In Vivo Measurement of Radionuclides in the Skull: Factors Affecting K-40 Background in the Detector and Effects of the Control Group Type on Activity Assessment

Authors: Meng, Dr. Xiangpeng, Liu, Dr. Yuanyuan (Nuclear energy), Wu, Prof. Bin, Wang, Dr. Yu, Wang, Miss Jing, Zhou, Dr. Lai, Ju, Dr. Ao, Xiao, Mr. Yunshi, Yue, Prof. Qian, Cheng, Prof. Jianping, Meng, Dr. Xiangpeng

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Abstract

One of the grand challenges in the nuclear field is to establish the relationship between health risk and low-dose radiation. In vivo measurement of radionuclides in the skull, a promising method for studying the health effects of low-dose radiation, is being pursued by the TRACE (Trace-level RAdionuclides in vivo Counting Experiment) team at the China Jinping Underground Laboratory. Skull radionuclides exhibit low activity and emit low-energy gamma rays, making the measurements highly susceptible to background interference. This work aims to investigate human K-40 background to inform strategies for minimizing its interference, and to improve the accuracy of radionuclide activity assessment in the skull. Based on ICRP adult reference male phantom and Monte Carlo method, this paper examined factors affecting K-40 background in the detector. First, a key finding is that the top of the head is the best measurement position, yielding MDA values on average 2.12 times lower than the side and 1.56 times lower than the bottom position. This is attributed to the lowest K-40 background and highest counting efficiency for target radionuclides (Pb-210, Am-241, Th-234, U-235). Second, although K-40 is commonly assumed to be uniformly distributed in the body, the results of this study suggest that this assumption can underestimate background counts in the ROI by more than 10% compared with the actual distribution, which is mainly in soft tissues. Third, among all body parts, the head, as the largest source of K-40 background, is approximately proportional to the whole-body background. This suggests that a head phantom alone can represent the whole body for studying K-40 background, thereby simplifying phantom fabrication. Furthermore, this work developed a K-40 head phantom suitable for the Chinese adult reference male. Using this phantom, the effect of different control groups on the evaluation of skull radionuclide activity is investigated by comparison with the blank group and the normal individual group. The experimental results suggest that the phantom group offers both flexibility and accuracy, making it more suitable for activity assessment.

Full Text

Preamble

In vivo measurement of radionuclides in the skull: factors affecting K-40 background in the detector and effects of the control group type on activity assessment∗ Xiang-Peng Meng,1, 2, 3 Yuan-Yuan Liu,1, 3, 4, † Bin Wu,1, 3, 4, ‡ Yu Wang,1, 3, 4 Jing Wang,1, 3, 4 Lai Zhou,1, 3, 4 Ao Ju,1, 3, 4 Yun-Shi Xiao,5 Qian Yue,2 and Jian-Ping Cheng1, 3, 4

1 School of Physics and Astronomy, Beijing Normal University, Joint Laboratory of Jinping Ultra-low Radiation Background Measurement of Ministry of Ecology and Environment Beijing Normal University, Beijing, 100875, China 2 Department of Engineering Physics, Tsinghua University, Beijing, 100084, China 3 Jinping Deep Underground Frontier Science and Dark Matter Key Laboratory of Sichuan Province, 615000, China 4 Key Laboratory of Beam Technology of Ministry of Education, 100875, China 5 China Institute for Radiation Protection, Taiyuan, 030006, China

One of the grand challenges in the nuclear field is to establish the relationship between health risk and lowdose radiation. In vivo measurement of radionuclides in the skull, a promising method for studying the health effects of low-dose radiation, is being pursued by the TRACE (Trace-level RAdionuclides in vivo Counting Experiment) team at the China Jinping Underground Laboratory. Skull radionuclides exhibit low activity and emit low-energy gamma rays, making the measurements highly susceptible to background interference. This work aims to investigate human K-40 background to inform strategies for minimizing its interference, and to improve the accuracy of radionuclide activity assessment in the skull. Based on ICRP adult reference male phantom and Monte Carlo method, this paper examined factors affecting K-40 background in the detector. First, a key finding is that the top of the head is the best measurement position, yielding MDA values on average 2.12 times lower than the side and 1.56 times lower than the bottom position. This is attributed to the lowest K-40 background and highest counting efficiency for target radionuclides (Pb-210, Am-241, Th-234, U-235). Second, although K-40 is commonly assumed to be uniformly distributed in the body, the results of this study suggest that this assumption can underestimate background counts in the ROI by more than 10% compared with the actual distribution, which is mainly in soft tissues. Third, among all body parts, the head, as the largest source of K-40 background, is approximately proportional to the whole-body background. This suggests that a head phantom alone can represent the whole body for studying

K-40 background, thereby simplifying phantom fabrication.

Furthermore, this work developed a K-40 head phantom suitable for the Chinese adult reference male. Using this phantom, the effect of different control groups on the evaluation of skull radionuclide activity is investigated by comparison with the blank group and the normal individual group. The experimental results suggest that the phantom group offers both flexibility and accuracy, making it more suitable for activity assessment.

Keywords

In vivo measurement, K-40 background, low-dose radiation

INTRODUCTION

rays from internal radionuclides, enables activity calculation and internal dose assessment. Moreover, the skeleton can be 19 regarded as a dosimeter [6], reflecting the cumulative expo20 sure caused by bone-seeking radionuclides. Thus, researchers 21 are exploring a new method based on in vivo measurement of 22 skeletal radionuclides to study the health effects of low-dose 23 radiation. For example, measuring skull Pb-210 can reflect 24 cumulative exposure in miners exposed to high-radon envi25 ronments, thereby helping to investigate the relationship be26 tween radon and lung cancer risk [7–10].

The UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) has been encouraging re4 search on the health effects of low-dose radiation [1–3]. The 5 dose-response relationships for the cancer risk in the low dose 6 range, represented by the LNT (Linear No-Threshold) hy7 pothesis, depend on extrapolations from high-dose exposure 8 results and lack support from experimental data [4]. In 2017, 9 the ANS (American Nuclear Society) listed “Establish the sci10 entific basis for modern low-dose radiation regulation” as one 11 of the nine nuclear grand challenges [5].

Low-dose radiation exposure exhibits long-term and con13 tinuous characteristics, particularly as radionuclides can enter 14 and accumulate in the human body through inhalation and in15 gestion, leading to prolonged internal radiation exposure. In 16 vivo measurement, which uses external detectors to record $ $2

The skull is one of the optimal sites for detecting boneseeking radionuclides [11] because it has the largest surface 29 area of all bones and is covered by relatively thin soft tissue, 30 minimizing self-absorption of γ-rays.

Moreover, the skull 31 shows small inter-individual variability and accounts for 1332 15% of total skeletal mass [12, 13]. Therefore, measuring 33 radionuclide activity in the skull allows estimation of the to34 tal skeletal burden. However, the activity of radionuclide in 35 the skull is low, typically at the Bq level. The energy of γ-rays 36 emitted is also low, usually below 200 keV [14]. As a result, $*$

Supported by the National Natural Science Foundation of China 37 the detection of radionuclide in the skull is highly susceptible (No.12505211 & 12222502 & 12441508) and China Postdoctoral Science 38 to background interference.

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† Corresponding author, E-mail: yyliu@bnu.edu.cn

‡ Corresponding author, E-mail: bwu6@bnu.edu.cn

According to Estrada et al. [15], background in vivo measurement comes from ambient background and human K-40.

The ambient background primarily consists of four compo- 99 counts of K-40 in the human body. In addition, the top, side, nents [15, 16]: radioactivity from shielding material and de- 100 and bottom of the head are common measurement positions 43 tection equipment, cosmic ray, environmental gamma radia- 101 for the in vivo measurement of radionuclides in the skull [33]. 44 tion, and radon in the air. To address these sources of ambient 102 In this case, the K-40 background in the detector originates 45 background, researchers have successfully developed various 103 from the head, neck, trunk, and LL (Lower Limbs). Since the 46 background suppression techniques [17–20]. Among them, 104 distances between the detector and these body parts vary with 47 compared with laboratories on the ground, the deep under- 105 the measurement position, the contributions of K-40 back48 ground laboratory can provide an ultra-low background en- 106 ground from each body part to the detector also differ. There49 vironment, making it ideal for in vivo measurements of ra- 107 fore, this study will quantitatively analyze the differences in 50 dionuclides [21–23]. The CJPL (China JinPing underground 108 K-40 background counts among various measurement posi51 Laboratory) is the deepest underground laboratory in the 109 tions and assess the contributions from different body parts. 52 world, with a vertical rock overburden of 2400 meters, which 110 Moreover, by taking into account the counting efficiency of 53 effectively shields cosmic-ray-induced background [17, 24–111 the target radionuclide, the optimal measurement position can 54 26].

The average muon flux is approximately 2.0$×10−10112*bedetermined.Therefore,onepurposeofthisstudyistop*
255*cms*−1, *about*108*timeslowerthanontheground*[17, 21].113*videinsightsintohowdistributionregion,measure*
*levelRAdionuclidesinvivoCounting*114*tion,andbodypartsaffecttheK* −
40*background,whichcan*57*Experiment)teamatBeijingNormalUniversity,towhich*115*informstrategiestomi*
*doseradiationbasedoninvivomeasure*117*howtoimprovetheaccuracyofradionuclideactivityevalua*60*mentsofr*
40, *asan*119*bydividingthecountsitproducesbythedetectionefficiency.*62*importantsourceofbackground,canno*
40*isdifficulttoeliminateand*63*deepundergroundlaboratory,whichlimitsfurtherimprove*121*targetradionucli*
40*isanaturallyoccurringradioactiveisotopeofpotas*−123*thehumanbody.Therefore,researchersestablishacon*
*lifeof*1.25×$10 years. According to ICRP 124 group to replicate the subject' s measurement conditions in 67 (International Commission on Radiological Protection) pub- 125 order to obtain background counts. According to the type 68 lication 23 [27], an adult has a total body activity of approxi- 126 of object measured in the control group, three types can be 69 mately 4000 Bq of K-40,

of which about 300 Bq is distributed 127 identified [6, 15, 34, 35]: blank (i.e., air), anthropomorphic 70 in the head.

This level is significantly higher than that of 128 phantom, and an individual without occupational internal ex71 the target radionuclides. There are two primary mechanisms 129 posure. When evaluating background counts with different 72 by which K-40 contributes to background radiation: first, 130 measurement subjects, several issues arise, as outlined below. 73 Compton scattering resulting from the 1461 keV gamma First, using a blank as the measurement subject excludes 74 rays emitted during its decay; second, low-energy X-ray ra132 the body' s own K-40 background interference, producing a 75 diation generated by bremsstrahlung when the 1311 keV 133 spectral shape different from a real subject. The absence of − decay interact with body 76 beta particles produced by its β 134 body attenuation can also overestimate environmental back77 tissues. According to the results of Turko et al. [28] and our 135 ground, leading to underestimation of net counts and ra78 prior research [29], the anti-coincidence technique can reduce 136 dionuclide activity.

Second, an anthropomorphic phantom 79 the Compton scattering background to roughly half its orig137 made of tissue-equivalent materials with incorporated K-40 80 inal level, but has almost no effect on the bremsstrahlung138 can closely replicate measurement conditions of a real sub81 induced background. Moreover, since the X-rays generated 139 ject. However, phantom fabrication is time-consuming and 82 by bremsstrahlung are primarily concentrated in the 0-200 140 labor-intensive. Most phantoms used for in vivo measurement 83 keV energy range, which overlaps with that of the target ra141 of skull radionuclides are based on anatomical parameters of 84 dionuclides, they constitute a significant source of K-40 back142 Caucasian and lack designs specifically for Chinese popula85 ground [15, 29]. 143 tion. Third, the ideal control subject would be the twin of the Researchers commonly assume that K-40 is uniformly dis- 144 measured individual, with no internal exposure. Nevertheless, 87 tributed throughout the body when studying K-40 background 145 when measuring natural radionuclides in the human body, it is 88 [15, 28, 30, 31]. For example, Pillalamarri and Jagam [30] 146 difficult to find subjects completely free of the target radionu89 studied the K-40 background interference on the measure- 147 clides, which may result in an underestimation of radionu90 ment of Am-241 and Pb-210 by distributing the source uni- 148 clide activity. For example, besides radon and its progeny in 91 formly within the BOMAB (BOttle Manikin ABsorption) 149 the air, Laurer et al. [6] suggest that smoking, food, and drink92 phantom. However, K-40 distribution in human body is het- 150 ing water are also significant sources of Pb-210 in the human 93 erogeneous; for example, fat tissue contains almost no K-40 151 body. To compare the performance of different control groups 94 [27, 32]. Therefore, the assumed distribution region of K-40 152 in activity evaluation, this paper will quantitatively analyze 95 differ from its actual distribution in the human body, which 153 the differences in background under the blank, anthropomor96 raises the question of whether this difference affects the back- 154 phic phantom, and individual without occupational internal 97 ground characteristic. To address this question, the work is to 155 exposure, respectively. Specifically, a high-fidelity K-40 head 98 study the influence of distribution regions on the background 156 phantom for the Chinese adult reference male is developed.

The purpose of this work is to study factors affecting human K-40 background to inform strategies for minimizing its 159 interference, and to improve the accuracy of radionuclide ac160 tivity assessment in the skull. First, the effects of source dis161 tribution region, measurement position, and body part on K162 40 background in the human body are studied. Furthermore, 163 to accurately evaluate radionuclide activity in the skull, back164 ground differences among control groups, including a blank, 165 an anthropomorphic phantom, and a subject without occupa166 tional internal exposure, are compared. A high-fidelity K-40 167 head phantom is developed to serve as a control, specifically 168 designed for the Chinese adult reference male.

FACTORS AFFECTING K-40 BACKGROUND IN THE DETECTOR

Simulation setup

liquid nitrogen tank, the base, and the cold finger are represented by the gray components, occupying the ranges of 0-35 cm, 35-40 cm, and 40-45.5 cm, respectively. The blue part represents the probe, with a casing made of 1.5 mm thick aluminum. The green part represents the Ge crystal, with a diameter of 80.5 mm and a length of 31.3 mm. The black part represents the carbon window, with a thickness of 0.6 mm. The distance between the crystal and window is 7.25 mm.

In this work, the Monte Carlo software Geant4 (version 10.7.4) [36–38] is used to simulate the transport and interac- 212 (Region Of Interest) is less than 1%. The simulation condi174 tion of radiation in matter. For in vivo measurement of ra- 213 tions described above represent a general setup. Furthermore, 175 dionuclides in the skull, the models constructed in Geant4 in- 214 by setting different simulation conditions for various factors, 176 clude the detector and a phantom, which are described below. 215 including source distribution region, measurement position, 177 The detector used is an HPGe BE5030 detector manufactured 216 and body part, this study quantitatively analyzes their effects 178 by Canberra, as shown in Figure 1 [Figure 1: see original paper]. The gray components 217 on the characteristics of K-40 background. These aspects will 179 represent the liquid nitrogen tank (0-35 cm), the base (35-40 218 be discussed in the corresponding section below. 180 cm), and the cold finger (40-45.5 cm), respectively. The blue 181 part represents the probe, with an outer casing made of alu182 minum with a thickness of 1.5 mm. The green part represents 183 the germanium crystal, which is 80.5 mm in diameter and 184 31.3 mm in length. The black part represents the carbon win185 dow, which has a thickness of 0.6 mm. Moreover, the detector 186 was calibrated by the NIM (National Institute of Metrology), 187 China, using standard point sources of Am-241 (5.70\$$\times 10188 Bq), Cs-137(9.64\times 10 Bq), andCo-$

60(2.17×10*Bq*), *po*189*sitioned*25*cmfromthedetectorend*−*capface*.*TheFWHM*190(*FullWidthHalfMaximu*
3, 1.08×10−3, 192*respondingdetectionefficienciesof*4.80×10193*and*5.71×$10
, respectively. In addition, the accuracy of the 194 detector’ s Geant4 model has also been validated in our previ196 ous work [18].

The human phantom used is the Caucasian adult reference 198 male computational phantom recommended by ICRP Publi199 cation 110 [32], with a height of 176 cm and a weight of 200 73 kg. The phantom consists of 140 anatomical structures 201 and 53 types of materials.

The total number of voxels in 202 the phantom is 1.95$×10, *witheachvoxelmeasuring*2.137203*mm*×2.137*mm*×
mm, as shown in Figure 2 [Figure 2: see original paper]. In the figure, 204 human tissues are represented by different colors. Among 205 them, green, red, and white represent skin, muscle, and bone, male recommended by ICRP publication 110 [32]. Different colors 206 respectively. The blue circles represent the position of the derepresent various human tissues. Among them, muscle (red), skin 207 tector relative to the phantom, with the shortest distance be(green), and bone (white) are clearly visible. The blue circles near the head represent the detector’ s measurement positions, including 208 tween the detector and the skin surface being 0 cm. The meathe top, left side, and bottom of the head, with a detector-to-skin 209 surement positions include the top, side, and bottom of the distance of 0 cm. The phantom is divided into four parts, which are 210 head. The simulated source is K-40, with a total of 10 billion the head, neck, trunk, and lower limbs. 211 particles. The statistical uncertainty of the count in the ROI 219

biases in background counts for the top, side, and bottom detector under the two source distribution regions. The results 260 show that the value of largest bias occurs at the top of the 261 head, with deviations in all three energy regions being simi220 B. Factor 1: K-40 distribution region 262 lar, approximately 20%. At the side and bottom of the head, 263 the relative biases are around 10% in the ROI and Compton K-40 is commonly assumed to be uniformly distributed 264 continuum regions, and approximately 5% in the full-energy 222 throughout the whole body.

However, according to ICRP 265 peak region. Moreover, K-40 in the head is a key contributor 223 publication 110 [32], certain tissues such as adipose tissue, 266 to the whole-body background (see Section II.D for details). 224 breast tissue, and compact bone do not contain potassium, 267 The number of K-40 particles in each body part depends on 225 with K-40 mainly distributed in soft tissues like muscle. 268 its voxel count. If the total particle number remains constant, 226 Based on the calculation, human tissues containing potassium 269 altering the source distribution can affect K-40 background in 227 account for approximately 61% of the total body mass. To 270 the head. However, this study found that shifting the source 228 compare the differences in background characteristics caused 271 from the whole body to only potassium-containing tissues 229 by the assumed whole-body distribution versus the real distri272 causes only a slight increase in head K-40 particles num230 bution region of K-

40, two source distribution scenarios are 273 ber, from 6.9% to 7.4%. Therefore, the background count 231 implemented in the simulation: one in which K-40 is uni274 differences across measurement positions mainly arise from 232 formly distributed throughout all body tissues, and another in 275 changes in self-absorption and solid angle due to the modi233 which it is distributed only in tissues containing potassium. 276 fied source distribution, rather than from variations in source 234 The human has a complex anatomical structure composed of 277 strength across body regions. 235 numerous tissues, but the potassium content of these tissues To clarify why the top detector shows a larger count vari236 are relatively similar. This work assumes a uniform potas279 ation than the other positions under the two source distri237 sium concentration across all tissues. Therefore, in the con280 butions, we analyzed the effects of solid angle and self238 text of the computational phantom, K-40 is uniformly dis281 absorption. The spectrum produced by K-40 in the human 239 tributed in the voxels that make up each tissue. 282 body is continuous, making it difficult to evaluate each γ-ray 283 component individually. Therefore, this work focuses on the 241 by a detector placed at the top, side, and bottom of the 284 1.46 MeV γ-ray. Since the solid angle determines the geo242 head under two different source distribution regions. “WB” 285 metric efficiency, defined as the ratio of γ-rays reaching the 243 and “TCP” represent the cases where K-40 is uniformly dis286 detector’ s active volume without attenuation in matter to the 244 tributed throughout the whole body and only in tissues con287 total number of emitted γ-rays, we performed simulations to 245 taining potassium, respectively.

The blue and red curves 288 quantify the geometric efficiency at each measurement posi246 represent the K-40 background spectra with the “WB” and 289 tion. In Geant4, the particle type was set to Monte Carlo ray247 “TCP” setups, respectively.

The results suggest that the 290 tracing particles (“geantinos”), which do not undergo phys248 “WB” underestimates the background count compared to the 291 ical interactions with matter. As shown in Table 2 , the rela249 “TCP” .

To quantitatively analyze the differences in K-40 292 tive deviations in geometric efficiency between the “WB” and 293 “TCP” distributions are -14.93%, -7.78%, and -7.98% for the and bottom detector under two source distributions across different 295 can be seen that the geometric efficiency change at the top energy regions. The distributions include uniform K-40 throughout 296 detector is larger than that at the other two positions, which is the body and within potassium-containing tissues. The first column 297 an important reason for the greater variation in its counts.

lists measurement positions, and columns two to four show relative deviations in background counts for 0-200 keV (ROI), 200-1245 keV (Compton continuum), and 1458-1463 keV (full-energy peak).

Position

0-200 keV

200-1245 keV

1458-1463 keV

-20.62%

-19.55%

-19.37%

-10.24%

-8.90%

-5.92%

BOTTOM

-10.84%

-9.42%

measurement positions under the “WB” and “TCP” distributions.

The first column lists the measurement positions, while the second to fourth columns represent the geometric efficiencies under the two distributions and the relative deviations between them, respectively.

Geometric efficiency Position

Relative bias

3.07$×$10−3

3.61$×$10−3

-14.93%

3.32$×$10−3

3.60$×$10−3

-7.78%

3.10$×$10−3

3.37$×$10−3

-7.98%

-5.17%

background between the two source distribution settings, the 253 energy spectrum is divided into three regions: the region of 254 interest (ROI, 0-200 keV), where the gamma rays emitted by 255 radionuclides in the skull are concentrated; the Compton conBottom 256 tinuum region (200-1245 keV); and the full-energy peak re- 298 257 gion of K-40 (1458-1463 keV). Table 1 calculated the relative 299

uniformly distributed throughout the whole body and only in potassium-containing tissues, respectively. The spectra are depicted as blue and red curves for the "WB" and "TCP" setups, respectively.

This work also analyzed the variations in self-absorption 336 the top detector is notably larger than at the other two posiat different measurement positions. Gamma-ray attenuation 337 tions, which is a key factor contributing to the greater count 302 in matter follows an exponential law, and the SAF (Self- 338 deviation observed at the top detector. 303 Absorption Factor) can be expressed by the following equa304 tion:

I = I0 e−µx , SAF =

lists the measurement positions. The second and third columns present the material thickness and SAF for the "WB" distribution.

The fourth and fifth columns present the material thickness and SAF for the "TCP" distribution. The last column shows the relative deviations in SAF between the two distributions.

where I0 is the number of γ-rays that would enter the detector in the absence of attenuation, µ is the linear attenuation co−1), x is the material thickness (cm), and I is the 308 efficient (cm Position Relative bias 309 number of γ-rays that reach the detector after passing through 310 a material of thickness x. Since human tissues are diverse x (cm) SAF x (cm) SAF 311 and structurally complex, it would in principle be necessary 312 to calculate µ for each γ-ray along its specific path through -15.79% 313 different tissues before reaching the detector. To expedite the 314 estimation of the SAF, an approximate approach is adopted in -14.88% 315 this study, whereby all tissues traversed by the γ-rays prior to 316 detection are assumed to be soft tissue. Under this assumpBOTTOM 66.94 0.0180 64.25 0.0212 -14.90% 317 tion, the differences in count biases at different measurement 318 positions are analyzed solely in terms of the penetrated ma319 terial thickness x.

Here, µ is approximated as 0.06 cm−1 320 (corresponding to soft tissue at 1.46 MeV) [39], and x is 321 defined as the average distance from the center of all voxels 339 C. Factor 2: measurement position 322 containing K-40 in the phantom to the center of the detec323 tor' s germanium crystal. It should be noted that this simpli340 The measurement position can affect K-40 background 324 fication has certain limitations, as it cannot provide the true 341 counts, as shown in Figure 4 Figure 4: see original paper. The blue, red, and green 325 SAF in the human body; however, it can still capture the self342 curves represent spectra from the top, side, and bottom de326 absorption changes caused by the two source distributions at 343 tector, respectively, with the source distributed in potassium327 a given measurement position. 344 containing tissues. The results suggest that in the ROI, where

330 tions. It can be seen that the SAF relative biases at the top, 347 while the counts from the side and bottom detectors are com331 side, and bottom of the head are similar (-15.79%, -14.88%, 348 parable.

Thus, the top of the head is the optimal position 332 and -14.90%), suggesting that changes in measurement posi- 349 to minimize K-40 background interference.

Additionally, 333 tion have little effect on SAF bias. Therefore, the above anal- 350 the MDA (Minimum Detectable Activity), defined by Cur334 ysis suggests that when the source distribution changes from 351 rie [40], is used to quantify detection capability and is given 335 "WB" to "TCP" , the relative bias in geometric efficiency at 352 by the following expression:

U-235) with the detector placed at the top, side, or bottom of the head. (a) K-40 background spectrum; (b) Counting efficiency. Blue, red, and green curves correspond to the spectrum of top, side, and bottom detector, respectively.

2.71 + 4.65 NB

and counting efficiency, this study compares the detection capabilities of the side and bottom positions relative to the top 378 using the following formula: 354 where NB is the background count in the ROI, t is the meap 355 surement time, and v is the counting efficiency, defined as the 1 + 1.72 NS/B MDAS/B 356 product of detection efficiency and the emission probability 379 1 + 1.72 NT 357 of gamma rays. With fixed measurement time, the formula 358 shows that both background count and counting efficiency 380 where MDAS/B , vS/B , and NS/B represent the detection ca359 are key factors influencing the MDA. In this study, detec381 pability, counting efficiency, and K-40 background count for 360 tion capability at the three measurement positions is quantita382 the side or bottom detector, respectively. MDAT , vT , and NT 361 tively analyzed by combining K-40 background and counting 383 denote the corresponding parameters for the top detector. It 362 efficiency. Common radionuclides in the skull include Pb384 is assumed that the background of in vivo measurement of 385 radionuclides in the skull comes entirely from K-40. Table 4 column represents the measurement position, while the second to 388 suggest that the top of the head is the optimal measurement last columns show the MDA ratios of the side or bottom detector to 389 position, with MDA values on average approximately 2.12 the top detector for different radionuclides. 390 times and 1.56 times lower than the side and bottom, respec391 tively. Therefore, with a limited number of detectors, they MDAS/B /MDAT 392 should be placed as close to the top of the head as possible Position Pb-210 Am-241 Th-234 U-235 393 for measurements. 46.5 keV 59.5 keV 92.5 keV 186 keV

BOTTOM

Factor 3: body part

To quantify the K-40 background contribution from different body parts for in vivo measurement of radionuclides in the 365 210 (46.5 keV, 0.0425), Am-

241 (59.5 keV, 0.359), Th-234 397 skull, the ICRP computational phantom is divided into four 366 (92.5 keV, 0.0424), and U-235 (186 keV, 0.58). These ra- 398 segments: head, neck, trunk, and LL (Figure 2). As described 367 dionuclides are simulated as distributed in the skull, and their 399 in Section II.B, K-40 is assumed to be uniformly distributed 368 counting efficiencies at different measurement positions are 400 across all potassium-containing tissues, neglecting variations 369 calculated, as shown in Figure 4(b). With 5$×$10 simulated 401 in potassium concentration. The number of K-40 particles 370 particles (resulting in less than 1% statistical uncertainty), the 402 in each region is proportional to its voxel fraction, which is 371 results show that the top detector yields the highest efficiency, 403 7.4%, 2.8%, 44.3%, and 45.5% for the head, neck, trunk, and 372 followed by the bottom, while the side shows the lowest. This 404 LL, respectively. 374 tom, offering a larger solid angle for the detector compared to 406 ent body parts under different measurement positions. The 375 the irregular side structure. Combining the K-40 background 407 blue, red, green, purple, and orange curves represent K-40

represent the whole body, head, neck, trunk, and lower limbs, respectively.

curves represent the whole-body and normalized head K-40 background spectra, respectively.

background in the whole body, head, neck, trunk, and LL, reTABLE 5 . Relative bias between normalized head and whole-body spectively. In all positions, the head contributes the most to K-40 background counts. The first column shows measurement po410 the background, followed by the trunk, neck, and LL. When sitions; columns two to four show relative deviations in the 0-200 411 the detector is at the top, side, and bottom of the head, the keV (ROI), 200-1245 keV (Compton continuum), and 1458-1463 412 head accounts for 87.9%, 64.0%, and 62.7% of the wholekeV (full-energy peak), respectively. 413 body K-40 background, respectively. This suggests that the 414 head largely determines the shape of the K-40 background 0-200 keV 200-1245 keV 1458-1463 keV Position 415 spectrum.

After normalizing the head K-40 background by its proTOP -0.30% -0.53% 4.28% 417 portion of the total body background, it is compared with 418 the whole-body spectrum, as shown in Figure 6 [Figure 6: see original paper].

The red -2.37% -0.17% 9.42% 419 and blue curves represent the whole body and the normal420 ized head, respectively, showing near-complete overlap. TaBOTTOM -3.88% 1.56% 6.32% 421 ble 5 shows that the relative bias between them is within 5% 422 in the ROI and Compton continuum region, and within 10% 423 in the full-energy peak region. This suggests that the head III. THE EFFECT OF CONTROL GROUP TYPES ON 424 K-40 background is approximately proportional to that of the 432 ACTIVITY ASSESSMENT 425 whole body. Thus, the head phantom can serve as a substitute 426 for the whole body, with a closely similar spectral shape and 427 trends in count variation, thereby simplifying phantom fabri- 434 To calculate skull radionuclide activity, the control group 428 cation. Moreover, the large deviation in the full-energy peak 435 is used to obtain background counts of target radionuclides in 429 is mainly due to its strong penetration capability, which al- 436 the environment, which are subtracted to yield the subject's 430 lows 1461 keV gamma rays from other body parts outside the 437 net counts. This work evaluated differences in background 431 head to reach the detector. 438 counts and radionuclide activity assessment among three con408

trol types: a blank, an anthropomorphic phantom, and an individual without occupational internal exposure. Among them, 441 according to the results of Section II.D, a K-40 head physi442 cal phantom for Chinese adult reference male is developed to 443 substitute for constructing the whole-body model. Moreover, 444 the physical phantom is converted into computational phan445 tom based on CT scanning for comparison with the head part 446 of ICRP phantom. The fabrication process of the phantom 447 and the results are detailed in the following sections.

adult reference male.

Comparison of K-40 background with the ICRP phantom

Fabrication of the K-40 head phantom

This work compared the CARMH and ICRP head phanThe national standard " Reference Individuals for Use in 474 toms, as shown in Figure 8 [Figure 8: see original paper]. Panels (a)-(c) show top, left, 475 and bottom view shape comparisons, with purple and yellow 450 Radiation Protection" (GBZ/T 200.1-2007) [41] defines a 476 representing the ICRP and CARMH phantoms, respectively. 451 Chinese adult reference male (age 20-50) as 170 cm in height 477 The CARMH phantom closely matches the ICRP in width (x452 and 63 kg in weight. The head dimension is specified as fol478 axis) and height (z-axis), but is notably shorter in length (y453 lows: head circumference 57 cm, length 19 cm, width 16 cm, 479 axis), with a maximum relative bias of 17%. Panels (d)-(f) 454 and height 23 cm. The tissues in the head mainly include 480 compare the K-40 background spectra from both phantoms 455 brain, muscle, nerves, bone, and other soft tissues. Based 481 for the detector placed at the top, side, and bottom of the 456 on the density recommended by ICRP publication [27, 32] 482 head, respectively. Blue and red curves represent the ICRP 457 and ICRU (International Commission on Radiation Units and 483 and CARMH phantoms, respectively. The number of K-40 458 measurements) report [42], non-skeletal tissues have similar 484 particles is set to 5$\times$10 , with a counting statistical error of 459 densities. Therefore, the head phantom materials are simpli485 less than 1%. 460 fied into soft tissue and bone, with reference densities of 1.03 As shown in the figure, the spectra are similar at the top de461 g/cm and 1.40 g/cm , respectively. 487 tector, while the side and bottom detector show good agree488 ment in the ROI but larger differences in the Compton continTABLE 6 . Comparison of fabricated K-40 head phantom parameters 489 uum and full-energy peak region. Table 7 presents the relative 490 biases across energy regions and positions. With the detector with reference values. 491 on top, the absolute values of biases are small with 10% in Parameter Measured Reference Relative bias 492 all regions. At the side and bottom positions, deviations in 493 the ROI remain under 10%, whereas larger differences are 494 observed in the Compton continuum and full-energy peak reCircumference 55.0 cm 57.0 cm -3.5% 495 gions, exceeding 10% and 20%, respectively. The above re496 sults suggest that differences between head phantoms repreLength 18.6 cm 19.0 cm 497 senting Caucasian and Chinese populations can lead to vari498 ations in the human K-40 background spectrum. Therefore, Width 15.2 cm 16.0 cm 499 developing population-specific phantoms is important to im501 500 prove measurement accuracy.

Height 23.1 cm 23.0 cm

Soft tissue density 1.08 g/cm3 1.03 g/cm3

1.38 g/cm3 1.40 g/cm3

-1.4%

Bone density

In collaboration with the CIRP (Chinese Institute for Radiation Protection), this work developed a CARMH (Chinese 464 Adult Reference Male Head) phantom containing K-40. As 465 shown in Table 6, its dimensions and densities deviate by less 466 than $\pm5\times10 voxels 471 (0.61914 mm \times 0.61914 mm \times$0.5 mm each).

Chinese adult reference male and ICRP head phantoms across different detector positions and energy regions. The first column shows the detector position, while the second to fourth columns list the relative deviations in the 0-200 keV (ROI), 200-1245 keV (Compton continuum), and 1458-1463 keV (full-energy peak), respectively.

Position

0-200 keV

200-1245 keV

1458-1463 keV

-9.43%

-5.23%

-3.49%

4.33%

12.71%

20.91%

BOTTOM

9.73%

17.83%

35.10%

side, and bottom views, with the ICRP in purple and the Chinese phantom in yellow. Panels (d)-(f) compare K-40 background spectra at the top, side, and bottom detectors, with blue and red curves representing the Chinese and ICRP phantoms, respectively.

To further clarify why the two phantoms exhibit large count biases in the high-energy region, particularly in the K-40 full504 energy peak, at the side and bottom detectors, we performed 505 simulations of the geometric efficiency at each measurement 506 position. The results in Table 8 show that the relative bias of 507 the top detector in geometric efficiency between the CARMH 508 and ICRP phantoms is small, approximately -1.83%. How509 ever, at the side and bottom positions, the deviations are sig510 nificant, reaching 12.35% and 19.45%, respectively. There511 fore, the difference in geometric efficiency is an important 512 reason for the larger count deviations in the full-energy peak 513 region at the side and bottom positions.

The first column lists the measurement positions, and the second to fourth columns represent the CARMH phantom geometric efficiency, the ICRP phantom geometric efficiency, and their relative deviation, respectively.

Geometric efficiency Position

Relative bias CARMH

3.33$\times$10−2

3.39$\times$10−2

-1.83%

3.31$\times$10−22.95×10−212.35×10−22.81×$10−2 19.45% 516 also by differences in self-absorption arising from variations 517 in head tissue structure. Based on the same assumptions as 518 in Section II.B and using Equation (1), the SAF and its rel519 ative bias for 1.46 MeV γ-rays were calculated, as shown in 530 C.

Comparison of control group types for activity assessment 520 Table 9 . The results suggest that the SAF relative bias de521 pends on the measurement position. The difference in head 522 length between the two phantoms has a greater effect on the 531 The activity of the target radionuclide can be determined 523 bottom detector, resulting in a relative bias of 8.45%, com- 532 by calculating the ratio of its counts to the counting effi524 pared with 0.06% and 4.89% at the top and side positions, 533 ciency.

A key step is to use a control group to determine 525 respectively. Based on the above analysis, for the CARMH 534 the background counts of target radionuclides in the environ526 and ICRP phantoms, the relative biases in geometric effi- 535 ment, thereby obtaining the net counts in the subject by sub527 ciency and self-absorption at the side and bottom detectors 536 traction. In this work, different control groups are used to 528 are larger than at the top, which is a key factor contributing to 537 compare background variations and evaluate their impact on 529 the greater count deviations observed. 538 activity assessment. The measurement setups and results are

measurement positions and their relative biases. The first column lists the measurement positions. The second and third columns present the material thickness and SAF for the CARMH phantom.

The fourth and fifth columns present the material thickness and SAF for ICRP phantom. The last column presents the relative deviations in SAF between the two phantoms.

CARMH

Position

Relative bias

x (cm)

0.06%

4.89%

BOTTOM

8.45%

x (cm)

shown in Figure 9 [Figure 9: see original paper]. Panels (a)-(c) show measurement conditions using a blank, control groups. Panels (a)-(c) show setups for the blank, K-40 head 541 a K-40 head phantom, and a normal individual without occuphantom, and a subject without occupational internal exposure, re542 pational internal exposure, respectively. With a single HPGe spectively. Panel (d) shows background spectra, with red, blue, and 543 BE5030 detector, measurements are performed with the degreen curves representing the blank, phantom, and subject, respec544 tector placed at the top of the head, the optimal measurement tively. 545 position, in close-contact geometry. Measurement times are 546 144 h for the blank and phantom, and 10 h for the individual, 547 limited by human tolerance. Radon, a key background factor, 548 is maintained at a consistent level through ventilation, with 549 average concentrations of approximately 10.0, 12.0, and 11.6 550 Bq/m during the blank, phantom, and subject measurements, 551 respectively.

Panel (d) shows the background spectra for the blank, 553 phantom, and subject, represented by red, blue, and green 554 curves, respectively. Within 40 to 1500 keV, the blank count555 ing rate is 2.17 cps, lower than the phantom (3.34 cps) and 556 subject (3.33 cps) due to the absence of K-40.

The simi557 lar spectrum shape of the phantom and subject support using 558 the K-40 head phantom as a surrogate for whole-body back559 ground in skull radionuclide measurements.

This work calculated the counting rates of the target ra561 dionuclide for each control group by gamma energy spectra 562 analysis [43], as shown in Figure 10 [Figure 10: see original paper]. Points and lines rep563 resent the counting rates and their uncertainties for the blank 564 (red), phantom (blue), and subject (green). The results are the ROI for blank (red), phantom (blue), and individual without oc565 consistent within the uncertainty range. The uncertainty for cupational internal exposure (green) control groups. 566 the subject is significantly larger, mainly due to his limited 567 tolerance, which prevents achieving the same measurement 568 time as in the blank or phantom cases, resulting in signifi569 cant statistical fluctuations. Moreover, in practical measure-578 Furthermore, it can be found that the Pb-210 counting rate 570 ments, when measurement conditions such as detection dis- 579 for the phantom is lower than that for the blank, with a ratio of 571 tance or position change, the background spectrum must be 580 about 0.72. This is because Pb-210, a radon progeny present 572 remeasured, which is difficult to achieve when using a normal 581 in air as aerosols and emitting low-energy gamma rays (46.5 573 individual as the control group. Therefore, compared to the 582 keV), is partially blocked by the phantom placed in front of 574 other two groups, performing long-duration measurements on 583 the detector. Therefore, using the blank group can cause an 575 a normal individual group is logistically prohibitive due to the 584 underestimation of Pb-210 activity in the skull. For Am-241, 576 physiological constraints on subject immobility (10 h vs. 144 585 Th-234, and U-235, the phantom and blank group yield con577 h in this work). 586 sistent background counting rates within uncertainty. Among

them, Am-241, being an anthropogenic radionuclide absent 620 with the real distribution of human K-40, which is mainly in in the unexposed environment, has a counting rate is signifi- 621 soft tissues, the whole-body distribution underestimates back589 cantly lower than that of other radionuclides, nearly zero. Th- 622 ground counts in the ROI by more than 10% for the top, side, Third, the head makes the 590 234 and U-235 are natural radionuclides, commonly found in 623 and bottom detectors of head. 591 soil and ores. Their background signals mainly originate from 624 largest contribution (followed by the trunk, neck, and lower 592 shielding materials and the detector. Additionally, the count 625 limbs) and is approximately proportional to the whole-body The normalized head agrees well with 593 of U-235 ROI can include contributions from Ra-226 (186.2 626 K-40 background. 627 the whole body in the ROI and Compton continuum (biases 594 keV) due to the proximity of their peak energies.

The above results suggest that the normal individual group 628 <5%), allowing the head phantom to substitute for the whole Moreover, contributions 596 is inflexible due to limited measurement time arising from 629 body and simplifying fabrication. 597 the physiological constraints on subject immobility (10 h vs. 630 from non-head parts should be considered, as using the head598 144 h for the other two control groups in this work). More- 631 only approximation reduces precision for 1.46 MeV γ-rays 599 over, compared with the phantom group, the use of the blank 632 from whole-body K-40, with deviations up to 9.42%. 600 group can cause an underestimation of Pb-210 activity in the 633 This study also compared the effects of different con601 skull because it fails to account for the attenuation of airborne 634 trol groups, including the blank, phantom, and non602 Pb-210 by the person' s own head. Based on this analysis, em- 635 occupationally exposed individual, on radionuclide activity 603 ploying the phantom as the control group provides both flex- 636 estimation. The K-40 head phantom based on the Chinese 604 ibility and accuracy, making it the more suitable choice for 637 adult reference male is developed and compared with the head 605 activity assessment of skull radionuclides. 638 part of ICRP phantom, showing similar width and height but 639 17% shorter length. The difference in head length signif640 icantly affects the K-40 background counts at the side and IV. CONCLUSION 641 bottom detectors, particularly in the full-energy peak region, 642 where the count deviations between the two phantoms ex607 The work analyzed the influencing factors of the K-40 643 ceed 20%. Therefore, it is crucial to develop population608 background in in vivo measurement of radionuclides in the 644 specific phantoms for improving measurement accuracy. Fur609 skull and investigated the impact of the control group type on 645 thermore, using a normal individual as a control group is 610 the accuracy of activity assessment. The results are as fol- 646 inflexible due to limited measurement time arising from the 647 physiological constraints on subject immobility (10 h vs. 144 611 lows:

Based on the ICRP adult reference male phantom and 648 h for the other two control groups in this work). Moreover, 613 Monte Carlo method, this work quantitatively analyzed fac- 649 the blank and phantom gave consistent background counting The Pb-210 back614 tors affecting K-40 background in the detector. First, an im- 650 rates for Am-241, Th-234, and U-235. 615 portant finding of this work is that the top detector of the head 651 ground counting rate for the phantom is about 72% of that for 616 recorded the lowest background and the highest counting ef- 652 the blank, causing skull Pb-210 activity to be underestimated 617 ficiency for Pb-210, Am-241, Th-234, and U-235, with the 653 when the blank is used. Thus, in comparison with the other 618 MDA on average 2.12 and 1.56 times lower than those of the 654 two control groups, the phantom can provide both flexibility 619 side and bottom detectors, respectively. Second, compared 655 and accuracy, making it more suitable for activity assessment.

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