A unique high natural background radiation area in Indonesia: a brief review from the viewpoint of dose assessments

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Abstract
Some areas around the world have anomalies with high natural radiation that may affect public health due to chronic-low-dose radiation exposure. In the paper, we summarized several studies that find Mamuju, Indonesia, a unique high natural radiation area. The majority of the relevant papers are about monitoring, main sources, and influential factors for the enhancement of radon and dose assessments. Under these circumstances, the Mamuju region is regarded as a promising area for conducting epidemiological studies, and it will provide a unique opportunity for improving and expanding low-dose-rate data on human health effects.

Keywords
High natural background radiation area · Public health · Chronic-low-dose radiation exposure · Natural radiation

Introduction
Some populations are exposed to natural background radiation at several-fold higher levels than the worldwide average: as much as 2.4 mSv annually. This situation may pose a health risk to the public due to the chronic external and internal exposures. Health studies of populations living in high natural background radiation areas (HNBRA) can serve as a potential source of information on the effects of chronic low-dose-rate exposures. Although the studies of atomic bomb survivors provide strong evidence of health effects such as cancer and noncancerous diseases associated with a single acute exposure to moderate-to-high doses of ionizing radiation, the effect of low dose rates on health and cancer risks after exposure to ionizing radiation is as yet unclear [1, 2].

Some studies in HNBRA focusing on Yangjiang (China) and Kerala (India) have received attention in recent years [2–7]. Based on studies in Kerala, India, it was found that external radiation makes a significant contribution to the annual effective dose. Whereas in Yangjiang, internal exposure was a major contributor to the annual effective dose [4].

Recently, another area of high natural radiation has been found in Mamuju, West Sulawesi Province of Indonesia. This area still has natural landscapes, and there is no mining activity. We will discuss in full detail research in this area with several studies that have been carried out, as shown in Table 1.

A unique high natural background radiation area: research background
Indonesian Law No. 10 of 1997 concerning nuclear power emphasizes that every activity related to the use of nuclear...
energy must pay attention to safety, security, the health of workers and community members, as well as protection of the environment [19]. Furthermore, the law is further elaborated in Government Regulation no. 33 of 2007 concerning the safety of ionizing radiation and the safety of radioactive sources [20]. The Center for Technology of Radiation Safety and Metrology (PTKMR) is a working unit of National Nuclear Energy Agency of Indonesia (BATAN) with the task of formulating and controlling technical policies, implementation, and guidance in research and development in the fields of radioecology, nuclear medicine and biology radiation, occupational safety and dosimetry, and radiation metrology. The radioecology sector has the task of carrying out research and development and services in radioecology and environmental safety at the national level. In line with this task, the Radioecology Division of PTKMR has carried out mapping of radiation and environmental radioactivity throughout Indonesia.

This radiation mapping in Indonesia found several areas with high levels of natural radiation, such as Mamuju Regency-West Sulawesi Province, Biak Island-Papua Province, Tual Island-Maluku Province, and others. Of the several areas with high levels of natural radiation, Mamuju Regency has the highest and most extensive levels of natural radiation [21].

In the Mamuju area, points are showing high levels of environmental radiation. Nationally, the average environmental gamma radiation dose rate in Mamuju Regency is nine times the average radiation dose in Indonesia (national average = 50 nSv h⁻¹). The average radiation dose rate in Takandeang-Mamuju village is 22 times the average national environmental gamma radiation dose. In addition, in the village of Botteng-Mamuju, an environmental gamma radiation dose of 10,000 nSv h⁻¹ was found, which is 200 times the national average [21]. However, the dose of internal exposure in these areas is still unknown. Therefore, in 2015, BATAN started collaborating with Hirosaki University on comprehensive environmental radiation and radioactivity assessments at Mamuju.

### Study area

Mamuju Regency is located at position 1° 38' 110"–2° 54’ 552" south latitude and 11° 54" 47”–13° 5” 35" east longitude. Mamuju Regency is the largest district in West Sulawesi Province, with an area of 5056 km². Rivers and mountainous topography can be found across almost all sub-districts in Mamuju Regency. In 2013 Mamuju district was divided into the districts of Mamuju and Mamuju Tengah. Then Mamuju district has 11 sub-districts with 88 villages and 11 sub-districts [22].

The population of Mamuju City is 252,295, with businesses in the agricultural sector accounting for 62.2% of the total workforce. Some of the Mamuju residents are transmigrants from other areas in Indonesia, and some are local indigenous residents who have lived there for 3–5 generations. Judging from the quality of the housing

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### Table 1: List of studies in Mamuju

| Type of studies                                      | Area of sampling                  | References                  |
|------------------------------------------------------|-----------------------------------|-----------------------------|
| Man-borne survey of radiometric using NaI(Tl) detector for radioactive mineral exploration | All Mamuju Area                  | Syaeful et al. [8]                      |
| Geosciences                                          | West Sulawesi Province            | Sukadana et al. [9]          |
|                                                      | All Mamuju area                   | Mu’awanah et al. [10]        |
|                                                      | All Mamuju area                   | Sukadana et al. [11]         |
| Rock and soil measurements                           | Ahu, Takandeang, Botteng, Taan, Hulu Mamuju | Rosianna et al. [12]         |
|                                                      | Northern Botteng                  | Nurokham et al. [13]         |
|                                                      | All Mamuju area                   | Nugraha et al. [14]          |
| Ambient dose                                          | Northern Botteng                  | Shilha et al. [15]           |
|                                                      | Botteng Village                   | Hosoda et al. [16]           |
|                                                      | All Mamuju area                   | Nugraha et al. [14]          |
| Dose assessment in drinking water                     | All Mamuju area                   | Nugraha et al. [14]          |
|                                                      | Botteng Village                   | Hosoda et al. [16]           |
|                                                      | All Mamuju Area                   | Nugraha et al. [14]          |
| Radon and thoron in dwelling                          | Takandeang Village                | Saputra et al. [18]          |
|                                                      | Botteng Village                   | Hosoda et al. [16]           |
|                                                      | All Mamuju                       | Nugraha et al. [14]          |
| Radioactivity concentration in foodstuff              | All Mamuju                       | Nugraha et al. [14]          |
| Comprehensive dose assessment                         | All Mamuju                       | Nugraha et al. [14]          |
type, most household wall types use wood (57.6%) and walls with cement floors (42.8%) [22].

Most of the diseases suffered by the community were upper respiratory tract infection, with 56,243 cases [22]. The Mamuju region has a tropical climate with two seasons: the dry season from April to September and the rainy season from October to March (Fig. 1).

Geological aspects and naturally occurring radioactive materials in rock and soil samples

Mamuju is located on Sulawesi Island, which has a very complex geological arrangement. This complex tectonics is the result of the interaction of three actively moving plates, namely the Australian Continental Plate moving to the north, the movement of the Pacific Ocean Plate moving to the west, and the Eurasian Continent Plate, which is moving to the south-southeast, relatively. According to Sukadana

Fig. 1 The map of Mamuju and its surrounding area
et al., the Mamuju area is heavily influenced by the rock formation of the Adang volcano [9]. Volcanic rocks of the Adang complex are composed of trachyte, tephra-phonolite, phono-tephrite, and phonolite rocks with ultrapotassic affinity formed in the active continental margin arrangement with the micro-continental crust of the SW Sulawesi block [9].

Syafaeful et al. reported that the highest uranium content, which is ~1000 Bq kg\(^{-1}\), in soil was observed using a NaI(Tl) scintillation spectrometer in the study area [8]. This is similar to the results carried out by Hosoda et al., which found the estimated activity concentrations in soil ranged from 223–1807 Bq kg\(^{-1}\) for potassium (40K), 190–3706 Bq kg\(^{-1}\) for uranium (238U) and 340–1102 Bq kg\(^{-1}\) for thorium (232Th), respectively [12].

Rosianna et al. reported measurements of radioactivity in rock samples from the type of trachyte, tephra-phonolite, phono-tephrite, phonolite, and breksi rock in several areas of Mamuju using a high-purity germanium detector (HPGe) with an activity concentration of 238U from 539–128,699 Bq kg\(^{-1}\) and 232Th from 471–288,639 Bq kg\(^{-1}\) [12].

Nurokhim et al. reported measuring soil samples in Northern Botteng Village by using a HPGe detector with activity concentrations of radium (226Ra), 232Th and 40K 269–2921, 993–3154 and 116–438 Bq kg\(^{-1}\), respectively [13]. Similar results reported by Nugraha et al. were measuring radioactivity in the soil over the entire Mamuju area using a HPGe detector showed average activity concentrations of 238U, 232Th, and 40K were 1387 Bq kg\(^{-1}\), 1468 Bq kg\(^{-1}\), and 301 Bq kg\(^{-1}\), respectively. The 238U activity concentration ranged from 570–3456 Bq kg\(^{-1}\), 232Th activity concentration ranged from 819–3577 Bq kg\(^{-1}\), and 40K activity concentration ranged from 121–555 Bq kg\(^{-1}\). Dominant areas for 238U include Botteng and Taan Villages, and dominant areas for 232Th include Takandeang, Northern Botteng, and Ahi [14]. This value is significantly higher than that of the worldwide average value reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The Worldwide average values of 40K, 238U and 232Th, were reported as 412 Bq kg\(^{-1}\), 33 Bq kg\(^{-1}\) and 45 Bq kg\(^{-1}\), respectively. The activity concentrations of natural radionuclides in soil have a wide variability, with reported levels of up to 1000 Bq kg\(^{-1}\) for 238U and 360 Bq kg\(^{-1}\) for 232Th and 3200 Bq kg\(^{-1}\) for 40K [1].

Terrestrial gamma radiation

According to the Indonesian gamma radiation map and Alatas et al. in 2014, the Mamuju region has an ambient dose equivalent rate of 100–2800 nSv h\(^{-1}\) [21, 23]. Furthermore, Hosoda et al. in 2015 carried out a car-borne survey using a NaI(Tl) scintillation gamma spectrometry. The absorbed dose rates in the air north and south of Mamuju City are significantly lower than those in Mamuju City itself. The absorbed dose rates in the air around Mamuju City, including Botteng Village, vary widely between 50 and 1109 nGy h\(^{-1}\) with a median value of 366 nGy h\(^{-1}\). The absorbed dose rate in Botteng Village has ranged between 417 to 814 nGy h\(^{-1}\), with a median value of 623 nGy h\(^{-1}\) [16].

Shilfa et al. in 2020 conducted indoor ambient dose rate monitoring using an optically stimulated luminescent dosimeter (OSLD) (Nagase, Japan) in Northern Botteng Village with a range of 420–1430 nSv h\(^{-1}\) [15]. While Nugraha et al. in 2021 reported indoor and outdoor measurements in 450 houses in whole Mamuju areas using pocket survey meters. The measurement was carried out in 200 houses in normal background radiation areas (NBRA); Topoyo and 250 houses in high radiation areas; Botteng, Takandeang, Northern Botteng, Ahu and Taan Villages. The measurement results of ambient dose equivalent rates in the HNBRRA for residential houses indoors had a geometric mean (GM) of 551 nSv h\(^{-1}\) with a range of 250–1653 nSv h\(^{-1}\); the rates outdoors had a GM of 613 nSv h\(^{-1}\) with a range of 200–2300 nSv h\(^{-1}\). The measurement results of ambient dose equivalent rates in the indoor control area had a GM of 81 nSv h\(^{-1}\) with a range of 38–127 nSv h\(^{-1}\); the outdoor rates had a GM of 71 nSv h\(^{-1}\) with a range of 39–116 nSv h\(^{-1}\). Indoor-to-outdoor dose rate ratio in the HNBRRA had a range of 0.57–1.51 with a GM of 0.90, and for the control area had a range of 0.66–2.02 with a GM 1.13 [14]. From these results, there are differences between HNBRRA and NBRA. The HNBRRA areas have higher ambient dose equivalent rates outdoor than indoor, while in NBRA, the indoor ambient dose equivalent rate values are slightly higher than outdoor. This may be the influence of the building materials used. In Topoyo Village (NBRA) and Salugatta Village (a medium radiation area), the houses are made with brick walls and ceramic floors. Meanwhile most houses in the HNBRRA have wood walls and coated cement floors. This indicates that the radiation originates from outside the house because inside, there is a shielding effect.

Measurement radon, thoron and thoron progeny

Hosoda et al. conducted simultaneous indoor and outdoor radon measurements at traditional style houses using a pulse-type ionization chamber (AlphaGUARD PQ2000PRO, Saphymo GmbH, Germany) in Botteng Village for 3-day measurement. This measurement aimed to obtain the time variation of indoor and outdoor radon concentrations. Indoor and outdoor radon concentrations ranged between 24–566 Bq m\(^{-3}\) and 30–552 Bq m\(^{-3}\), respectively. Surprisingly, the outdoor radon concentrations have the same activity concentration or higher than those indoors. Even though there is an adequate ventilation at homes in the study area, this is not a sufficient countermeasure against indoor radon
under such circumstances. This aspect is what makes the Mamuju area a unique HNBRA [16].

Outdoor and indoor radon concentrations are strongly influenced by many factors such as meteorological parameters, geology, building materials, building construction type and the degree of ventilation of closed environments. Therefore, for dose assessment, it is necessary to measure long-term radon concentrations. Furthermore, Hosoda et al. also conducted indoor radon measurements in 47 Botteng Village houses using a passive radon-thoron discriminative detector namely RADUET® (Radosys, Hungary) [24]. The radon activity concentration ranged from 124 to 1015 Bq m\(^{-3}\), and the median and GM were calculated to be 369 and 398 Bq m\(^{-3}\), respectively [14, 25]. Saputra et al. in 2020 reported the average activity concentration of indoor radon, thoron, and thoron progeny in 45 houses in Takandeang Village using RADUET® and thoron progeny detector (CR-39) were 221, 152, and 13 Bq m\(^{-3}\), respectively. As for outdoor radon, thoron, and thoron progeny, the concentration activities were 208, 139, 15 Bq m\(^{-3}\), respectively [18]. Nugraha et al. reported in full the radon measurements for 408 houses in the entire Mamuju area using RADUETs®. Radon concentrations in the HNBRA (Botteng, Takandeang, Northern Botteng, Ahu, Taan) had a GM of 270 Bq m\(^{-3}\) with a range of 90–1644 Bq m\(^{-3}\) while \(^{220}\)Rn concentrations had a GM of 210 Bq m\(^{-3}\) with a range of 46–2244 Bq m\(^{-3}\). The equilibrium equivalent thoron concentration (EETC) in the HNBRA obtained with the thoron progeny monitor had a range of 2–42 Bq m\(^{-3}\) with a GM of 11 Bq m\(^{-3}\). For the NBRA, the EETC had a range of 0.4–4 Bq m\(^{-3}\) with a GM of 1.9 Bq m\(^{-3}\) [14]. According to this value, more than 90% of the houses in HNBRA exceed the reference level from the World Health Organization (WHO) of 100 Bq m\(^{-3}\), and more than 70% exceed the International Commission on Radiological Protection (ICRP) recommendation of 300 Bq m\(^{-3}\) [26–31].

Influential factors for the enhancement of radon

To discover the reason for the high radon activity concentration in Mamuju, Hosoda et al. reported several measurements regarding time variation of radon, radon exhalation rate, and vertical radon distribution. The indoor concentration of radon in Mamuju increased at night up to 760 Bq m\(^{-3}\) and decreased down to 22 Bq m\(^{-3}\) during the day. This is inversely proportional to the pattern of the radon exhalation rate, where the radon exhalation rate concentration of 256 mBq m\(^{-2}\) s\(^{-1}\) during the day decreased to 91 mBq m\(^{-2}\) s\(^{-1}\) at night [16].

According to vertical radon distribution, and calculated using the Jacobi and Andre model, the atmospheric conditions might become stable a few meters above the ground during the night so that radon gas would accumulate, which might enhance the radon concentration [16].

Natural radionuclide activity concentration in foodstuffs and drinking water samples

Nugraha et al. in 2020 reported a total of 13 drinking water samples were obtained from the HBRA in Mamuju using liquid scintillation countermeasurements, and 18 drinking water samples in 2021 for the entire Mamuju area, including HNBRA and NBRA, had a concentration range of 14–238 mBq L\(^{-1}\). These concentrations are below the World Health Organization recommendation, which is 1 Bq L\(^{-1}\) [14, 17, 32, 33].

Despite having a small concentration of radium in drinking water, the radon concentration in drinking water in Mamuju is very high. For radon concentrations in drinking water, Hosoda et al. reported that seven drinking water measurements by RAD7 (Durridge, USA) in Botteng Village found radon concentrations ranging from 164 to 1114 Bq L\(^{-1}\) [16]. Nugraha et al. in 2021 also carried out as many as 30 drinking water measurements in the Mamuju area, including HNBRA and NBRA, using the same method. Drinking water samples were measured in both the dry season and the rainy season. Radon concentration in drinking water ranged from 1–1141 Bq L\(^{-1}\) in the dry season and 1–652 Bq L\(^{-1}\) in the rainy season. The Environmental Protection Agency (EPA) suggests the maximum concentration limit (MCL) should be 11 Bq L\(^{-1}\), and an alternative maximum concentration level (AMCL) of 148 Bq L\(^{-1}\) is also recommended by the EPA [34, 35]. Several cases of drinking water in Takandeang and Botteng villages contained dissolved \(^{222}\)Rn activity concentrations higher than the MCL and AMCL recommend. Based on the UNSCEAR 2000 report, the AMCL of 148 Bq L\(^{-1}\) is the limit that determines the concentration of \(^{222}\)Rn in the water that will produce an indoor \(^{222}\)Rn increment equal to an outdoor \(^{222}\)Rn activity concentration of 15 Bq m\(^{-3}\) with the transfer coefficient from water to indoor air applied as 1 × 10\(^{-4}\) [1, 35].

Nugraha et al. in 2021 reported measurements of radioactivity in 30 foodstuff samples obtained with a HPGe detector. The respective average activity concentrations for \(^{226}\)Ra, \(^{232}\)Th, and \(^{40}\)K in foodstuffs were rice, 0.4, 6, and 88 Bq kg\(^{-1}\); meat/fish/vegetables, 36, 57, and 972 Bq kg\(^{-1}\); fruits, 7, 7, and 391 Bq kg\(^{-1}\). Almost all foodstuffs in Mamuju have a concentration activity that exceeds the reference value of the International Atomic Energy Agency (IAEA) [36], although they do not exceed a value of about 1 mSv annually [14]. In addition, measurements of Po-210 and Pb-210 in foodstuffs will be carried out in the future.
Estimation of annual effective dose

The effective dose is calculated as the accumulation of the dose received from external and internal exposure. External exposure derives from exposure to environmental gamma radiation, and internal exposure through digestion can occur due to the ingestion of food/drink into the body, while internal exposure through breathing can occur due to inhalation of air containing radioactive substances (e.g., radon, thoron, and thoron progeny). An effective dose calculation methodology can use the equation by UNSCEAR [1].

Hosoda et al. reported the villagers of Botteng, Mamuju received an average annual effective dose of 27 mSv, where this value excludes external exposure due to cosmic radiation, internal exposure due to intake of radioactivity in foodstuffs and inhalation of thoron [16]. Meanwhile, Nugraha et al. reported an annual effective dose more comprehensive than Hosoda et al. including internal exposure due to intake of radioactivity in foodstuffs and internal exposure due to Inhalation from thoron. However, it excluded the contribution of $^{210}\text{Po}$ and $^{210}\text{Pb}$ in foodstuffs and external exposure due to cosmic radiation. That residents of HNBRAs Mamuju received an average annual effective dose of 32 mSv where the geometric mean is 29.7 mSv. This value exceeds the global mean of 2.4 mSv, and also the highest value exceeds the limits of the reference level for existing exposure situations. The most contributed to the annual effective dose comes from radon and thoron progeny. Radon progeny accounted for 48% of the annual effective dose, while thoron progeny, external dose, foodstuffs, and drinking water accounted for 33, 16, 1, and 2%, respectively [14]. It is noted that the estimated dose for all measurements excludes external exposure due to cosmic radiation and internal exposure due to intake of $^{210}\text{Po}$ and $^{210}\text{Pb}$ in foodstuffs.

A comparison characteristic exposure between HNBRAs Mamuju and other previously studied HNBRAs

Some parts of the world have radiation levels above the global average. These HNBRAs include Yangjiang (China), Kerala (India), Ramsar (Iran), Guarapari (Brazil), which have different characteristics.

In India, Kerala is an area with higher natural radiation exposure and has been extensively investigated. The maximum value of the annual effective dose is 13 mSv, mostly from $^{232}\text{Th}$ contribution to air kerma [4]. As for internal exposure, the geometric mean of the annual effective dose due to radon and thoron was calculated as 0.10 and 0.44 mSv, respectively [3]. The presence of monazite and other heavy minerals such as zircon, rutile, and ilmenite causes high radiation levels in this area. As reported by Mohanty et al., radioactivity on bulk sand has values of 350 Bq kg$^{-1}$ for $^{238}\text{U}$, 2825 Bq kg$^{-1}$ for $^{232}\text{Th}$ and 180 Bq kg$^{-1}$ for $^{40}\text{K}$ [37].

In China, Yangjiang is a part of Guangdong province (also known as HNBRAs), which has a large population spanning five generations. The annual effective dose received from external radiation was estimated to be 0.6–1.8 mSv by using CsI(Tl) scintillation survey meters [38]. Meanwhile, Wei et al. reported that the annual dose of external radiation by thermoluminescence dosimeter (TLD) was 2.1 mSv [39]. The internal radiation dose due to radon and thoron were 3.1, 2.2 mSv, respectively [5]. Wei et al. estimates the annual internal effective dose received by residents in Yangjiang from all sources ($^{40}\text{K}$, $^{87}\text{Rb}$, $^{226}\text{Ra}$, $^{222}\text{Ra}$, $^{222}\text{Rn}$, radon progeny and thoron progeny) to be 4.3 mSv. The presence of monazites is a major element in the high radiation exposure in Yangjiang [39].

In Brazil, Guarapari, as well as Minas Gerais State is an HNBRAs with 12,000 inhabitants [40, 41]. The existence of monazite sand on black sand beaches is the main cause of increased radiation exposure in this region, which also contains rare earth elements (REE). It is recorded that radiation exposure in the area reaches 50 µGy h$^{-1}$ [42]. Anjos et al. reported that the Guarapari radiation dose ranges from 3.5 to 10 mSv y$^{-1}$ [43].

In Iran, Ramsar is an HNBRAs caused by $^{226}\text{Ra}$ being carried by hot spring water to the earth’s surface [44]. Sohrabi and Esmaili et al. reported that the annual effective dose is 0.6–131 mSv with a mean of 6 mSv and an indoor radon level of around 31 kBq m$^{-3}$ [45].

In Mamuju, the main sources come from volcanic rocks containing uranium and thorium [9, 11, 12]. The concentrations of uranium and thorium are 42, 33 times greater than the world average, respectively. Similar to uranium and thorium concentrations in soil, atmospheric radon and thoron concentrations have high concentrations. Radon and thoron (thoron progeny) contributed about 81% (26 mSv) to the annual effective dose. Meanwhile, the external effective dose contributed 16% (5 mSv) to the annual effective dose. Thus, Mamuju has a high contribution of internal and external doses. The value of the annual effective dose in Mamuju is 13 times higher than the world average annual effective dose. Furthermore, HNBRAs Mamuju covers a wide geographical area and is heavily populated. Considering this fact, Mamuju can be regarded as a promising area for conducting a risk assessment on HNBRAs through epidemiological studies for understanding health effects related to chronic low-dose-rate radiation exposure. A comparison between the present study of the Mamuju HNBRAs and other previously studied HNBRAs is shown in Table 2. It is noted that the estimated annual effective dose of radon and thoron in the Mamuju study used the dose conversion factor of ICRP 137, which is higher than the previous dose conversion factor. The dose conversion factor for radon of $1.7 \times 10^{-5}$ mSv (Bq h m$^{-3}$)$^{-1}$.
Conclusions

Mamuju is well recognized as a unique HNBRA with characteristics of high exposures, both internal and external. The value of the annual effective dose exceeds the worldwide average annual effective dose of 2.4 mSv and that for radiation workers of 20 mSv. With this fact, Mamuju can be regarded as a promising area for conducting a risk assessment on HNBRA through epidemiological studies for understanding health effects related to chronic low-dose-rate radiation exposure. The information gleaned from studying Mamuju can be used as the empirical basis for a future epidemiological study.

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