | 1.70 | 1.9 | – |
| Jordan, 2009 [21] | Disi groundwater | Adults | 1.019 | 1.891 | – |
| Jordan, Present Study | Disi groundwater | Adults | 0.087±0.02 | 0.383±0.01 | 0.252±0.067 |
| | | Children | 0.144±0.01 | 0.828±0.20 | 0.519±0.102 |
| | | Infants | 0.085±0.02 | 0.532±0.20 | 0.322±0.095 |
| Nigeria, 2017 [22] | Groundwater | Adults | 0.042 | 1.471 | – |
| | | Children | 0.071 | 2.521 | – |
| | | Infants | 0.036 | 1.261 | – |
| Palestine, 2012 [23] | Natural water resources | Adults | – | – | 0.625 |
| Romania, 2021 [12] and 2019 [24] | Drinking and Mineral water | Adults | 0.01545 | 0.04738 | 0.0345 |
| Saudi Arabia, 2016 [25] | Well water | Adults | 0.355 | 3.627 | 1.333 |
| | | Treated water | 0.157 | 1.123 | 0.485 |
| | Bottled water | 0.102 | 0.602 | 0.421 |
| Spain, 2004 [26] | Groundwater | Adults | – | – | 2.4 |
| Sweden, 2002 [27] | Well water | Adults | 0.05 | 20.4 | – |
| Thailand, 2018 [28] | Groundwater | Adults | 0.106 | 0.188 | – |
| UK, 1993 [29] | Well water | Adults | 0.02 | 0.40 | – |
| USA, 2006 [30] | Groundwater | Infants | – | 0.134 | – |
| Yemen, 2015 [31] | Groundwater | Adults | 0.185 | 0.65 | 0.4 |
| | | Children | 0.31 | 1.06 | 0.62 |
| | | Infants | 0.17 | 0.57 | 0.34 |

SD = Standard Deviation

The mean AED from the direct ingestion of $^{226}$Ra and $^{228}$Ra in groundwater for children were found higher than that for infants and adults; this is in agreement with the previously published results from other countries.

The TAED from direct consumption of $^{226}$Ra and $^{228}$Ra in groundwater for different age groups were below the MRL of 1 mSv/y as reported by ICRP, 2000. The TAED from direct consumption of radium in groundwater for infants and adults were found to be about three times higher than that reported by WHO 2008 of 0.1 mSv per year, while for children from the consumption of groundwater was found to be five times higher than that suggested by WHO, 2008.

From the present study, groundwater from Disi wells must be blended in Dabouk and Abu Alanda reservoirs with natural water resources with a ratio of 5:1 of natural resources water to
Disi groundwater to bring the groundwater to be safe for drinking and acceptable for human consumption (WHO, 2008).

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