In order to assess radiological exposure of the public due to natural occurring radioactive materials from gold mining areas of Betare-Oya and vicinity, Eastern Cameroon, a preliminary study was carried out in 2015 for laboratory measurements of activity concentrations of primordial radionuclides. In terms of annual effective dose, results revealed a mean value of 0.34 mSv y⁻¹. However, it was necessary to make air absorbed dose rate contour map for a detailed evaluation of external dose. For this purpose, a car-borne survey using a 3-in × 3-in NaI(Tl) scintillation spectrometer was carried out in Betare-Oya and vicinity. Absorbed dose rates in air ranged from 23 to 80 nGy h⁻¹ with a mean value of 44 ± 7 nGy h⁻¹. The average values of activity concentrations in soil of ⁴⁰K, ²³⁸U and ²³²Th were 197 ± 21 Bq kg⁻¹, 37 ± 13 Bq kg⁻¹ and 32 ± 7 Bq kg⁻¹ respectively. ²³²Th was found to be the main contributor to the absorbed dose rate in air from outdoor terrestrial radiation in the study areas with a mean value of 43%. External annual effective dose ranged from 0.17 to 0.60 mSv y⁻¹ with a mean value of 0.33 ± 0.05 mSv y⁻¹, in agreement with the result (0.34 mSv y⁻¹) of the previous study performed in the same areas using gamma spectrometry in laboratory for radioactivity measurements in soil samples. This survey first and widely revealed an aspect of natural radiation exposures in soil mining areas of Eastern Cameroon.

KEY WORDS: absorbed dose rate in air, annual effective dose, car-borne survey, Betare-Oya, gold mining, dose rate contour map.

I INTRODUCTION

Continuous irradiation of human beings by ionizing radiation leads to external and internal exposures related mainly to sources of natural radioactivity.¹⁻³ Among the notable sources of natural radiation exposures, there are cosmic rays and radionuclides of terrestrial origin. Varying with altitude, the worldwide average dose rate in free air at sea level of external irradiation associated with charged particles of cosmic radiation is 31 nGy h⁻¹.⁴ ⁴⁰K and the members of the radioactive decay chain of ²³⁸U and ²³²Th series are the main isotopes responsible for terrestrial irradiation.⁵, ⁶ These primordial radionuclides contribute to 35% (⁴⁰K), 25% (²³⁸U) and 40% (²³²Th) on the terrestrial absorbed dose rate in air as gamma radiation.⁷ The global mean value of this dose according to the distribution of the population ranges from 50–59 nGy h⁻¹.⁷⁻⁹ Cameroon has one of the richest sub-soils in sub-Saharan central Africa in terms of mineral resources (rutile, diamond, iron, bauxite, gold, etc). Gold production in Cameroon dates from 1934 with a peak production of 717 kg in 1942.¹° This production is mainly carried out in the East region of Cameroon, particularly in the towns of Yokadouma, Garoua-Boulai, Batouri and Betare-Oya.¹¹ Nowadays exploitation of gold has been transformed into a semi-industrial activity, which remained purely artisanal until the dawn of the 2000s.¹² This activity is often accompanied by pollution of the environment by radioactive materials. Although several studies have been carried out on natural radiation exposure in Cameroon,¹³⁻¹⁷ there are very few research results available on environmental radioactivity in mining areas. DALLOU et al.¹⁵ evaluated natural radiation exposure to the public in the gold mining areas of Eastern Cameroon, particularly in Batouri and Betare-Oya. Activity concentrations
of natural radionuclides were determined using gamma spectrometry to analyze 32 soil samples collected from these areas. The corresponding mean external annual effective dose to the public was 0.34 mSv y⁻¹.

The objective of the present study is to establish for the first time, a dose contour map of the study area for detailed evaluation of external radiation dose. For this purpose, in situ measurement campaign by car-borne survey technique using a 3-in × 3-in NaI(Tl) scintillation spectrometer was carried out in Betare-Oya from July 8 to 10, 2016. The data obtained in the frame of this study will also be used to compare the results with those recently published for the same areas.

II MATERIALS AND METHODS

1. Survey areas

This study was carried out in the town of Betare-Oya and also on the main road linking Betare-Oya to its surrounding localities (Ndokayo and Mali) as shown in Fig. 1. This route map was drawn using the Generic Mapping Tools (GMT) created by Wessel and Smith. With a population of about 70,000 inhabitants in 2011, the region is located in the Southern Cameroon plateau with heights ranging from 700 m to 900 m. It is characterized by a monotonous landscape of undulating hill-shaped domes. The study area is dominated by several abandoned open pits scattered in areas of ancient or recent gold mining. These pits are of various sizes that can reach 200 m² and often contain stagnant water. This situation leads to a severe disturbance of the land surface and the disappearance of the cultivable land and increases the risk of contamination.

2. Car-borne survey

The detailed method of the car-borne survey was described in many publications, only an outline is described here. A car-borne survey which used a 3-in × 3-in NaI(Tl) scintillation spectrometer (EMF-211, EMF Japan Co., Japan) was carried out in the gold mining areas of Betare-Oya from July 8 to 10, 2016. This spectrometer was positioned inside the car and the car speed was kept around 30–40 km h⁻¹. Measurements of the counts inside the car were carried out every thirty seconds (30-s) along the route. In order to generate a dose rate distribution map, the latitude and longitude coordinates were recorded using a global positioning system (GPS) in each measurement point at the same time as the gamma-ray count rates. Since count rate is measured inside the car, it is necessary to estimate a shielding factor of the car body towards terrestrial gamma-rays in order to represent the unshielded external dose rate. The shielding factor was estimated by making measurements inside and outside the car at 10 points. Those measurements were recorded consecutively at 30-s intervals during a total recording period of 2 min. Measurements of gamma-ray pulse height distributions were

Fig. 1 The route map of the study area a), detailed location of Betare-Oya town b) and measurement points of gamma ray pulse height distribution using a NaI(Tl) scintillation spectrometer.
also carried out 1 m above the ground surface outside the car for 15 min at 24 points along the survey route. The gamma-ray pulse height distributions were unfolded using a 22 × 22 response matrix for the estimation of absorbed dose rate in air.26, 27 These dose rates were used to evaluate the dose rate conversion factor (nGy h⁻¹ cpm⁻¹) because, it is difficult to obtain the photon peak for each gamma-ray energy in a 30-s measurement in the natural environment. In fact, photon peaks obtained with the NaI(Tl) scintillation detector are affected by air temperature.28

3. Activity concentrations and the contribution of ⁴⁰K, ²³⁸U and ²³²Th to absorbed dose rate in air

In order to evaluate activity concentrations in soil, the 24 measurement points shown on Fig.1, used for the evaluation of the conversion factor of absorbed dose rate in air were considered. The calculation methodology for the activity concentration and the contribution of ⁴⁰K, ²³⁸U and ²³²Th to absorbed dose rate in air are well described by HOSODA et al.20, 23 The respective standard deviations of absorbed dose rate and activity concentrations for ⁴⁰K, ²³⁸U and ²³²Th depend on the integral absorbed dose (nGy) at each measurement point,29 and these were evaluated in this study as 2–3%, 1–3%, 5–9% and 3–6%, respectively.

4. External annual effective dose estimation

The total external annual effective dose \( E_{\text{ext}} \) (mSv y⁻¹), due to gamma rays from primordial radionuclides in the study area was calculated using equation (1), which takes into account of the indoor and outdoor contributions of external exposure:4

\[
E_{\text{ext}} = F_c \times D \times T \times \left[ (1 - I_{\text{in}}) + SF \times I_{\text{in}} \right] \quad (1)
\]

where \( F_c \) is the dose conversion factor from dose rate to the external effective dose for adults (0.7 Sv y⁻¹), \( D \) is the absorbed dose rate in air, \( I_{\text{in}} \) is the indoor occupancy factor (0.6), which implies that people spend 40% of their time outdoors.30 Most of houses in the study area were built using soil bricks made with soil collected around the houses. However, since the materials used in the construction of most of buildings contain natural radionuclides, the average shielding factor \( SF \) of 1.4 was applied to take into account of their contribution and estimate the indoor rate.13 \( T \) is the number of hours in one year (8,760 h y⁻¹).

III RESULTS AND DISCUSSION

1. Shielding and dose rate conversion factors

The distribution of the total count rates (counts per 30-s) measured inside and outside of the car is shown in Fig. 2. The slope of this regression line gives the shielding factor of the car used which was found to be 1.6. This value falls in the range (1.3–1.9) as reported by other studies.20, 23, 24 Fig. 3 shows the correlation between absorbed dose rate in air (nGy h⁻¹) calculated using the 22 × 22 response matrix method and count rate outside the car (cpm). The slope of this regression line was used as the dose rate conversion factor which was found to be \( 1.8 \times 10^{-3} \) nGy h⁻¹ cpm⁻¹.

2. Distribution map of absorbed dose rate in air

With shielding and dose rate conversion factor values, the absorbed dose rates in air \( (D) \) outside the car, 1 m above the ground surface at each measurement points can be estimated using the following equation:

\[
D = 2N_{\text{in}} \times 1.6 \times 1.8 \times 10^{-3} \quad (2)
\]

where \( N_{\text{in}} \) is the count inside the car during 30-s which is doubled in order to convert into the counts per minute. The contour map of the absorbed dose rates in air is shown in Fig. 4 (a and b) which presents a heterogeneous distribution of the air absorbed dose rate. Fig. 4a shows the dose rate of all the study areas (Betare-Oya town and vicinity) which ranged from 23 to 80 nGy h⁻¹ with a mean value of 44 ± 7 nGy h⁻¹.
The highest absorbed dose rate was observed on asphalt road around NDOKAYO. In the Southern part of the survey route (Fig. 4a), one observes a relative high absorbed dose rates in air. This shall be investigated in detail within the framework of a future work. The lowest absorbed dose rate was observed near Mali village on a dirt road.

Fig. 4b (Betare-Oya town) was also produced by the GMT software. The air absorbed dose rate distribution model was based on a constant one second (1 s) interval gridding of all the raw data. A minimum curvature algorithm with a tension factor of 0.25 was used to interpolate all the raw air absorbed dose rate data in a constant 1 s interval. The average value of air absorbed dose rate was 40 nGy h⁻¹ ranged from 30 to 62 nGy h⁻¹.

3. Contribution to absorbed dose rate in air and activity concentrations of ⁴⁰K, ²³⁸U and ²³²Th

Table 1 shows primordial radionuclide activity concentrations with related contribution in absorbed dose rate in air. The contributions (%) to absorbed dose rate in air of ⁴⁰K, ²³⁸U and ²³²Th range from 5 to 40, 28 to 47 and 29 to 63 with mean value of 22, 36 and 43 respectively as shown in Fig. 5. It can be seen that ²³²Th is the main contributor to the absorbed dose rate in air from outdoor terrestrial radiation in the study areas. Fig. 6 presents the distribution of activity concentrations of primordial radionuclides in study area. For ⁴⁰K, activity concentrations range from 16 to 414 Bq kg⁻¹ with a mean value of 197 ± 21 Bq kg⁻¹ corresponding to 48% of the worldwide average value (412 Bq kg⁻¹). Values of activity concentrations of ²³⁸U vary from a low of 29 Bq kg⁻¹ to a high of 63 Bq kg⁻¹ with a mean value of 37 ± 13 Bq kg⁻¹ slightly above the worldwide average value of 33 Bq kg⁻¹ given by UNSCEAR. Activity concentration of ²³²Th ranges between 13 and 87 Bq kg⁻¹ with a mean value of 32 ± 7 Bq kg⁻¹ lower than the worldwide average value (45 Bq kg⁻¹).

4. Comparison between in situ and laboratory activity concentration of ⁴⁰K, ²³⁸U and ²³²Th

Comparative analyses were done between in situ and laboratory measurements and the ratio; 0.91, 0.91 and 1.09 were obtained for ⁴⁰K, ²³⁸U and ²³²Th, respectively, as shown in Table 2.

A slight difference between the two methods could be explained by the fact that, in situ gamma spectrometry gives representative source concentration in the horizontal plane. In practice, an infinite half space can be taken as a large area of open ground with a radius up to 70 m, where there are few obstructions while gamma spectrometry in laboratory measures radioactivity in soil samples collected from the top 5 cm of a 1 m² area providing a dry mass of approximately 500 g. Table 2 suggests that the two methods are in agreement.
ranges from 0.17 to 0.60 mSv y\(^{-1}\) with the mean value of obtained previously with laboratory measurements in 2015. 5) However, using F\(_c\) (0.748 Sv y\(^{-1}\)) revised by MORUCHI 32) from the revised tissue weighting factor in ICRP publication 103 33) the new mean value of external annual effective dose will be 0.35 mSv y\(^{-1}\), which is about 6% greater than the result obtained using UNSCEAR F\(_c\) factor.

### IV CONCLUSION

A gamma in situ measurement campaign by car-borne...
method was performed from July 8 to 10, 2016 in the gold mining area in Eastern Cameroon. Data obtained from this campaign allowed the establishment of a detailed dose distribution map of the study area. Activity concentrations of $^{40}$K, $^{238}$U and $^{232}$Th were determined and their values ranged respectively from 16 to 414 Bq kg$^{-1}$, 29 to 63 Bq kg$^{-1}$ and 13 to 87 Bq kg$^{-1}$ with respective average values of 197 ± 21 Bq kg$^{-1}$, 37 ± 13 Bq kg$^{-1}$ and 32 ± 7 Bq kg$^{-1}$. The contributions of $^{40}$K, $^{238}$U and $^{232}$Th to absorbed dose rate in air range respectively from 5 to 40%, 28 to 47% and 29 to 63%. $^{232}$Th was the main contributor to absorbed dose rate in air with a mean value of 43%. The external annual effective dose of all the study area ranged from 0.17 to 0.60 mSv y$^{-1}$ with a mean value of 0.33 ± 0.05 mSv y$^{-1}$. This mean value is in agreement with the value reported in a previous publication 5) using gamma spectrometry measurements of soil samples at laboratory followed by corresponding external dose assessment.

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Table 2 In situ and laboratory measurements of activity concentrations of $^{40}$K, $^{238}$U and $^{232}$Th and their respective ratios for comparison.

| Radionuclides | In situ measurements (Bq kg$^{-1}$) | Laboratory measurements (Bq kg$^{-1}$) | Ratio (In situ/Laboratory) |
|---------------|-----------------------------------|---------------------------------------|---------------------------|
| $^{40}$K       | $^{238}$U                          | $^{232}$Th                              |                           |
| 197 ± 21       | 216.9                              | 24.9                                   | 0.91                      |
| $^{238}$U      | $^{232}$Th                          |                                        | 1.09                      |
| 37 ± 13        | 28.4                               |                                       |                           |
| $^{232}$Th     |                                    |                                        |                           |
| 32 ± 7         | 129.4                              |                                       |                           |

Fig. 6 Distribution of activity concentrations of $^{40}$K, $^{238}$U and $^{232}$Th in soil.
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