Calibration of whole body counter for assessment of internal dose in the human body

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Abstract. In the Malaysian Nuclear Agency (Nuklear Malaysia), the ORTEC Whole Body Counter System, bed type was used for assessing internal dose due to intake of gamma radionuclides in the human body. In this study, the performance of ORTEC Whole Body Counter System includes energy calibration, counting efficiency, validation test and minimum detectable activity (MDA) for the radionuclides of interest (ROI) has been investigated using ORTEC whole body counter phantom and mixed standard sources having gamma energies between 59.5 keV and 1836.2 keV. Later, the whole body counting was performed to determine the existence of any gamma radionuclides in the body. The result of the energy calibration was within the tolerance limit of ± 5%. The counting efficiency varies between 0.0000881 cps/Bq and 0.000332 cps/Bq. The results of the validation test show that the bias (B_r) and repeatability (S_{Br}) are within the acceptable range of -0.25 ≤ B_r ≤ +0.50 and S_{Br} ≤ 0.40, respectively. The MDA for each ROI of I-131, Cs-137 and Co-60 were 165.4 ± 10.0 Bq, 144.6 ± 11.5 Bq and 167.3 ± 30.5 Bq, respectively. A total of 14 volunteers from Postgraduate Educational Course in Radiation Protection and Safety of Radioactive Sources (PGEC-16) were invited to perform the whole body counting. Each volunteer was scanned for 1200 s with the bed speed of 0.065 inch/s. The results show that there is no internal exposure found for all monitored person. Consequently, it can be concluded that the ORTEC Whole Body Counter System (WBC) is now ready to be used for internal dose assessment.

1. Introduction

Whole Body Counter (WBC) is an instrument used to measure radioactivity within the human body, which plays an important role in nuclear safety. The evaluation of radioactivity within the human body is one of the key measures to assess the safety in nuclear facilities, which leads to the welfare of workers who involve in handling of unsealed radioactive materials in their daily activities. The WBC not only used for routine monitoring on radiation worker during occupational exposure but also for the preparedness of response in the case of radiological and nuclear emergencies [1].

To ensure that the WBC system is operating correctly and the overall characteristics of the instrument are within acceptable limits, the quality control procedures need to be applied. Michael, V. et al. have suggested three keys of maintenance and quality control procedures for WBC system: (1) Daily controls and efforts to maintain a low and constant background counting rate; (2) monitoring the sensitivity and linear response of the detection system; and (3) performance evaluation, such as evaluation of reproducibility and accuracy of measurements [2]. Moreover, there are several studies of WBC system
calibration in various parameter and condition. Momose T. et al. performed the efficiency calibration of WBC system as a part of whole-body counting of Fukushima Residents after the TEPCO Fukushima Daiichi nuclear power station accident study. The calibration performed on two types of WBC, each of which has two large-sized Sodium Iodide Thallium activated (NaI(Tl)) detectors and the results of this calibration were verified by comparing them with different-sized Bottle Mannequin Absorber (BOMAB) phantoms imitating an adult male, a 10 year old child, and a 4 year old child [3]. In 2016, Pak M. et al. performed calibration on 2 whole body counters using BOMAB phantom and Radiation Management Corporation (RMC-II) phantom. The reliability of WBC system was evaluated by participating in the intercomparison programme in collaboration with the International Atomic Energy Agency (IAEA). This study focused on counting efficiency and relative bias of activity [4].

Accordingly, in this study, the performance of the ORTEC WBC system which belongs to the Malaysian Nuclear Agency (Nuklear Malaysia) was tested. The results will report the energy calibration, counting efficiency, radiation background measurement, validation test and minimum detectable activity (MDA). Besides, the results of internal dose assessment for 14 volunteers will be presented.

2. Material and methodology

2.1. Whole body counter system

2.1.1. Detector and software. ORTEC WBC System was used in this study (figure 1). The system comprises ORTEC High Purity Germanium Detector model GEM-FX8530P4 for detecting gamma emitters from 50 keV to 2000 keV. The detector was shielded in the steel frame and lead-lined to minimize the influence of background radiation. It was also connected to the X-COOLER II compressor for controlling the detector’s temperature. The Renaissance Supervisor Software model RENPLUS-B32 Version 4.10 was used for spectrum analysis.

Figure 1. ORTEC Whole Body Counter System, moveable bed type with a single high purity germanium detector for whole body scanning.

Figure 2. (a) ORTEC WBC Phantom. (b) Eckert & Ziegler Analytics mixed standard sources positioning in the WBC phantom.
2.1.2. Whole-body counter phantom. ORTEC WBC Phantom used in this study was constructed of plastic materials (polyethylene) designed to approximate the gamma rays scattering properties of human tissue (figure 2). The source positions were designed to represent the positions of certain body organs such as lung and gastrointestinal. The design approximates the attenuation of gamma rays from the internal sources as well as the scattering or attenuation of gamma rays from external sources. The overall phantom dimensions follow the guidelines of the Medical Internal Radiation Dose (MIRD) Committee [5].

2.2. Calibration sources
A total of five mixed standard sources manufactured by the Eckert & Ziegler Analytics, USA consists of Am-241 (59.5 keV), Cd-109 (88.0 keV), Co-57 (112.1 keV), Ce-139 (165.9 keV), Hg-203 (279.2 keV), Sn-113 (391.7 keV), Cs-137 (661.7 keV), Y-88 (898.0 keV & 1836.1 keV) and Co-60 (1173.2 keV & 1332.5 keV) were used in the calibration of the WBC (figure 2). The sources were contained in the Quart bottle and having reference activities of 2.5 µCi on 1 October 2012.

2.3. Energy calibration and counting efficiency
The WBC system was calibrated using the WBC phantom that was positioned in the center under the detector with the mixed standard sources embedded. The calibration was performed in static mode with the counting time of 1200 s. The photo peaks obtained from this measurement were analysed to verify the gamma energy was centered within the operating channel number. Later, the counting efficiency for each interest radionuclides was estimated by interpolating the graph of counting efficiencies against gamma energies.

2.4. Measurement of background radiation
In this study, the background radiations in the WBC Laboratory were monitored using the WBC phantom as a blank. This measurement was performed to ensure that the background radiations in the laboratory are low and as constant as possible. The measurements were done at 1200 s for five replications.

2.5. Validation test
The validation test was carried out by measuring the activity (in count) of two interest radionuclides, Cs-137 and Co-60, which are in the mixed standard sources that embedded in WBC Phantom. The measurements were carried out at 1200 s counting time with 5 times repetitions for 1 data set. The test was performed 2 times by 2 weeks interval to obtain 2 data sets, the bias and repeatability then were calculated using the following equations.

\[ B_{\text{rel}} = \frac{A_i - A_{\text{act}}}{A_{\text{act}}} \]  

In equation (1), \( B_{\text{rel}} \) denotes the relative bias of the \( i^{th} \) measurement, \( A_i \) denotes the \( i^{th} \) measurement of radioactivity (second data set) and \( A_{\text{act}} \) denotes the actual activity of the \( i^{th} \) measurement (first data set).

The relative bias (\( B_r \)) is the average of the relative biases of the measurements and can be evaluated using equation (2).

\[ B_r = \overline{B_{\text{rel}}} = \frac{\sum_{i=1}^{n} B_{\text{rel}}}{n} \]  

Here, \( n \) denotes the number of replicate measurements. Repeatability, \( S_{\text{BR}} \) can be calculated using equation (3).
\[ S_{Br} = \sqrt{\frac{\sum_{i=1}^{n}(B_i - \bar{B})^2}{n-1}} \]  

The relative bias and repeatability should be within the range of \(-0.25 \leq Br \leq +0.50\) and \(S_{Br} \leq 0.40\), respectively [6].

2.6. Determination of minimum detectable activity (MDA)

Using the same measurement set-up as in 2.4, the MDA of I-131, Cs-137 and Co-60 for 1200 s counting was determined. The activity for each interest radionuclide was counted. The MDA then was calculated using equation (4), where \(K\) is the counting efficiency, \(T\) is the counting time and \(S_{B}\) is the square root of background radiation [6].

\[ MDA = \frac{4.65S_{B} + 3}{K \times T} \]  

2.7. Internal dose assessment

The internal dose assessments were performed on fourteen volunteers from Postgraduate Educational Course in Radiation Protection and Safety of Radioactive Sources (PGEC-16) Malaysia. The entire volunteers were monitored for 1200 s counting time with the bed speed of 0.065 inch/s by ORTEC WBC System. The setup of the whole body counting measurement is shown in figure 3. The monitored person was considered free from internal dose when the body counts were two times less than background counts. If not, the committed effective dose will be estimated accordingly.

![Figure 3](image.png)

Figure 3. The setup of the whole body counting measurement.

3. Results

3.1. Energy calibration and counting efficiency

Figure 4 shows the calibration curve of gamma energies against the channel number. The gamma energies of 59.5 keV, 88.08 keV, 661.7 keV, 1173.2 keV and 1332.5 keV are linearly dependent with the channel number at determination coefficient of 0.9987. These gamma energies then were compared with the given fit gamma energies of 59.5 keV, 88.0 keV, 661.7 keV, 1173.2 keV and 1332.5 keV to determine the different percentage. The gamma energy at 88.08 keV was recorded to have the maximum different percentage, which was 0.09% while the other gamma energy has 0.00% different in percentage. Overall, all gamma energies comply with the tolerance limits of ± 5%.
The results of counting efficiency against gamma energy are shown in figure 5. The gamma energies of 364.1 keV, 391.7 keV, 661.7 keV, 1173.2 keV, 1332.5 keV and 1836.1 keV indicated in power equation are dependent with gamma energies at determination coefficient of 0.9806. The power equation between counting efficiency and gamma energy obtained from figure 5 is shown in equation (5). This equation will be used in determining the counting efficiency for each interest radionuclide as shown in table 2.

\[ \text{Counting efficacy (cps/Bq)} = 0.0457 \times \text{gamma energy (keV)}^{-0.846} \]  

(5)

3.2. Background radiations
The results of background radiation for interest radionuclides of I-131, Cs-137 and Co-60 at 1200 s were 164.8 ± 20.4 count, 30.4 ± 5.3 count and 15.8 ± 3.3 count, respectively. These values were used as base data in considering whether the monitored person is free from internal dose or not i.e there was no internal dose when the whole body counts were less than twice background radiations.

3.3. Validation test
Table 1 shows the results of the validation test for standard sources of Cs-137 and Co-60. All results of the relative bias and repeatability were within the acceptable range of - 0.25 ≤ Br ≤ + 0.50 and SBr ≤ 0.40, respectively.

| Radionuclide | Gamma Energy (keV) | Relative Bias, Br | Repeatability, SBr |
|--------------|--------------------|-------------------|--------------------|
| Cs-137       | 661.6              | -0.006            | 0.036              |
| Co-60        | 1173.2             | 0.017             | 0.022              |
| Co-60        | 1332.5             | -0.009            | 0.072              |

3.4. Minimum detectable activity
Table 2 presents the MDA values of interest radionuclides of I-131, Cs-137 and Co-60 at 1200 s counting time. The determined MDA values for I-131, Cs-137 and Co-60 were comparable with the values obtained by the other institutions which has participated in the EURADOS 2004 intercomparison exercise [7].
Table 2. Counting efficiency and minimum Detectivity.

| Radionuclide | Counting efficiency (cps/Bq) | MDA (Bq) |
|--------------|------------------------------|----------|
| I-131        | 3.15E-04                     | 165.4 ± 10.0 |
| Cs-137       | 1.65E-04                     | 144.6 ± 11.5 |
| Co-60<sup>a</sup> | 1.13E-04                   | 172.0 ± 14.9 |
| Co-60<sup>b</sup> | 9.72E-05                   | 162.6 ± 15.6 |

<sup>a</sup>Co-60 Energy 1173.2 keV
<sup>b</sup>Co-60 Energy 1332.5 keV

3.5. Internal dose assessment
A total of fourteen volunteers from PGEC-16 comprise seven males and seven females were monitored for the internal dose assessment. The results demonstrate that the mean value of the whole body counting of I-131, Cs-137, Co-60<sup>a</sup> (1173.2 keV) and Co-60<sup>b</sup> (1332.5 keV) were 137.4 ± 13.8 count, 34.1 ± 5.0 count, 19.6 ± 2.9 count and 10.3 ± 3.8 count, respectively (figure 6). All results presented were two times lower than background radiation. Therefore, we can concluded that all volunteers were free from internal contamination.

Figure 6. The results of internal dose assessment (Bar graph) comparing to two times background radiations (Round dot line) in count.

4. Conclusion and discussion
The performance of ORTEC WBC System has been investigated. The result of energy calibration showed that all gamma energies comply with the tolerance limits of ± 5%. The counting efficiency results were described in power equation which can be used to predict the unknown efficiency of interest radionuclide. The relative bias and repeatability, which carried out from validation test, were within the acceptable range. The MDA for each interest radionuclide were found comparable with the EURADOS 2004 intercomparison results. The results of internal dose assessment on fourteen volunteers showed no internal contamination found. Based on these studies, it can be concluded that ORTEC WBC is now fully operational and suitable to be used in assessing internal exposure. In addition, the laboratory should participate in the intercomparison exercise to validate the quality of measurement and improve the measurement methods.

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