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IRD-CNEN whole body counter capabilities for *in vivo* monitoring of internally deposited radionuclides in human body

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Abstract: Internal exposure to radionuclides may occur as a result of a variety of practices, such as in nuclear industry; production of radiopharmaceuticals and nuclear medicine, biological research and agriculture; as well as in mining and milling of minerals with associated NORM. The IRD whole-body counter consists of shielded room equipped with an array of four HPGe detectors and two NaI(Tl) with dimensions of 8"x4" and 3"x3". The detection systems are able to detect and quantify a large variety of radionuclides emitting photons in the energy range from 10 to 3000 keV. The minimum detectable activities for most of the radionuclides of interest allow occupational monitoring as well evaluation of accidental intakes.

Keywords: internal dosimetry, in vivo measurement, whole-body counter

1. INTRODUCTION

Occupational exposure to radioactive materials may occur as a result of a variety of professional human activities, such as in (i) nuclear industry; (ii) use of unsealed sources in nuclear medicine, biological research and agriculture; (iii) production of radiopharmaceuticals, as well as in (vi) mining and milling of minerals in which radioactive materials are naturally present.

Individual monitoring is recommended as an essential tool in the control of internal exposures and to guarantee that the doses are as low and reasonably achievable [1]. Such control requires the use of methodologies aimed to identify and quantify a variety of radionuclides in the human body. The measurements are carried out as part of Monitoring Programmes designed by the Radiation Safety Officer of the facility and approved by the Regulatory Board. The Brazilian Nuclear Energy Commission is responsible for approval of Radiation Protection Programmes and periodic evaluation of radiological safety and source security conditions of each facility. Dosimetry laboratories which perform individual monitoring play an important hole in this process.

The results of *in vivo* monitoring are also useful for the estimation of the severity of accidents involving intakes of radioactive materials. In any case, after determining the activity in the body, in Bq, and assuming an exposure scenario, and applying a dosimetric and biokinetic model of the radionuclide of interest, it is possible to estimate the committed effective dose, in mSv [1]. Therefore, the objective of this work is to present the methodologies applied at the *In vivo* Monitoring Laboratory of IRD for the direct measurement of radionuclides in organs and tissues of the human body.

2 – MATERIALS AND METHODS

One of the main components of a whole-body counter is the shielding, aimed to reduce background level associated to the presence of naturally occurring radionuclides from uranium and thorium series as well as ^{40}K, and also to the

interaction of cosmic rays with the atmosphere and building materials. The IRD whole-body counter consists of a shielded room with internal dimensions of 2.5 m x 2.5 m x 2.62 m. The walls are made of steel and have a graded-Z interior lining made of 3 mm of lead, 1.5 mm of cadmium and 0.5 mm of copper. Such thin layers are aimed to reduce environmental sources of natural background radiation that would interfere with the measurements of radionuclides emitting low energy photons. The shielding reduces background in two orders of magnitude in the energy range of the photons of 662 keV emitted by ^{137}Cs [2]. An array of four high-resolution High Purity Germanium Detectors (HPGe) is used to perform low-energy measurements of radionuclides emitting photons in the energy range from 10 to 200 keV in the lungs, liver and bone tissue. High energy measurement of photon-emitting radionuclides in the range from 100 to 3000 keV in the whole body and in specific organs such as lungs, liver and thyroid are performed with two NaI(Tl) scintillation detectors, with dimensions of 8”x4” and 3”x3”. The detectors supports allow positioning over various parts of the body of an individual laid on a comfortable monitoring chair.

The detection systems are calibrated with physical anthropomorphic phantoms of the organ of interest containing certified activities of the radionuclide of interest. The calibration process consists of measuring the phantoms at standard geometries. Similarly, an inert phantom is measured to estimate the background count rate [2]. It is important to point out that the quality of the measurement and consequently the reliability of the results relies, among other factors, on the calibration procedure adopted.

The calibration factor, expressed in cpm/Bq, for each specific geometry and radionuclide is calculated as the ratio between the net count rate and the activity of the phantom.

The activity of an exposed individual is calculated by dividing the net count rate registered on the *in vivo* measurement by the calibration factor. In the case of a lung measurement of a radionuclide emitting photons of low energy it is also necessary to correct the count rate due to the attenuation related to the chest thickness (CWT) of the tissue over the lung region [3]. Such correction is carried out considering the weight (w) and height (h) of the individual.

The minimum detectable activity (MDA), calculated for each radionuclide and counting geometry, is directly proportional to the square root of the background of an unexposed individual [4] as shown in Equation 1:

$$MDA = \frac{4.65\sqrt{N}}{E \times T} + \frac{3}{E \times T} \qquad (1)$$

where MDA is the minimum detectable activity, in Bq; N is the total counts in the region of interest of the background of an unexposed individual; E is the calibration Factor, in (cpm/Bq), and T is the count time, in minutes.

The total uncertainty of the *in vivo* measurement is associated to the uncertainty of the Calibration Factor and the counting of the individual. The uncertainties associated to the various parameters of the calculation and the quality control of the detection systems are estimated according to the criteria suggested by ISO 17025:2005 [5].

The committed effective doses for the most relevant radionuclides is estimated using biokinetic and dosimetric models developed by the International Commission on Radiological Protection (ICRP) and suggested by the International Atomic Energy Agency (IAEA). ICRP classifies the compounds into three categories according to their solubility in the pulmonary fluids: Type F (very soluble), Type M (moderately soluble), and Type S (insoluble).

In this work, activities and doses are estimated with the software AIDE [6], allowing the interpretation of *in vivo* measurements and the comparison of the internal doses with the limits established by the Regulatory Board.

Table 1 presents a list of measurements performed at the IRD whole body counter and the parameters used for the calculation of doses for selected radionuclides, considering single intake via inhalation of particles with Activity Median Aerodynamic Diameter (AMAD) equal to 1μm, which is classified as inhalable particle fraction. In the specific cases of ^{131}I and ^{123}I it was assumed the intake of volatile elemental iodine, class F.

Table 1. List of measurements performed at the IRD whole body counter and corresponding activities of selected radionuclides in organs of interest, 1 day after the intake of 1 Bq via inhalation (m_t)

Nuclide	Organ of interest	Detector	Scenario [1]Type/ [2]AMAD	Dose Coefficient (mSv.Bq^{-1})	m(t) (Bq/Bq)
^{241}Am	Lungs	HPGe	M / 1	3.91 x 10^{-5}	1.09 x 10^{-1}
^{241}Am	Head	HPGe	M / 1	3.91 x 10^{-5}	9.10 x 10^{-4}
^{137}Cs	Whole Body	NaI(Tl)8"x4"	M / 1	1.20 x 10^{-5}	4.03 x 10^{-1}
^{18}F	Whole Body	NaI(Tl)3"x3"	F / 1	3.00 x 10^{-8}	4.58 x 10^{-5}
^{18}F	Head	NaI(Tl)3"x3"	F / 1	3.00 x 10^{-8}	3.70 x 10^{-6}
^{131}I	Thyroid	HPGe	F, Gas	1.98 x 10^{-5}	2.29 x 10^{-1}
^{123}I	Thyroid	HPGe	F, Gas	2.13 x 10^{-7}	7.09 x 10^{-2}
^{210}Pb	Head	HPGe	M / 1	9.23 x 10^{-4}	5.07 x 10^{-4}
^{210}Pb	Knee	HPGe	M / 1	9.23 x 10^{-4}	3.87 x 10^{-4}
^{210}Pb	Lungs	HPGe	M / 1	9.23 x 10^{-4}	1.09 x 10^{-1}
^{226}Ra	Lungs	NaI(Tl)8"x4"	M / 1	3.14 x 10^{-3}	1.09 x 10^{-1}
^{232}Th	Lungs	HPGe	M / 1	4.24 x 10^{-2}	1.09 x 10^{-1}
^{235}U	Lungs	NaI(Tl)8"x4"	M / 1	2.75 x 10^{-3}	1.09 x 10^{-1}

[1]Solubility class according to ICRP 78 [2]Activity Median Aerodynamic Diameter

3 – RESULTS AND DISCUSSION

Table 2 presents the calibration results of the HPGe and NaI(Tl) detection systems available at the IRD whole body counter, for a variety of radionuclides, and an evaluation of the sensitivity of the detection system based on a comparison of the minimum detectable activities with the corresponding expected activities in the organs or tissues of interest associated to the respective committed effective doses of 1 and 20 mSv.

The calibration factors obtained for the various counting geometries present uncertainties in the range of 0.5 to 7%, which is compatible with values usually found in the literature related to *in vivo* measurement procedures [3,4,7,8].

Uncertainties associated to the calibration factors and the efficiency values based on efficiency *vs* energy curves are estimated through the propagation of counting statistics and standard source activity uncertainty, and are below 2% in all cases.

Table 2. Calibration Factors for the radionuclides monitored in the IRD whole body counter and comparison between MDA of the IRD whole body counter detection system and expected activities in measured organ 24 hours after an intake corresponding to committed effective doses of 1 and 20 mSv

Nuclide	Geometry (organ)	Calibration Factor (cpm/Bq)	Activity in measured organ (Bq)		MDA (Bq)
			1 mSv	20 mSv	
^{241}Am	Lungs	0.5229. e$^{(-0.039.CWT)}$	**2.8**	56	6.8
^{241}Am	Head (skull)	0.389 ± 0.003	**2.3x 10^{-2}**	**4.6 x 10^{-1}**	2.1
^{18}F	Whole Body (skeleton)	0.40 ± 0.02	1500	30000	32
^{18}F	Head (brain)	0.737 ± 0.004	180	36000	7.5
^{131}I	Thyroid	0.397 ± 0.005	1.2 x 10^{4}	2.4 x 10^{5}	23
^{123}I	Thyroid	0.394 ± 0,022	3.3 x 10^{6}	6.6 x 10^{7}	5.0
^{210}Pb	Head (skull)	0.039 ± 0.003	**0.55**	**1.1**	16
^{210}Pb	Knee	0.046 ± 0.01	**0.42**	**8.4**	14
^{210}Pb	Lungs	0.0501 e$^{(-0.04.CWT)}$	120	2400	34
F&A	Whole Body	0.00422 e$^{(-0.000759.E)}$	3.4 x 10^{6}	6.8 x 10^{7}	88
^{226}Ra	Lungs	0.0345. e$^{(-0.034.CWT)}$	**60**	120	83
^{232}Th	Lungs	2.27 ± 0.01	**2.6**	52	6.1
^{235}U	Lungs	0.4544 e$^{(-0.0344.CWT)}$	40	800	6.5

F&A = Fission and Activation Products
CWT = Chest wall thickness (mm)
E = Energy (keV)

The use of the software AIDE allows the calculation of the activities of radionuclides in the organs and tissues of interest 24 hours after the intake of respective activities that would result in committed effective doses of 1 and 20 mSv. It should be highlighted that MDA values for the radionuclides and geometries evaluated in this work refer to the application of the *in vivo* monitoring technique in situations where it is assumed a single incidental intake.

A comparative analysis between the results for head and knee geometries, for the radionuclides ^{241}Am and ^{210}Pb, shows that the methodologies are not sensitive enough if the measurement is performed 24 hours after the intake. This limitation is related to the biokinetic of those nuclides and their respective dose coefficients, since the corresponding retention fractions in bone tissue is quite low one day after intake [1].

In the case ^{226}Ra and ^{232}Th, the techniques are suitable for the detection at the 20 mSv level, considering the intake of those radionuclides without their respective progeny.

On the other hand, in the case of ^{18}F, considering its low dose coefficient, the *in vivo* measurement techniques can be considered suitable for monitoring purposes even 24 hours after the intake, since the activity in the compartments corresponding to an effective dose of 1 mSv is approximately two orders of magnitude higher than the minimum detectable activity.

In other cases, like the measurement of ^{131}I and ^{123}I in the thyroid, ^{210}Pb and ^{235}U in the lungs, and ^{137}Cs in the whole body, the techniques are comfortably sensitive for their application in the evaluation of accidental intakes.

4 – CONCLUSIONS

The IRD whole body counter is able to perform *in vivo* measurement of a large variety of radionuclides emitting photons in the energy range from 10 to 3000 keV. The minimum detectable activities for most of the radionuclides of interest allow its application for occupational monitoring as well as in the case of accidental intakes.

It should be highlighted that the evaluation of each technique in terms of sensitivity for their application in routine monitoring should be established considering that the minimum detectable activity of the detection system is below the expected activity in the compartment of interest, considering the most likely exposure scenario as well as the monitoring frequency established in the Radiation Protection Plan implemented in the facility.

5 – REFERENCES

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