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Assessment of environmental gamma dose in air in Ho Chi Minh city, Vietnam

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Abstract

Measurement of environmental gamma dose in air in Ho Chi Minh city, Vietnam has been conducted at 2245 locations using a portable dosimeter installed on a motobike with GPS integrated and positioned 1 m above the ground surface. Cumulative gamma dose rates have also been measured using the TLD dosimeters located at 20 fixed locations around the city to evaluate the total component and the contribution of cosmic rays in the rainy and dry seasons. The gamma dose rates in the city were found in the range of 0.05–0.18 μSv/h with the average value of 0.10 μSv/h. The cumulative gamma dose in the dry season is greater than that in the rainy season by about 15%.

Keywords Gamma dose in air · Cumulative gamma dose · Portable dosimeter · TLD dosimeter

Introduction

Two main sources of exposure of humans to environmental radiation are terrestrial gamma rays and cosmic rays. Terrestrial gamma rays are mainly from the primordial radioactive nuclides occurring naturally in soils, rocks existing in the earth's crust and building materials, such as ^{238}U, ^{232}Th series and ^{40}K [1, 2]. The terrestrial gamma radiation level and associated external exposure due to the natural radioactivity, in particular outdoor gamma dose, depend on the geological structure and the activity concentration in the soil. However, indoor absorbed gamma dose, in addition to geology, relies also on building materials. It means that human activities with new construction materials could lead to the change of the environmental radiation background. On the other hand, cosmic ray particles interact with the atmosphere to produce a number of radioactive nuclei and cause radiation dose. According to UNSCEAR 1993, the average annual effective dose for adults due to cosmic rays is about 0.38 mSv [3]. The radiation dose induced by cosmic rays increases with latitude and altitude. The radiation dose due to cosmic radiation is about double at the altitude of 2100 m compared to that at sea level [4]. Measurement of gamma dose rate in air is considerably essential to determine the environmental radiation background in a region and to estimate the risk to human health from both natural and artificial sources [1, 2].

Among several techniques for measuring gamma dose in air, portable survey meter, thermoluminescent dosimeter (TLD) and gamma spectrometer are widely used [5–12]. Gamma spectrometer is extensively used to measure the radioactivity concentrations of ^{238}U, ^{232}Th series and ^{40}K in surface soils. Then, the gamma dose rate is calculated using the Beck formula [13]. TLDs are commonly used to accumulate the radiation response for a period of time. Then, the gamma dose rate is evaluated from the accumulative dose in the time period [4, 14, 15]. The mean values of outdoor and indoor annual gamma dose rates in air in Udupi district, Karnataka, India measured by the TLDs were reported as 0.75 ± 0.18 mGy/yr and 0.74 ± 0.13 mGy/yr, respectively [16]. Direct measurement of gamma dose rate in air in

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the area surrounding the Mexican Nuclear Research Centre using the TLDs gave the mean value of 86.35 ± 12.57 nGy/h (range in 58.42–115.11 nGy/h) [17]. As reported by Liu et al. (2022), the outdoor ambient dose equivalent rate in Canada is about 0.072 μSv/h, with 0.020 μSv/h for terrestrial radiation and 0.052 μSv/h for cosmic radiation, corresponding to the contributions of terrestrial radiation and cosmic radiation of 20.6% and 79.4%, respectively [18]. A portable survey meter consisting of a plastic scintillator or a Geiger-Muller counter is used to assess the instant gamma dose rate in air from both surface soil and cosmic rays [5–9, 18, 19]. Measurement of absorbed dose rates in air in Odisha, India using a NaI(Tl) scintillation spectrometer installed on a car reported that the average values for seaside and inland areas were 230 ± 116 nGy/h and 123 ± 18 nGy/h, respectively [5].

Assessment in natural radioactivity and radiological hazards in surface soils has been extensively conducted using gamma spectrometer technique to establish a baseline data in Vietnam [20–25]. Southern Vietnam consists of 19 provinces covering the area of 64000 km^2, in which Ho Chi Minh is the biggest city in the region, contributing significantly in the transportation and economic development in the region and Southeast Asian countries. Therefore, assessment of natural radioactivity and radiological hazards in the city has been extensively paid attention for the purpose of environmental protection. A past work assessed the absorbed gamma dose rates in air in whole Vietnam using a car-borne survey technique, i.e., a dosimeter located inside the car driven on asphalt pavements [6]. The gamma dose rates measured by the dosimeter in the car were then corrected by a shielding factor for obtaining the dose distribution over the country. The average gamma dose rate in air in whole Vietnam was reported as 71 ± 28 nGy/h (range in 20–217 nGy/h) [6]. The gamma dose rate in the North tends to higher than that in the South because the Northern part of Vietnam concentrates more mining regions of rare-earth elements, such as in Lai Chau and Lao Cai provinces.

In the present work, the gamma dose rates in air in Ho Chi Minh city, Vietnam have been measured using a portable survey meter (FAG FH 40 dosimeter) installed on a motobike with GPS integrated and positioned 1 m above the ground surface. The measurement was conducted at 2245 locations in 24 districts of the city. Assessment on cumulative gamma dose rates were also conducted using TLD dosimeters located at 20 locations distributed evenly in the city to evaluate the total gamma doses and the contribution of cosmic rays. Measurement and comparison of the cumulative dose rates in the rainy and dry seasons have also been conducted and presented.

Instruments and methods

Sampling site

Ho Chi Minh city is located on the latitude of 10°10′N – 10°38′N and the longitude of 106°22′E – 106°54′E in the South of Vietnam. The area of the city is about 2095 km^2, and the population is about 9.0 millions. The altitude of the city is within 1–32 m above the sea level. The altitudes of Northern an d Southern parts of the city are about 32 m and 0.5–1.0 m, respectively. While that of the central part is 5–10 m. The soil structure is originated from the weathering of granitic and basaltic rock materials, old alluvial soils and Holocene sediment [20]. The climate is tropical with two seasons: rainy season from May to November and dry season from December to April. The humidity is about 80% and 74.5% in the rainy season and the dry season, respectively. The annual rainfall is 1800 mm. The average annual temperature is 28 °C with the range of 14–40 °C.

Gamma dose measurement

Table 1 shows the detailed measurement conditions, including the number of measured points in 24 districts of the city and the locations of the Thermoluminescent dosimeters. Measurement of the gamma dose rates in air at 2245 locations distributed evenly in the 24 districts of the city was performed using the portable dose survey FAG FH 40 dosimeter. This measurement was conducted by installing the FAG FH 40 dosimeter on a motobike and driving on the main roads of the city. The distribution of the 2245 measured points is displayed in Fig. 1. The FAG FH 40 dosimeter, a Geiger Mueller (GM) counter, is a battery-operated low-level dose rate meter used to measure gamma radiation in the range of 0.01 μSv/h – 10 mSv/h, with the energy range from 45 keV to 3.0 MeV. The power supply is the 9-volt dry battery type IEC 6 LF 22 or a suitable accumulator for a minimum life of 70 h of continuous use. The measured value is displayed in both digitals by means of a numeric readout and in analog form. To ensure the reliability of the FAG FH 40 dosimeter, the detector was calibrated to a standard gamma radiation field of a ^{137}Cs source, which has the reference standard dosimeters traceable to the primary standard dosimetry laboratory (PSDL). Figure 2 displays the total ambient dose equivalent rate in the standard gamma radiation field of ^{137}Cs source.

To measure the total cumulative gamma dose in air and evaluate the contribution of cosmic rays, the in-house Thermoluminescent dosimeters (TLDs) with CaSO4:Dy powder were used. The dosimetric parameters of the TLDs

Table 1 Detailed condition of gamma dose measurement in air in Ho Chi Minh city

District name	Area (km^2)	Population density ($people/km^2$)	No. of measured points	No. of TLD dosimeter	No. of TLD_Pb dosimeter
Cu Chi	434.5	834	490	2	1
Hoc Mon	109.18	3326	166	2	1
Go Vap	19.74	28423	68		–
Binh Tan	51.89	11778	83	1	–
Tan Phu	16.06	26104	27	1	–
Tan Binh	22.38	19229	45	1	–
Binh Thanh	20.76	23109	31	1	–
Phu Nhuan	4.88	35990	18		–
Thu Duc	47.76	9936	110	1	1
District 1	7.73	24025	24	1	1
District 2	49.74	2744	62	1	–
District 3	4.92	38394	19		–
District 4	4.18	43788	8	1	–
District 5	4.27	41034	16	1	–
District 6	7.19	35035	21		–
District 7	35.69	7453	40	1	–
District 8	19.18	21978	25	1	–
District 9	114.01	2360	178	1	–
District 10	5.72	40942	12		–
District 11	5.14	45582	20		-
District 12	52.78	8559	102	1	–
Binh Chanh	252.69	1841	330	1	–
Nha Be	100.41	1095	121	1	1
Can Gio	704.22	100	229	1	1
Total	2095.01	–	2245	20	6

such as glow curve with temperature, homogeneity of the batch, reproducbility of measurement, linearity of dose response, limit of detection, fading, and energy dependent response function were determined by radiating with the gamma rays of ^{137}Cs source (662 keV) within dose interval of 0.05–24.24 mSv, and filtered X-rays (Pantak standard X-ray generator) with energies of 33 keV, 48 keV and 65 keV for dose interval of 0.3– mSv at the Secondary Standards Dosimetry Laboratory (SSDL) of Institute for Nuclear Science and Technology (Hanoi, Vietnam). Then, the irradiated TLDs were measured by Rexon-UL320 Reader System which has the consecutive heating cycle of 30 s with four nodes: node 1 for increasing from room temperature to 135 °C in 6 s, node 2 for keeping the temperature at 135 °C in 4 s, node 3 for increasing the temperature from 135 to 280 °C in 12 s, and node 4 for keeping the temperature at 280 °C in 8 s. Figure 3 shows the energy dependent response function of the TLD dosimeter.

The TLD dosimeters were installed at 20 positions distributed evenly in the city for measuring the cumulative gamma doses in air. In which, at six positions in Cu Chi, Hoc Mon, Thu Duc, District 1, Nha Be and Can Gio were located double TLD dosimeters. One of the two TLD dosimeters was included with a lead shielding layer (TLD_Pb) to prevent the gamma rays coming from surface soils for measuring only the cumulative gamma dose from the cosmic rays. The other TLD dosimeter was used without the lead shielding layer for measuring the total cumulative gamma dose in air, i.e., including the components of gamma doses from cosmic rays and surface soils. The use of TLDs to measure the lower environmental dose rate from surface soil or building material with shielding layers to eliminate the effect of cosmic rays is quite common. For example, the shielding layers to prevent cosmic rays was used to measure the natural background radiation in a 20-story office building in Taiwan [14]. In the present work, to measure the contribution of cosmic rays we used the lead shielding layers to prevent the terrestrial gamma rays. The locations of the TLD and TLD_Pb dosimeters are depicted in Fig. 1 and Table 1. The measurements were conducted in four time periods in a year, in which two periods are in rainy season and two other correspond to dry season.

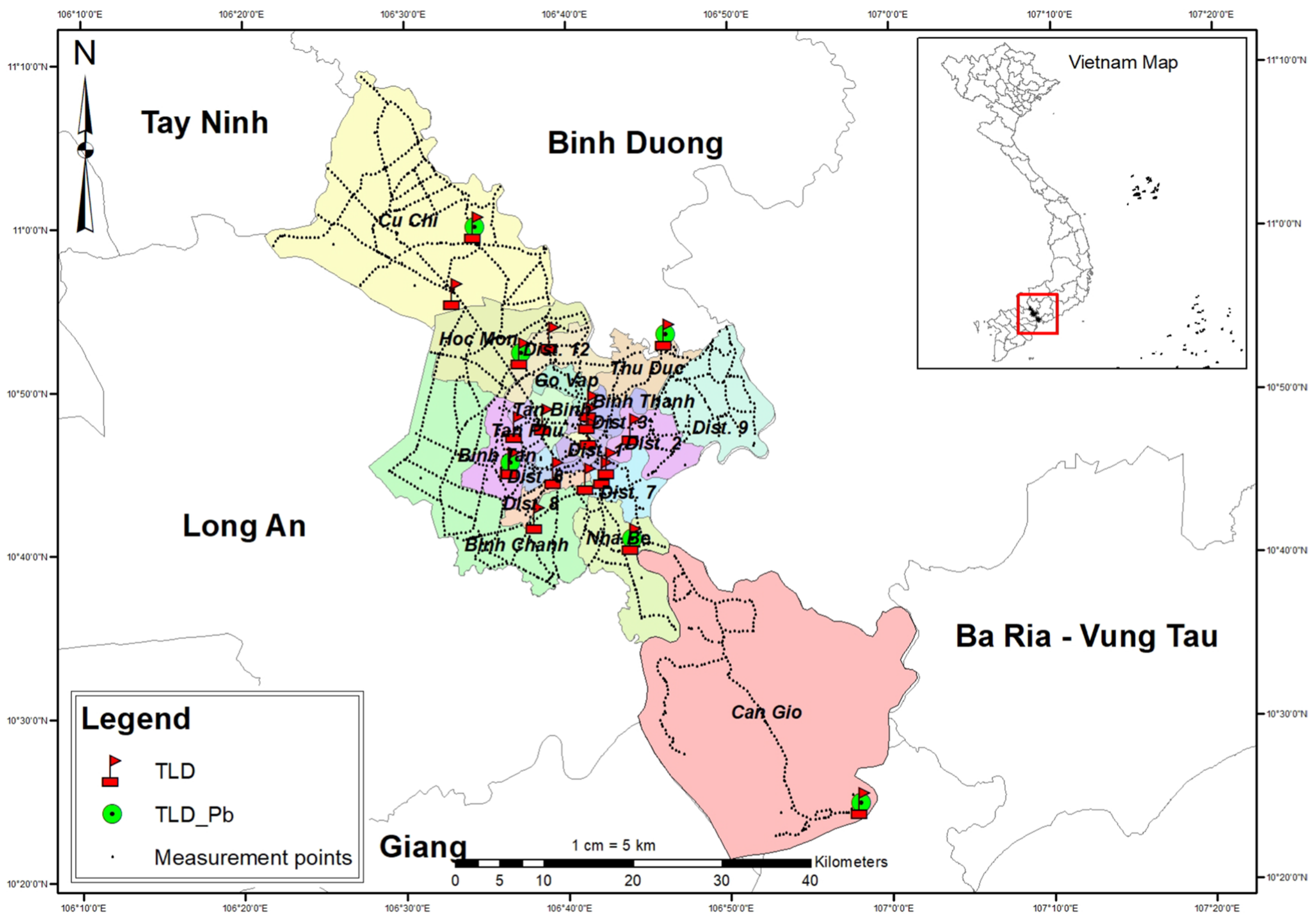

Fig. 1 Map of Ho Chi Minh city and the locations of gamma dose measurement

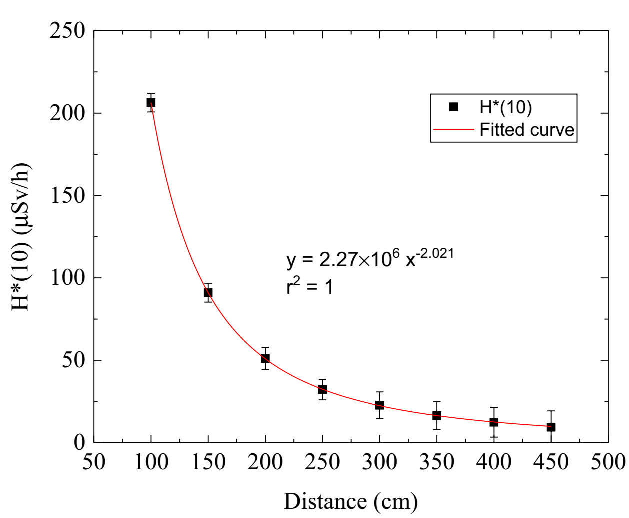

Fig. 2 The ambient dose equivalent rate of the standard gamma radiation field of a ^{137}Cs source calibrated using the FAG FH 40 dosimeter. The error bars indicate the 95% confident interval of the data

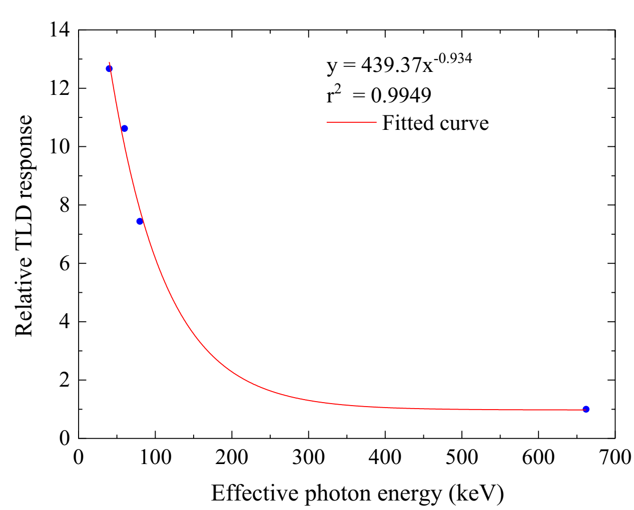

Fig. 3 Energy dependent response function of the TLD dosimeter

Table 2 Measured gamma dose rates in air in 24 districts of Ho Chi Minh city

District name	Average dose rate (μSv/h)	Range of dose rates (μSv/h)
Cu Chi	0.10	0.05–0.17
Hoc Mon	0.10	0.05–0.18
Go Vap	0.10	0.08–0.15
Binh Tan	0.10	0.07–0.17
Tan Phu	0.10	0.07–0.13
Tan Binh	0.10	0.07–0.15
Binh Thanh	0.10	0.08–0.14
Phu Nhuan	0.10	0.08–0.15
Thu Duc	0.10	0.08–0.15
District 1	0.10	0.06–0.14
District 2	0.10	0.06–0.16
District 3	0.10	0.07–0.16
District 4	0.11	0.08–0.15
District 5	0.11	0.09–0.18
District 6	0.10	0.07–0.15
District 7	0.10	0.08–0.18
District 8	0.10	0.07–0.15
District 9	0.10	0.07–0.16
District 10	0.11	0.09–0.17
District 11	0.10	0.08–0.17
District 12	0.11	0.05–0.17
Binh Chanh	0.10	0.05–0.18
Nha Be	0.10	0.07–0.18
Can Gio	0.10	0.05–0.18
Average	0.10	0.05–0.18

Results and discussion

Gamma dose distribution

Table 2 shows the average and the range of the equivalent gamma dose rates in air measured in 24 districts of Ho Chi Minh city. Figure 4 displays the distribution of the gamma dose rates in the city plotted from 2245 measured points. The locations and the number of measured points in each districts are shown in Fig. 1 and Table 1, respectively. It can be seen that the equivalent gamma dose rates in air in the city vary from 0.05 to 0.18 μSv/h with the average value of 0.10 μSv/h. The lowest values of the gamma dose rates in 24 districts are about 0.05–0.09 μSv/h, whereas the highest values are about 0.13–0.18μSv/h. The average gamma dose rates in all districts are approximate, within the values from 0.10 to 0.11 μSv/h. This means that the difference of the average gamma dose rates from district to district, as well as compared to the average value of the whole city, is within 10%. For further statistical analysis, Fig. 5 displays the frequency distribution of the gamma dose rates measured at 2245 locations in the city. One can see that the gamma doses rates in air in Ho Chi Minh city follow the symmetrical distribution around the mean value. The data follow a standard distribution in the range from 0.05 to 0.18 μSv/h, with the average value of 0.10 μSv/h. The smallest dose rates were in the range of 0.05–0.07 μSv/h corresponding to 121 measured points, accounting for 5.4%. The highest dose rate is in the range of 0.13–0.18 μSv/h, corresponding to 192 measured points, accounting for 8.5%. Most of the data range from 0.08 to 0.12 μSv/h (1932 points, accounting for 86.2%), equivalent to the annual dose of 0.70–1.05 mSv/yr. This range agrees with the natural radiation background in the world.

Together with the measurement of the gamma doses at 2245 locations using a portable dosimeter (model FAH FH 40), we also performed soil sample collection and dose assessment at 120 locations in Ho Chi Minh city. The detailed radioactivity characteristics and related hazard indices in soil samples in Ho Chi Minh city were presented in a previous work [25]. Since the dose measured directly in air consists of the contribution by the surface soils, it would provide useful information on the relationship between the equivalent gamma dose rates measured directly in air with that obtained from the terrestrial radioactivity concentrations in surface soils. The outdoor absorbed gamma dose, D_{out}, was calculated from the radioactivity of ^{226}Ra, ^{232}Th and ^{40}K as [26]:

$$D_{out}(\mathrm{nGy \cdot h^{-1}}) = 0.46A_{Ra} + 0.62A_{Th} + 0.042A_{K}, \quad (1)$$

where, the values of 0.46, 0.62 and 0.042 are the activity-to-outdoor dose conversion factors for ^{226}Ra, ^{232}Th and ^{40}K, respectively. Figure 6 displays the correlation of the gamma doses measured directly in air and that calculated from the radioactivity in surface soils. The correlation coefficient (r^2) between the measured and calculated values is 0.6336. Since the direct measurement was conducted along the road system, it is noticed that crushed granitic stones in the roadbed and the asphalt cover can also emit gamma rays and contribute to the low dose rate. Moreover, the roadbed and asphalt cover also function as a shielding layer, leading to the change of the environmental radiation background. According to Inoue et al. (2020), the shielding effect by asphalt pavement ($SF_{asphalt}$) in Southern Vietnam is about 1.37 [5]. However, the measurement in Ho Chi Minh city was conducted at only 11 points. In the present work, quantitative evaluation of the contribution or effect of roadbed and asphalt on the measured dose has not been conducted. This should be noticed in a future work.

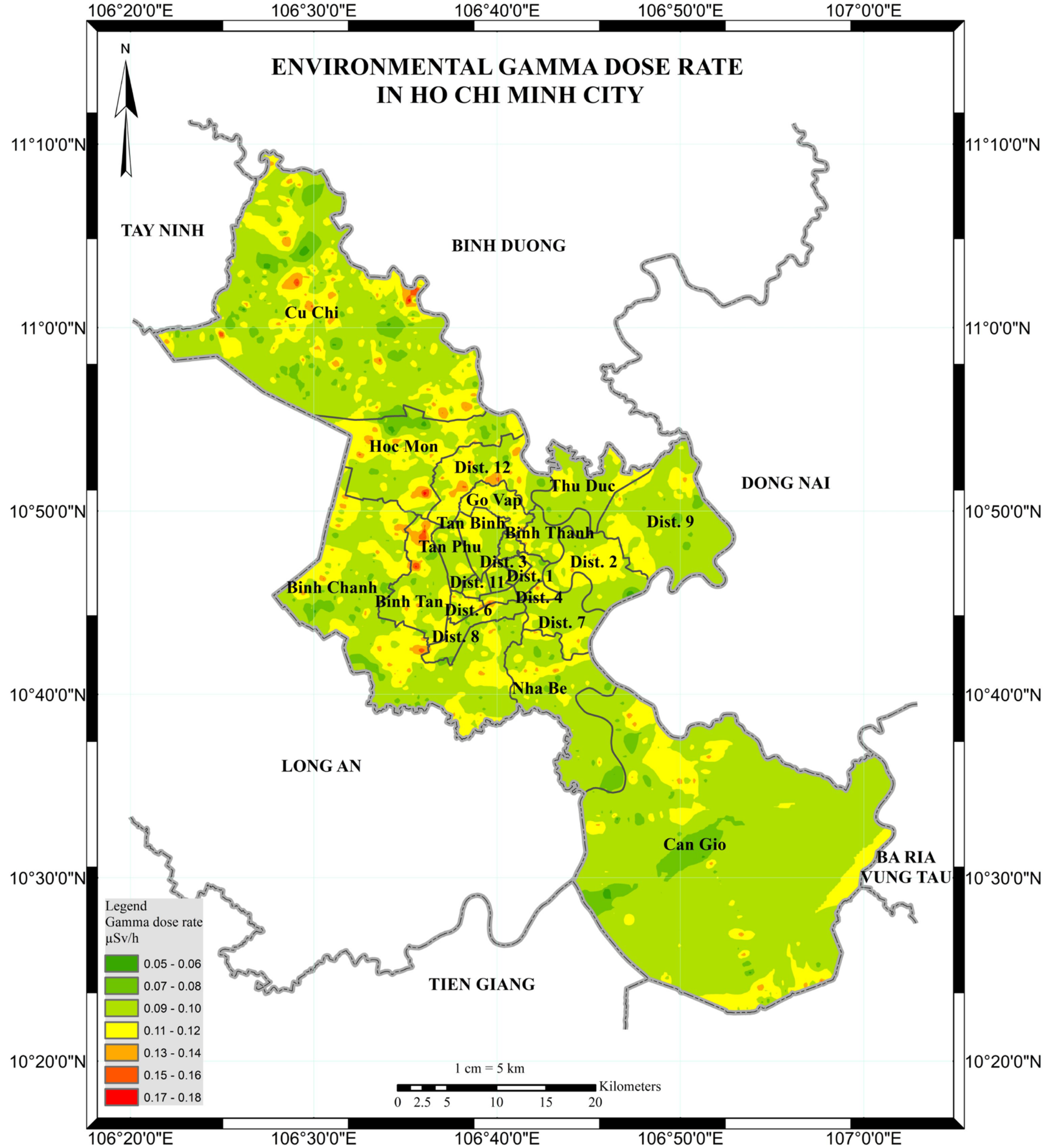

Fig. 4 Distribution of environmental gamma dose rate in Ho Chi Minh city

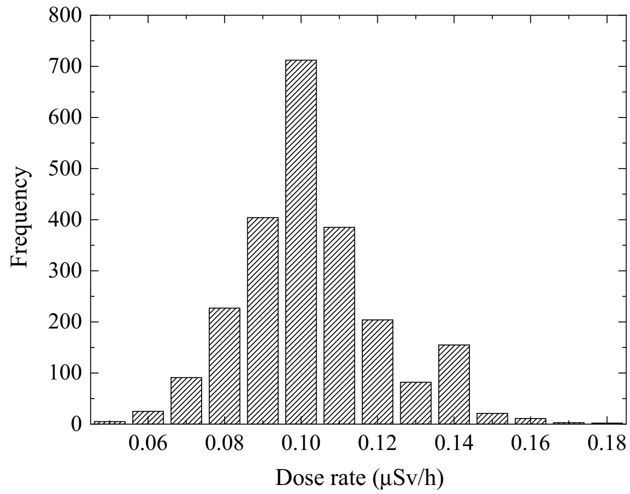

Fig. 5 Frequency distribution of total gamma dose rates in air at 2245 locations in Ho Chi Minh city measured by the FAG FH 40 dosimeter

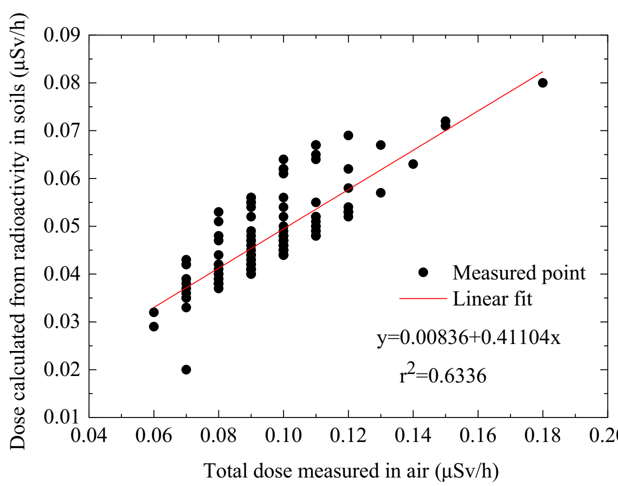

Fig. 6 Correlation between the total gamma dose measured in air and that calculated from radioactivity in surface soils in Ho Chi Minh city

Cumulative gamma dose rates

Table 3 shows the total cumulative gamma dose rates and the components due to the surface soils and the cosmic rays measured by the TLD dosimeters in the rainy and dry seasons, respectively. The average equivalent gamma dose rate calculated from the cumulative doses is about 0.98 μSv/h. This value agrees with that measured directly in air (0.10 μSv/h). The cumulative gamma doses due to the cosmic rays in the rainy season vary from 0.044 to 0.051 μSv/h with the average value of 0.048 μSv/h. Whereas, in the dry season, that values vary in the range of 0.046–0.068 μSv/h with the average value of 0.055 μSv/h. From Table 3, it is estimated that the contributions of the cosmic rays and

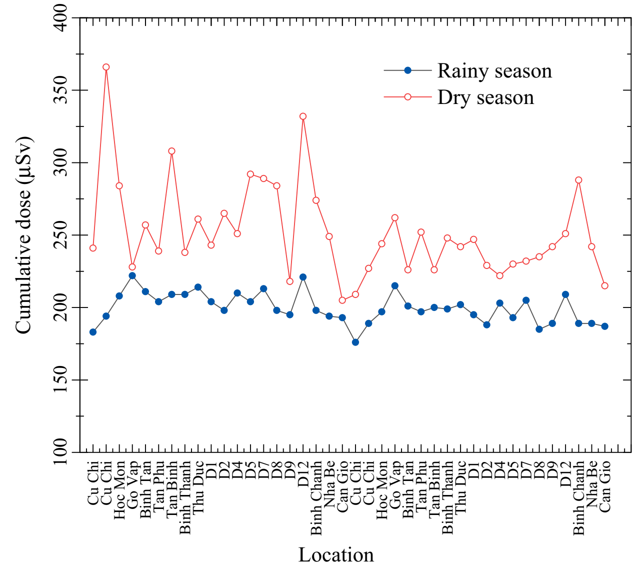

Fig. 7 Cumulative gamma doses in the rainy and dry seasons measured by the TLD dosimeters at 20 locations in Ho Chi Minh city

terrestrial gamma rays in the total equivalent gamma dose rate in air are about 53% and 47%, respectively. One can also evaluate that the average annual effective dose in Ho Chi Minh city is about 0.86 mSv. In which, the contributions of cosmic rays and terrestrial gamma rays are about 0.45 and 0.41 mSv, respectively. According to UNSCEAR report, the world average annual effective doses due to cosmic rays and terrestrial gamma rays are 0.4 and 0.5 mSv, respectively, and the ranges of the values are 0.3–1.0 mSv and 0.3–0.6 mSv [1]. This means that the average annual effective dose obtained in Ho Chi Minh city agrees with the world average values. Figure 7 displays the cumulative dose rates in the rainy and dry seasons measured by the TLD dosimeters at 20 locations distributed evenly in the city. It can be seen that the cumulative doses measured in the dry season are greater than that in the rainy season by about 15%.

As reported by Inoue et al. (2020), the average terrestrial gamma dose rates in whole Vietnam from direct measurement in air and fixed-point measurement were 0.075 and 0.71 μSv/h, respectively [5]. The value in the Southern part of Vietnam was 0.069 μSv/h (range in 0.029–0.074 μSv/h). Particularly, the terrestrial equivalent gamma dose rates in Ho Chi Minh city obtained from direct measurement and from soil concentration were 0.052 and 0.055 μSv/h, respectively [5]. However, the value obtained from soil concentrations was based on the measurement of only eleven soil samples [5]. Tran et al. (2020) conducted a survey with 120 soil samples distributed evenly in the city, and reported that the terrestrial equivalent gamma dose rate was about 0.044 μSv/h. The value agree better with that evaluated from the terrestrial contribution in this work (0.046 μSv/h).

Table 3 Cumulative gamma doses due to cosmic rays and total gamma doses in air in Ho Chi Minh city measured by the TLD dosimeters

Time period	Period 1 (rainy season)		Period 2 (dry season)		Period 3 (dry season)		Period 4 (rainy season)	
Parameters	D_{cos}* (μSv/h)	D_{total}** (μSv/h)	D_{cos} (μSv/h)	D_{total} (μSv/h)	D_{cos} (μSv/h)	D_{total} (μSv/h)	D_{cos} (μSv/h)	D_{total} (μSv/h)
Minimum value	0.044	0.082	0.049	0.085	0.046	0.084	0.046	0.084
Maximum value	0.050	0.100	0.068	0.153	0.055	0.116	0.051	0.103
Mean value	0.048	0.091	0.060	0.111	0.051	0.096	0.048	0.094
Standard deviation	0.002	0.004	0.006	0.016	0.004	0.007	0.002	0.004
Contribution of cosmic	0.048		0.060		0.051		0.048	
Contribution of soil	0.044		0.051		0.045		0.045	

* D_{cos}: cumulative gamma dose rate due to cosmic rays

** D_{total}: total cumulative gamma dose rate in air

According to the UNSCEAR report, the average dose rate of cosmic rays at sea level is about 0.030 μSv/h, while the world average terrestrial dose rate is about 0.059 μSv/h [1, 2]. The average gamma dose rate of cosmic rays in Ho Chi Minh city obtained in this measurement is greater than the world average value by a factor of 1.7, while that of terrestrial component is smaller by a factor of 0.8.

Conclusions

Assessment of gamma doses in air at in Ho Chi Minh city, Vietnam has been conducted using the FAG FH 40 dosimeter installed on a motobike driven around the city. Measurement of the cumulative gamma dose rates in rainy and dry seasons and the contribution of cosmic rays has also been conducted using 20 TLD dosimeters at fixed locations. It was found that the gamma dose rates measured in air in the city vary in the range of 0.05–0.18 μSv/h with the average value of about 0.10 μSv/h. The lowest gamma dose rates in each district are about 0.05–0.09 μSv/h, while the highest values are about 0.13–0.18 μSv/h. The contribution of cosmic rays in the total gamma dose rates is about 53%. The measurement of cumulative gamma dose rates shows that the average dose rate in the dry season is greater than that in the rainy season by about 15%.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest regarding the publication of this paper.

References

1. UNSCEAR (2000) Radiation sources and effects of ionizing radiation. In: Report of the United Nations scientific committee on the effect of atomic radiation to general assembly, Technical report. United Nations, New York
2. UNSCEAR (2008) Sources and effects of ionizing radiation, Annex B: exposures of the public and workers from various sources of radiation. United Nations, New York
3. UNSCEAR (1993) Sources and effects of ionizing radiation. In: United Nations scientific committee on the effect of atomic radiation. United Nations, New York
4. Lin PH, Chen CJ, Huang CC, Lin YM (1986) Measurement of cosmic-ray induced ionization intensity. Radiat Prot Dosim 15:185–189. https://doi.org/10.1093/oxfordjournals.rpd.a079690
5. Inoue K, Fukushi M, Le TV, Tsuruoka H, Kasahara S, Nimelan V (2020) Distribution of gamma radiation dose rate related with natural radionuclides in all of Vietnam and radiological risk assessment of the built-up environment. Sci Rep 10:12428. https://doi.org/10.1038/s41598-020-69003-0
6. Inoue K, Sahoo SK, Veerasamy N, Kasahara S, Fukushi M (2020) Distribution patterns of gamma radiation dose rate in the high background radiation area of Odisha, India. J Radioanal Nucl Chem. https://doi.org/10.1007/s10967-020-07176-8
7. Le TV, Inoue K, Tsuruoka H, Fujisawa M, Arai M, Nguyen LDH, Somboon S, Fukushi M (2017) Effective dose due to terrestrial gamma radiation estimated in Southen Vietnam by carborne survey technique. Radiat Prot Dosim. https://doi.org/10.1093/rpd/ncx185
8. Huang YJ, Guo GY, He Y, Yang LT, Shan Z, Chen CF, ShangGuan ZH (2016) A comparative study of terrestrial gamma dose rate in air measured by thermoluminescent dosimeter, portable survey meter and HPGe gamma spectrometer. J Environ Radioact 164:13–18. https://doi.org/10.1016/j.jenvrad.2016.06.020
9. Losana MC, Magnoni M, Righino F (2001) Comparison of different methods for the assessment of the environmental gamma dose. Radiat Prot Dosim 97(4):333–336. https://doi.org/10.1093/oxfordjournals.rpd.a006683
10. Bui VL, Leuangtakoun S, Bui TH, Vu TKD, Le TN, Duong TD, Singsoupho S, Tran HN (2020) Natural radioactivity and radiological hazards in soil samples in Savannakhet province, Laos. J Radioanal Nucl Chem 323:303–315. https://doi.org/10.1007/s10967-019-06965-0
11. Leuangtakoun S, Phan GTT, Duong TD, Le NT, Khong NK, Singsoupho S, Tran HN, Bui VL (2020) Natural radioactivity measurement and radiological hazard evaluation in surface soils in a gold mining area and surrounding regions in Bolikhamxay province, Laos. J Radioanal Nucl Chem 326:997–1007. https://doi.org/10.1007/s10967-020-07408-x
12. Van Bui L, Duong VH, Nguyen TD, Leuangtakoun S, Duong DT, Vu AH, Vu AD, Tran HN, Nguyen VD, Vuong THT (2021)

Natural radionuclides and assessment of radiological hazards in different geological formations in Khammouan province, Laos. J Radioanal Nucl Chem 329:991–1000. https://doi.org/10.1007/s10967-021-07854-1
13. Beck H, Decompo J, Gologak J (1972) In-situ Ge (Li) and NaI (Tl) Gamma Ray Spectrometry. In: Health and safety laboratory. US Atomic Energy Commission Report, 258
14. Lin YM, Chen CJ, Lin PH (1996) Natural background radiation dose assessment in Taiwan. Environ Int 22(I):45–48. https://doi.org/10.1016/S0160-4120(96)00087-6
15. Graham CL, Homann SG (1977) Gamma-ray dosimetry errors with TLDs. In: International symposium on national and international standardization in radiation dosimetry. Atlanta, Georgia
16. Shetty PG, Sahu SK, Takale RA, Swarnkar M, Karunakara N, Pandit GG (2017) Measurement of environmental gamma dose levels around Udupi district of coastal Karnataka, India. J Radioanal Nucl Chem. https://doi.org/10.1007/s10967-017-5306-y
17. Gaso MI, Segovia N, Gonzalez PR, Lopez MC (2013) Gamma dose rate due to natural and manmade radiation sources from a nuclear facility in Mexico. J Radioanal Nucl Chem 296:1213–1218. https://doi.org/10.1007/s10967-012-2386-6
18. Liu C, Benotto M, Ungar K, Chen J (2022) Environmental monitoring and external exposure to natural radiation in Canada. J Environ Radioact 243:106811. https://doi.org/10.1016/j.jenvrad.2022.106811
19. Srinivas Reddy M, Suman G, Vinay Kumar Reddy K, Sreenath Reddy M, Gopal Reddy Ch, Yadagiri Reddy P (2021) Natural background gamma radiation dose estimation in the surrounding villages of Devarakonda Town, Telangana State, India. J Radioanal Nucl Chem. https://doi.org/10.1007/s10967-021-07875-w
20. Huy NQ, Luyen TV (2005) Study on external exposure doses from terrestrial radioactivity in Southern Vietnam. Radiat Protect Dosim 118:331–336. https://doi.org/10.1093/rpd/nci341
21. Huy NQ, Hien PD, Luyen TV, Hoang DV, Hiep HT, Quang NH, Long NQ, Nhan DD, Binh NT, Hai PS, Ngo NT (2012) Natural radioactivity and external dose assessment of surface soils in Vietnam. Radiat Prot Dosim 151:522–531. https://doi.org/10.1093/rpd/ncs033
22. Ba VN, Van Thang N, Dao NQ, Thu HNP, Loan TTH (2019) Study on the characteristics of natural radionuclides in surface soil in Ho Chi Minh city, Vietnam and radiological health hazard. Environ Earth Sci 78:28. https://doi.org/10.1007/s12665-018-8026-x
23. Nguyen PTH, Nguyen VT, Vu NB, Nguyen VD, Le Cong H (2018) Soil radon gas in some soil types in the rainy season in Ho Chi Minh City Vietnam. J Environ Radioact 193–194:27–35. https://doi.org/10.1016/j.jenvrad.2018.08.017
24. Thu HNP, Thang NV, Loan TTH, Dong NV, Hao LC (2019) Natural radioactivity and radon emanation coefficient in the soil of Ninh Son region Vietnam. Appl Geochem 104:176–183. https://doi.org/10.1016/j.apgeochem.2019.03.019
25. Tran DK, Truong Y, Le NS, Nguyen VP, Tran HN (2020) Environmental radioactivity and associated radiological hazards in surface soils in Ho Chi Minh City Vietnam. J Radioanal Nucl Chem 326:1773–1783. https://doi.org/10.1007/s10967-020-07466-1
26. NEA-OECD (1979) Exposure to Radiation from Natural Radioactivity in Building Materials. In: Report by NEA group of experts. OECD, Paris