Calibration of two portable detection devices for in vivo measurements of high-energy photon emitters incorporated by humans in accidental situations

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Abstract. This work presents the evaluation of the applicability and sensitivity of two portable detection devices specially designed for in vivo measurement of high-energy photon emitters incorporated by humans. The calibration was performed at the In-Vivo Monitoring Laboratory of the IRD. The equipment consist of a NaI(Tl) 3”x3” and a NaI(Tl) 3”x1.5” scintillation detectors assembled on tripods. The detectors and their compact associated electronics are connected via USB cable to a portable PC. Spectrum acquisition and analysis are controlled by specific commercially available software. The calibrations were performed using a standard liquid source of $^{152}$Eu contained in 3.3 L polyethylene bottles. The evaluation of the systems is based on the estimation of the minimum committed effective doses associated to the minimum detectable activities, calculated using current biokinetic and dosimetric models available in the literature. The dose detection limits for selected radionuclide of interest in an emergency scenario have shown to be far below 1 mSv, allowing the system to be useful in accident situation.

Keywords. Internal monitoring; Internal dosimetry; Radiation measurement.

1. Introduction
Radiation technology is widely used throughout the world. It is present in power generation, health, industry, food, agriculture and scientific research. However, this knowledge must be accompanied by effective safety and security programs. Moreover, many international organizations are currently specially worried about the risk of nuclear terror events. In 2016, the International Atomic Energy Agency (IAEA) published the Information Circular in attention for Nuclear and Radiological Terrorism [1]. This document recognizes the need for ensuring adequate nuclear emergency preparedness and response capabilities.

Radiologic terrorism events include Radiological Dispersal Devices (RDD), referred as dirty bombs, which employ conventional explosives to disperse radioactive materials [2]. In Brazil, a government body was created for this purpose including civil and military entities [3].

The hospitals also should be prepared to identify and quantify intakes of radionuclides of interest in order to assess the committed effective doses associated to internal exposure. In such situations a fixed
whole-body counting system may not be suitable to attend an increased demand for \textit{in vivo} measurements [4].

Therefore, portable detection devices are versatile and effective equipment to be employed for prompt response to emergencies involving intakes of radionuclides, for whatever reasons.

2. Materials and Methods

The detection systems evaluated in this work consist in a NaI(Tl) 3”x3” and a NaI(Tl) 3”x1.5” scintillation detectors assembled on tripods and connected to the respective electronic compact modules. Spectrum acquisition and analysis is software-controlled. The procedures were carried out at the \textit{In Vivo} Monitoring Laboratory of the IRD.

Initially, NaI(Tl) 3”x3” and NaI(Tl) 3”x1.5” detectors calibration curves “Energy vs Channel” were obtained using a $^{152}$Eu standard point source.

A $^{152}$Eu standard liquid source (7.20 ± 0.13 kBq/g) was distributed in five 3.3 L polyethylene bottles to simulate the human thorax phantom. This is a low cost phantom, resistant and suitable for this purpose. A known mass of the liquid source known mass (masses differences method) was transferred to a volumetric flask of 25 mL. The activity transferred was calculated by mass difference. The volume of 25 mL was completed with deionized water. Aliquots of 4 mL were transferred to each polyethylene bottle containing 3.0 L of deionized water. The bottle set simulated a human chest in case of intake of high-energy photon emitter radionuclide.

The bottle set containing 15.07 ± 1.36 kBq of $^{152}$Eu radioactive liquid standard and the bottle set containing only deionized water (blank set) were positioned in standing geometry at 0.02 m, 0.20 m and 0.50 m distances from detectors surfaces (Figures 1a, 1b).

![Figure 1: (a) NaI(Tl)3”x3” and (b) NaI(Tl)3”x1.5” detection systems setup.](image)

Six Regions-of-Interest (ROI) of the $^{152}$Eu were defined in the spectrum and series of five 900 and 3,600-seconds counts were respectively performed with in the NaI(Tl) 3”x3” and the NaI(Tl) 3”x1.5” detectors with the bottle set containing $^{152}$Eu standard and the blank set containing only deionized water (BG). The average net count was recorded in each ROI. The efficiencies were calculated as follows:

$$\varepsilon = \frac{N_{\text{net}}}{A_e \times I_y} \quad \text{(1)}$$

where $N_{\text{net}}$ is the average net count in each ROI, $\Delta t$ is count time, $A_e$ is the standard activity and $I_y$ is the gamma yield of $^{152}$Eu in each ROI.

Then, six “Efficiency vs Energy” curves were obtained corresponding to three positions for each detector system.
The calibration was validated with a simulated thorax composed of five 3.3 L polyethylene bottles containing a potassium chloride solution (16.500 ± 0.050 L total volume). This method was chosen because $^{40}$K is a high-energy photon emitter (1460.8 keV) and commercial KCl salt is inexpensive and easily available.

The specific activity concentration of the $^{40}$K (2,804.90 ± 56.50 Bq/L) was determined with a High purity germanium (HPGe) detector (30% efficiency) from the IRD Bioanalysis Laboratory. The solution activity in the bottle set was calculated as follows:

$$A_{K_{40}} = C_{K_{40}} \times V_T$$  \hspace{1cm} (2)

where $A_{K_{40}}$ is the $^{40}$K activity in the bottle set, $C_{K_{40}}$ is the specific activity concentration and $V_T$ is the bottle set total volume.

In order to estimate the activity value using the “Efficiency vs Energy” curves, a series of five 900 and 3,600-seconds counts were performed respectively with the NaI(Tl) 3”x3” and the NaI(Tl) 3”x1.5” detectors with bottle sets containing the potassium chloride solution and the bottle set containing only deionized water (BG). The bottle sets were positioned at 0.02 m, 0.20 m and 0.50 m distances from detectors surfaces. The counts were registered at the ROIs adopted corresponding to $^{40}$K energy peak.

The activity present in the potassium chloride solution was calculated using the following equation:

$$A'_{K_{40}} = \left( \frac{N_{ctg}}{\Delta t_{K_{40}}} \right)_{\gamma_{K_{40}}} \left( \frac{\varepsilon \times I_{\gamma}}{\varepsilon_{K_{40}}} \right)$$  \hspace{1cm} (3)

where $\varepsilon$ is obtained from the “Efficiency vs Energy” curves corresponding to 1,460.8 keV ($^{40}$K energy peak) [5].

The goal of such procedure was to validate the “Efficiency vs Energy” curves by comparing the activity calculated from the equations (2) and (3).

Aiming the evaluation of the systems sensitivity, $^{137}$Cs was selected as the radionuclide of concern in an emergency scenario. One volunteer individual was counted with both detection systems, NaI(Tl) 3”x3” and NaI(Tl) 3”x1.5”, at 0.02 m, 0.20 m and 0.50 m distances with the same setup adopted with the bottle set.

The detection efficiency, in cps/dps, at 661.6 keV [5] was calculated from the six Efficiency vs Energy curves obtained previously. The calibration factor (CF) in cps/Bq was calculated from equation (4), where $I_{Y} = 0.851$ [5] is the gamma relative intensity for $^{137}$Cs at 661.6 keV:

$$CF = \varepsilon \times I_{Y}$$  \hspace{1cm} (4)

The evaluation of the system sensitivity is based on the estimation of the minimum committed effective doses associated to the minimum detectable activities [6].

The minimum detectable activity (MDA) in Bq was obtained from equation 5:

$$MDA = \left(4.65 \times \sqrt{N_{BG}} \right) / (t_{BG} \times CF)$$  \hspace{1cm} (5)

where $N_{BG}$ is the total background counts (volunteer non exposed subject) at the 661.6 keV region and $t_{BG}$ is the count time. The background count time ($t_{BG}$) was established as 120-seconds.

The MDI is a function of the MDA and depends on the exposure scenario and time elapsed between intake and in vivo measurement. It was calculated as follows (equation 6):

$$MDI = \frac{MDA}{m(t)}$$  \hspace{1cm} (6)

where $m(t)$ is the retention fraction in the compartment of interest, in Bq/Bq [7], [8].

The minimum detectable effective dose (MDED), in µSv, was obtained from equation 7:

$$MDED = MDI \times e(g)$$  \hspace{1cm} (7)

where $e(g)$ is the dose coefficient associated to the intake scenario adopted in the simulation.

For simulation purposes, in this work it was were considered a single intake by inhalation of particulate of $^{137}$Cs compound Type F with AMAD (Activity Median Aerodynamic Diameter) of 1 µm. In such scenario, the dose coefficient $e(g)$ equals 4.8 x 10^{-9} Sv/Bq [9]. The time elapsed between intake in vivo measurement is assumed as 1 day.

3. Results and Discussion

The $^{152}$Eu standard liquid source activity per mass was (7.20 ± 0.13) kBq/g. The liquid source mass transferred to the volumetric flask was 2.615818 g. This resulted in (18.84 ± 0.34) kBq (activity in the
flask). In 25 mL, the activity per mL was \(0.75 \pm 0.01\) kBq/mL. 4 mL of this solution was transferred to each bottle corresponding to \(3.01 \pm 0.05\) kBq. The total activity of the bottle set resulted in \(15.07 \pm 1.36\) kBq.

For NaI(Tl) 3”x3” and NaI(Tl) 3”x1.5” detectors, the average net count was recorded in each ROI. Based on the average net count, count times of 900 and 3,600-seconds, \(^{152}\text{Eu}\) standard activity contained in the bottles and gamma relative intensity, it was calculated the efficiencies using equation (1) for each ROI at 0.02 m, 0.20 m and 0.50 m distances, as shown in Tables 1, 2 and in figures 2 and 3.

| ROI | Energy (keV) | I gamma | Efficiency (cps/dps) |
|-----|--------------|---------|----------------------|
| ROI 1 | 121.78 | 0.28596 | 0.01069 ± 0.00006 |
| ROI 2 | 344.28 | 0.27682 | 0.00689 ± 0.00009 |
| ROI 3 | 778.90 | 0.13616 | 0.00541 ± 0.00006 |
| ROI 4 | 964.08 | 0.16243 | 0.00332 ± 0.00011 |
| ROI 5 | 1112.07 | 0.26048 | 0.00255 ± 0.00004 |
| ROI 6 | 1408.01 | 0.21842 | 0.00171 ± 0.00005 |

| ROI | Energy (keV) | I gamma | Efficiency (cps/dps) |
|-----|--------------|---------|----------------------|
| ROI 1 | 121.78 | 0.28596 | 0.00343 ± 0.00009 |
| ROI 2 | 344.28 | 0.00201 | 0.00201 ± 0.00009 |
| ROI 3 | 778.90 | 0.00150 | 0.00085 ± 0.00010 |
| ROI 4 | 964.08 | 0.00085 | 0.00085 ± 0.00010 |
| ROI 5 | 1112.07 | 0.00076 | 0.00076 ± 0.00003 |
| ROI 6 | 1408.01 | 0.00068 | 0.00068 ± 0.00004 |

Table 1. NaI(Tl) 3”x3” detector efficiencies.

| ROI | Energy (keV) | I gamma | Efficiency (cps/dps) |
|-----|--------------|---------|----------------------|
| ROI 1 | 121.78 | 0.28596 | 0.00977 ± 0.00006 |
| ROI 2 | 344.28 | 0.00519 | 0.00519 ± 0.00006 |
| ROI 3 | 778.90 | 0.00241 | 0.00241 ± 0.00003 |
| ROI 4 | 964.08 | 0.00157 | 0.00157 ± 0.00003 |
| ROI 5 | 1112.07 | 0.00122 | 0.00122 ± 0.00002 |
| ROI 6 | 1408.01 | 0.00075 | 0.00075 ± 0.00006 |

Table 2. NaI(Tl) 3”x1.5” detector efficiencies.
The math functions obtained from the six trend curves (0.02 m, 0.20 m and 0.50 m) above were respectively:

NaI(Tl) 3”x3”:
ε = 0.01258e^{-0.00138E}, \epsilon = 0.00354e^{-0.00128E}, \epsilon = 0.01260e^{-0.00145E}

NaI(Tl) 3”x1.5”:
ε = 0.01123e^{-0.00198E}, ε = 0.00341e^{-0.00203E}, ε = 0.00102e^{-0.00184E}

The $^{40}$K activity present in the bottle set (five bottles) is calculated by equation 2:

$A_{K^{40}} = (2,804.90 \pm 56.50 \text{ Bq/L}) \times (16.500 \pm 0.050 \text{ L}) = (46,280.85 \pm 942.74) \text{ Bq}$.

For NaI(Tl) 3”x3” and 3”x1.5” detection systems, with 900-s and 3,600-s count time respectively, the efficiencies calculated from math functions above for 1,460.8 keV ($^{40}$K energy peak), the emission relative intensity for $^{40}$K (0.1055) and average net count from the five counts, $N_{CTG}$, the activity values ($A'_{K^{40}}$) were estimated and compared to that calculated from equation 2, $A_{K^{40}} = (46,280.85 \pm 942.74) \text{ Bq}$ as shown in Table 3.
Table 3. Efficiencies and Activities calculated for NaI(Tl) 3”x3” and 3”x1.5” detection systems.

| Distance (m) | 0.02 | 0.20 | 0.50 | 0.02 | 0.20 | 0.50 |
|--------------|------|------|------|------|------|------|
| ε (cps/dps)  | 0.00168 | 0.00055 | 0.00015 | 0.00062 | 0.00018 | 0.00007 |
| A’K40 (Bq)   | ± 671.40 | ± 1,098.64 | ± 9,313.05 | ± 978.34 | ± 2,146.61 | ± 12,846.40 |
| relative     | (± 1%) | (± 3%) | (± 30%) | (± 2%) | (± 4%) | (± 31%) |
| uncertainty  |      |      |      |      |      |      |
| A’K40/AK40   | 0.998 | 0.822 | 0.680 | 1.135 | 1.110 | 0.908 |

Table 4 shows the minimum detectable effective doses (MDED) of the detection systems considering a single intake by inhalation of 137Cs particulate in an emergency scenario.

Table 4. MDED estimates for NaI(Tl) 3”x3” and 3”x1.5” detection systems.

| Distance (m) | 0.02 | 0.20 | 0.50 | 0.02 | 0.20 | 0.50 |
|--------------|------|------|------|------|------|------|
| ε (cps/dps)  | 0.00505 | 0.00152 | 0.00048 | 0.00303 | 0.00089 | 0.00030 |
| MDED (µSv)   | 13 | 44 | 141 | 17 | 59 | 181 |

4. Conclusion
Two portable detection systems, a NaI(Tl) 3”x3” and a NaI(Tl) 3”x1.5”, were calibrate for in vivo measurement of high-energy photon emitter radionuclides in human body. As expected, the detection efficiency is inversely proportional to photon energy and the distances.

Because of its larger crystal volume, the NaI(Tl) 3”x3” efficiency was higher than that of NaI(Tl) 3”x1.5” detector.

The relative uncertainties of the 40K activities estimated with both detection systems at 0.50 m distance were larger than at other distances.

The dose detection limits for the selected radionuclide of interest in an emergency scenario have shown to be far below 1 mSv allowing the evaluated systems to be useful in accident situations or unexpected event.

It is recommended to evaluate this technique considering other radionuclides of interest that could be used in malevolent actions.

The proposed calibration and measurement protocols could be easily applied to other detection devices owned by civil and military medical facilities in order to improve prompt response capabilities in case of emergency situations.

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