Spatial distribution, risk assessment and influence factors of terrestrial gamma radiation dose in China

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ABSTRACT

The current spatial distribution of the risk of terrestrial gamma radiation in China were investigated by using spatial interpolation. And the driving factors influence on the terrestrial gamma radiation dose (TGRD) distribution were identified using the geographic detector, a new statistical method based on the nonlinear hypothesis. The results showed that the values of TGRD were range from 60 to 195 nGy h$^{-1}$ with the average of 86.5 nGy h$^{-1}$, and the higher values were recorded in Qinghai-Tibet Plateau, which were all within the range of background value in China. In addition, the radiological indices, ELCR (Excess Lifetime Cancer Risk), TGRD and AEDE (Annual Effective Dose Equivalent) were also within the acceptable range of values by risk assessment. The results by use of the geographic detector showed that sunshine duration, atmospheric pressure, altitude, and rainfall condition have closely related to the TGRD distribution. In addition, these meteorological factors and altitude had more impact on TGRD than the air pollution-related factors. Our study can provide useful information on studying the influence mechanism of the TGRD distribution, the variability of the natural terrestrial gamma radiation in China, and exposure data for risk assessment from low dose chronic exposures.

1. Introduction

Inevitably, human beings are continuously exposed to the natural radiation, 84% of this comes from terrestrial, and 16% from cosmic sources (UNSCEAR, 2000). Terrestrial gamma radiation dose (TGRD) plays an important role in assessing the natural radiation, because it can be used as a comprehensive index, and reflect the true level of natural radiation (Al-Ghorabie, 2005; Tufail et al., 2006; Alomari et al., 2019). Additionally, terrestrial gamma dose rate can predict the radon flux or potential geogenic radon (Manohar et al., 2013; Torres et al., 2018). Although natural radiation exist in low doses in our environment, significant gamma radiation exposure may constitute potential risk for human health because of the long term exposure situation (Jibiri, 2001). Therefore, studies of natural radiation deserve to be conducted.

To date, there are many studies have reported the spatial distribution of TGRD and the assessment of related health risk in some countries and regions. The results of these studies focused on the specific areas, such as the uranium mines (Momcilovic et al., 2010; Sethy et al., 2014), riparian and coastal areas (Sharma et al., 2014; El Zrelli et al., 2019). Moreover, because of the increasing social concern, previous work studied the external irradiation by gamma radiation emitted by building materials with a mineral component, containing natural radionuclides from the U-238 series, the Th-232 series and K-40 (Ravisankar et al., 2016; Kumara et al., 2018; Ouakarrouch et al., 2019; Smetsers and Tomas, 2019; Kuang et al., 2020). Overall, these building materials are made of the natural materials, such as rock, sand, clay, etc, which also contain a certain amount of radionuclide. Thus, the radioactivity level of building materials are close related to the geochemical characteristics of natural materials (Lu et al., 2014). Assessment of natural radiation in the building materials or land areas usually using the hazards index methods. Health risk related indices including internal hazards index (HI$_{\text{int}}$), external hazard index (HI$_{\text{ext}}$), the effective dose rate (AED) and

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the excess lifetime cancer risk (ELCR), which were calculated in many references (Sethy et al., 2014; Alazemi et al., 2016; Belyaeva et al., 2019; Monica et al., 2019). However, the future study on health risk assessment of natural radiation should be concerned the health effect of long-term exposure to low doses.

Previous studies showed that terrestrial gamma radiation was strongly dependent on the composition of the soil and the rocks and the radionuclides contained within them (Momcilović et al., 2010; Sanusi et al., 2014). Actually, many environmental variations changes in space and time can also impact the natural radiation level (Abba et al., 2017; Szabo et al., 2017; Yeşilkanat et al., 2017; Torres et al., 2018). For instance, many studies showed that the rainfall or snowfall could seriously influence the environmental gamma radiation. This mainly because of the atmospheric radon daughters were scavenged, and reached to the ground, which was dubbed "radon washout", and that could significantly increase temporarily the environmental gamma radiation. Sometimes, it can increase gamma radiation by tens and even hundreds percent (Nishikawa et al., 1995; Mercier et al., 2009; Yakovleva et al., 2016). However, the impact of the environmental factors, such as the variations of meteorological indices and air pollution indices, on the radiation level are still unclear.

There are many different geographical regions in China as well as various types of climate. These various conditions can cause the changes of the terrestrial gamma radiation. There were total 79 sites sampled in National Radiation Environmental Monitoring System of China, which had been established to cover all province in mainland. The dynamic

Fig. 1. The distribution of monitoring sites in China.

Fig. 2. Statistical analysis of terrestrial gamma radiation dose rates measured at 1 m above the ground surface (n = 79 × 12). Pareto chart (a), box plot and scatterplot (b) showing the showing the distributions of TGDR in China.
data and the quarterly bulletin were also released online regularly by the system. Of that, the gamma radiation contains the natural radionuclides of Th-232, Ra-226, and K-40. The main aims of this study are to (1) describe the spatial distribution of TGRD in China using the interpolation method, (2) perform the evaluation of natural radioactivity levels in China, and (3) investigate the influencing factors driving the difference of spatial distribution of TGRD. The findings of this study are helpful in indicating the current situation of gamma radiation level and in assessing the associated radiation hazard to population health. Furthermore, these can also fill the gap of the study on driving mechanisms of geographical discrepancy of TGRD.

2. Methods and materials

2.1. Study area and data sources

As shown in Fig. 1, there are total of 79 monitoring sites distribute in different cities provinces of China mainland. The TGRD was measured at the 1 m above the ground, and the results were published on the national radiation environmental data evaluation system. In this study, the data of gamma dose rate were collected from the quarterly bulletin released by National Radiation Environmental Data Evaluation System (MEP, 2018). The prepared influence factors were used mainly include the meteorological factors, air quality and geographic factors. The meteorological data included rainfall, air temperature, atmosphere and vapour pressure, relative humidity, wind speed, and sunshine duration were provided by the National Meteorological Data Center (CMA, 2018). The air quality data were collected from the China National Environmental Monitoring Center (CNEMC, 2018; Feng et al., 2019a). The altitude data of monitoring sites were obtained on the National Tibetan Plateau Data Center. We selected 30 monitoring sites in 30 capital cities as the study objectives, because of the meteorological data could not be obtained in some small and medium cities.

2.2. Assessment method

The annual effective dose equivalent (AEDE), in mSv y\(^{-1}\), which represents effective dose equivalent to population from terrestrial gamma radiation, is estimated using the following equation (SEPA, 1993; Alazemi et al., 2016):

\[
AEDE = \text{TGRD} \times \text{DCF} \times \text{OF} \times T \times 10^{-6}
\]

where, the TGRD is terrestrial gamma radiation dose rate (nGy h\(^{-1}\)) for the measured samples were determined from the specific activity concentration, in addition to the associated radiological risks from the absorbed dose at 1 m above the ground surface (UNSCEAR, 2000; Alazemi et al., 2016); DCF is dose conversion factor, which is equal to 0.7 Sv Gy\(^{-1}\) for adults (UNSCEAR, 2000); OF is outdoor occupancy factor (20%), and T is the time to convert from year to hour (8760 h y\(^{-1}\)).

The excess lifetime cancer risk (ELCR) represents the probability of cancer incidence in a human population for a specific lifetime from the exposure to natural radiation (Taskin et al., 2009). The ELCR was calculated using the equation:

\[
\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF}
\]

where DL is duration of life, 77 years, according to the gazette released by the National Health Commission of China in 2019 (NHC, 2019; Feng et al., 2019b), and RF is risk factor, which represents fatal cancer risk per Sievert. For stochastic effects, the value of 0.05 Sv\(^{-1}\) for public (ICRP, 2008). In this work, the calculated results were compared with results reported from the rest urban areas of the world.

2.3. Statistical analysis

In order to further identify the critical factors influenced the distribution of gamma dose rate, the geographic detector method is used to identify those from potential influencing factors (Wang et al., 2010). The geographic detector is a new statistical method with the nonlinear hypothesis to measure spatial stratified heterogeneity and detect explanatory factors and analyze the interactive relationship among variables, which has been widely used in many fields of natural and social sciences (Ren et al., 2014; Luo et al., 2016; Wang et al., 2016; Wei et al., 2020; Zhang et al., 2020). The geographic detector included four modules, which are the risk detector, factor detector, ecological detector and interaction detector (Wang et al., 2016; Bai et al., 2019). In this study, the factor detector was used, which could examine the determinant

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**Fig. 3.** Isodose map of the outdoor terrestrial gamma radiation dose rate in China. (A, B and C were the sampling sites with the high values in the Qinghai–Tibet Plateau).
power of driving factors (Xs) to Y by the q statistic value. The gamma dose rate was Y, and the input data (Xs) were meteorological data, air quality and geographic data. The q value was calculated using Eq. (3) (Wang et al., 2010):

\[ q = 1 - \frac{1}{N\sigma^2} \sum_{i=1}^{L} N_i \sigma_i^2 \]

(3)

where q is the determinant power of the risk factor and the determinant power of heterogeneity of target variables, with range from 0 to 1, the larger the q value, the greater is the influence of the index on the variables (Wei et al., 2020). The \( \sigma \) denotes the variance of gamma dose rates of the study area. The i = 1, 2, …, L is stratification of impact factor X (Wang and Hu, 2012).

For visualization of the spatial distribution of terrestrial gamma radiation dose rate, the sites distribution and isodose map were generated by using the ArcGIS software (version 10.2). The Inverse Distance Weighting (IDW) method was conducted for interpolation and estimation of the overall spatial pattern (Belyaeva et al., 2019).

3. Results

3.1. General statistical description

The summary statistics for monthly gamma dose rates measured at 79 sites during the 12 months in China were shown in Table 2, and the data was listed in Table S1. The values were range from 60 to 195 nGy h\(^{-1}\) with the average of 86.5 nGy h\(^{-1}\) (Fig. 1b). However, the data was skewed and heavy-tailed and was not follow a normal distribution because of the high values of skewness. The higher frequencies were observed at the range from 70 to 90 nGy h\(^{-1}\), which accounting for 68.4% of total sites. Three higher values, 195, 179 and 140 nGy h\(^{-1}\), were recorded at the sites of Lhasa, Waliguan and Golmud in Qinghai–Tibet Plateau, respectively. The differences of TGRD among these sites may be results of fluctuation of some local environmental factors, such as the geological factors, meteorological factors and air quality indices.

3.2. Mapping and spatial analysis

The map of the TGRD distribution by using the IDW interpolate method was shown in Fig. 3. It was worth noting that the highest dose rate of 195 nGy h\(^{-1}\) was measured in Lhasa, and followed the Waliguan (179 nGy h\(^{-1}\)) and Golmud (140 nGy h\(^{-1}\)). These sites were all located in Qinghai–Tibet Plateau. These are consistent with the results mentioned in general statistical description. The TGRD values above 100 nGy h\(^{-1}\) were also recorded at the sites in Inner Mongolia, Northeastern and southeastern China. For other regions, the lower values are range from 60 nGy h\(^{-1}\) to 90 nGy h\(^{-1}\), which measured in the Tarim Basin, the central and southern China.

3.3. Radiological indices

In order to estimate the gamma dose rate and associated human health risks, the radiological indices AEDE and ELCR were calculated using the TGRD and other constants and results were listed in Table 1. The results showed that the AEDE values in range of 0.07–0.24 mSv y\(^{-1}\), with the average of 0.11 mSv y\(^{-1}\). The highest value (0.24 mSv y\(^{-1}\)) was also obtained from the Qinghai–Tibet Plateau. Most of the values of the ELCR were higher than the world average, 2.9E-04, account for about 96% monitoring sites. However, these were lower than the limited value of AEDE, 1 mSv, in the national standard, which indicated that the current radiation level was safety for public. Furthermore, the mean level of ELCR in Hainan Island, calculated at 2.7E-04, was comparable to world average. Although values of AEDE and ELCR were higher than world average, the values of TGRD were within the range of background values in 1983–1990 (He et al., 1992). In addition, the radiological index, ELCR, In is direct proportion to the TGRD and AEDE based on the analysis of calculating equations. With the above analysis, it can be concluded that radiological indices were also within the acceptable range of values (see Table 1).

3.4. Influencing factors

The q values of 14 potential factors on TGRD were obtained using the geographical detector method, and the results were listed in Tables 2 and 3. As shown in Table 2, the critical environmental factors influenced the TGRD distribution in order of q value were: sunshine duration (0.94), atmosphere pressure (0.87), altitude (0.86), and rainfall (0.83). In addition, these factors had significant difference compared with other factors (P < 0.001). However, among the air pollution factors, the main driving factor related to the TGRD was only the CO concentration (0.69) (Table 3). By contrast, the lowest influence factors were wind speed (0.19) and concentrations of gaseous pollutants, such as SO2 and NO2 (Tables 2 and 3). Therefore, the environmental factors including meteorological factors and altitude have more impact on TGRD, instead of the air pollution-related factors.

4. Discussion

In this study, the current spatial distribution of TGRD were presented using the geostatistical technology. The results showed the values of TGRD were range from 60 to 195 nGy h\(^{-1}\) with the average of 86.5 nGy h\(^{-1}\).
h\(^{-1}\), and the higher values were measured in Qinghai-Tibet Plateau. However, these were within the range of previous studies in China (He et al., 1992). Furthermore, the average value of this study is higher than the world average level. The spatial distribution of TGRD is influenced by many environmental factors, as a result, the distribution of TGRD vary from the different region. The TGRD rates in Jos Plateau, Nigeria ranged from 40 to 1265 nGy h\(^{-1}\) with a mean value of 250 nGy h\(^{-1}\) (Abba et al., 2017), which are higher than in China, even in the Qinghai-Tibet Plateau. In Negeri Sembilan, Malaysia, the values ranged from 71 \(\pm\) 3 nGy h\(^{-1}\) up to 1000 \(\pm\) 11 nGy h\(^{-1}\) with the average of 330 \(\pm\) 8 nGy h\(^{-1}\) (Norbani et al., 2014). However, the records from Saudi Arabia were 14 and 279 nGy h\(^{-1}\) with an average value of 89 nGy h\(^{-1}\), which is close to that in China. Additionally, the current assessing method of health risk is still limited for the TGRD, the further study should be focus on developing the novel assessment model for multi-pathway exposure based on the related results of toxicological or physiological studies.

The higher values of TGRD in the Qinghai–Tibet Plateau may be the results of the specific environmental types. In this study, the results of geographic detector showed that the sunshine duration, atmosphere pressure, altitude, and rainfall were driving factors of the TGRD in the region (Table 2 and Fig. 4). In fact, the altitude could significantly impact the weather and climate condition, such as the pressure, sunshine duration and precipitation (Cui et al., 2008).

It is generally known that the Qinghai–Tibet Plateau, at an average elevation of above 4000 m, belonging to the typical plateau continental climate such as drying, less air dense, long sunshine hours, which may enhance transmittance of the atmospheric layer and increase the radiation by ionization of cosmic rays come from space (Ma et al., 2008; Li et al., 2011). In addition, the higher TGRD value may be caused by the rock layers that composed of volcanic and granitic rocks (Zhao et al., 2015). The study reported that greatest TGRD originating from igneous rock of granitic formations, while the minimum value of TGRD was observed in an area covered by limestone composed of calcite mineral (Norbani et al., 2014). The higher value of TGRD above 100 nGy h\(^{-1}\) recorded in southeastern and southern China, which may also be caused by distribution of granitic rock layer (Yan et al., 2018; Zhao et al., 2018). Similarly, the high values of TGRD were also recorded by previous

Table 2

<table>
<thead>
<tr>
<th>Environmental Factor</th>
<th>Rainfall</th>
<th>Atmosphere pressure</th>
<th>Wind speed</th>
<th>Air temperature</th>
<th>Relative humidity</th>
<th>Sunshine duration</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>q</td>
<td>0.83</td>
<td>0.87</td>
<td>0.19</td>
<td>0.64</td>
<td>0.68</td>
<td>0.94</td>
<td>0.86</td>
</tr>
<tr>
<td>Atmosphere pressure</td>
<td>N</td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) N denotes there have no significant difference between two variations.
\(b\) Y represents there have significant difference between two variations.

Table 3

<table>
<thead>
<tr>
<th>Air pollution Factor</th>
<th>AQI</th>
<th>PM2.5</th>
<th>PM10</th>
<th>SO(_2)</th>
<th>CO</th>
<th>NO(_2)</th>
<th>O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>q</td>
<td>0.30</td>
<td>0.23</td>
<td>0.27</td>
<td>0.13</td>
<td>0.69</td>
<td>0.20</td>
<td>0.27</td>
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<tr>
<td>AQI</td>
<td></td>
<td></td>
<td>Y</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>PM2.5</td>
<td>N</td>
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<tr>
<td>PM10</td>
<td>N</td>
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<tr>
<td>SO(_2)</td>
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<td></td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NO(_2)</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(_3)</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\) Y represents there have significant difference between two variations.
\(b\) N denotes there have no significant difference between two variations.
studies in Pakistan and France, because of the cosmic radiation dose rates varied with altitude and solar activity (Billon et al., 2005; Jabbar et al., 2008). Additionally, many studies had reported the impacts of geological type and soil type on the TGRD (Ramlí, 1997; Garba et al., 2014; Belyaeva et al., 2019). Therefore, the distribution of TGRD in China is the results of radionuclides in typical rock, ionization of cosmic rays, and impacts of the dominant meteorological factors.

We found that meteorological factors and altitude have more impact on TGRD than the air pollution-related factors, which was mainly based on calculating the q value using the method of factor detector. The q values of meteorological factors were higher than those of air pollutants and quality indices (Table 2). Many previous studies verified the rainfall and snowfall, altitude had important effects on the distribution of TGRD (Billon et al., 2005; Inomata et al., 2007; Jabbar et al., 2008). For example, strong precipitation intensity effectively removes aerosols and Rn-222 progeny from the atmosphere and consequently, extraordinarily high γ-ray dose rates would occur (Inomata et al., 2007; Hirose et al., 1993). To date, the report about the influence of air pollutant and quality indices on the environmental radiation are still limited. Further studies are needed for the relationships between environmental radiation and air pollutants and the quality indices on regional and global scale. Our results provide useful information on studying the influence mechanism of the TGRD distribution and on the variability of the natural terrestrial gamma radiation in China and exposure data for risk assessment from low dose chronic exposures.

5. Conclusions

In this study, the current spatial distribution and the risk assessment of terrestrial gamma radiation dose (TGRD) in China were investigated by using spatial interpolation based on the multiple data released in 2018. The driving factors influence on the TGRD distribution were also identified by using the geographic detector. The results showed that the values of TGRD are range from 60 to 195 nGy h−1 with the average of 86.5 nGy h−1, and the higher values were recorded in Qingshi-Tibet Plateau. Most of values of AEDE and ELCR were higher than the world average, but these were all within the range of background value in China. The factors of sunshine duration (0.94), atmosphere pressure (0.87), altitude (0.86), and rainfall (0.83) have a significant impact on the TGRD distribution. Furthermore, meteorological factors and altitude have more impact on TGRD than the air pollution-related factors. The findings of our study can fill the gap of the study on driving mechanisms of TGRD to a certain extent, and provide a theoretical basis for the further study on evaluating the natural radioactivity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvrad.2020.106325.

References


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