Comparative evaluation of gamma cameras performance for internal monitoring of workers exposed to ^{131}I in nuclear medicine services

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ABSTRACT

Among the radionuclides handled in Nuclear Medicine Services (NMS), ^{131}I is one of the most used for both diagnostic and therapy proposes. This practice represents a risk of incorporation these radionuclides by workers. The International Atomic Energy Agency (IAEA) recommends the implementation of an internal monitoring program on workers potentially exposed to annual effective doses higher than 1 mSv, as for example, those who handle ^{131}I for therapy. In Brazil there are approximately 90 NMS authorized to handle ^{131}I for therapy and there are available only five laboratories qualified to provide internal monitoring services. This scenario turns impossible to attend all possible demand for internal monitoring if such regulation is required by the Brazilian Nuclear Energy Commission (CNEN). This work presents a simple and inexpensive method for *in vivo* routine thyroid monitoring of ^{131}I using gamma cameras available in the clinics itself and compares their performance for the proposed method. It has been verified that all equipment evaluated in this work present enough sensitivity for such application.

Keywords: internal monitoring, radiation protection, iodine-131, nuclear medicine.

1. INTRODUCTION

In the nuclear medicine practice, a variety of radionuclides in the form of unsealed sources are routinely handled for diagnostic and therapy purposes. This practice represents a significant risk of external and internal exposure for workers who handle these radionuclides.

The external exposure is predominant in SMN, however, depending on the scenario, internal exposure may be also significant as a consequence of intake of radionuclides via inhalation and ingestion. Based on international criteria of evaluation, the permanent risk of intakes of radionuclides requires the implementation of a routine monitoring plan, aiming to control and limit internal doses [1].

National and international regulations appoint the Radiation Safety Officer (RSO) of the facility as responsible for managing the Radiation Protection Programme (RPP). The RSO shall implement, based on monitoring results, the necessary measures to keep exposure levels as low as possible [2]. The RPP should consider the risks of external and internal occupational exposures and includes, when necessary, a routine monitoring plan with specific methodologies that allows identification and quantification of intakes as well as the estimation of the committed effective doses of the workers [3].

Currently, in Brazil, approximately 90 Nuclear Medicine Services (NMS) are authorized by the CNEN to handle ^{131}I for therapy purposes [4], resulting in a significant number of workers routinely exposed to internal exposures.

Iodine is a volatile element, and its isotope ^{131}I is still one of the most frequently used radionuclides in NMS. Because of its physical, chemical and radioactive properties, ^{131}I presents a high risk of intake and, consequently, internal doses. It should be also considered in this scenario the high activities routinely handled for therapy purpose.

Although the IAEA recommends implementing an internal monitoring program of such group of workers, in Brazil there are not enough qualified laboratories available to offer internal dosimetry services and attend the possible demand of internal monitoring in this field. Consequently, it would represent an impeditive high cost to the medical institutions if the Brazilian Nuclear Regulatory Board would apply the requirements of internal monitoring [5].

In order to overcome this situation, the Institute for Radiation Protection and Dosimetry (IRD), a branch of the CNEN, has developed several studies over the last 15 years proposing the use of devices available in the NMS itself for use in ^{131}I occupational monitoring [6]. Among such equipment, the gamma camera stands out to present the highest sensitivities for the proposed application. This work presents a performance comparison of gamma cameras available in NMS in Brazil for [131]I *in vivo* monitoring purpose.

2. MATERIALS AND METHODS

2.1. Materials

2.2.1 Gamma Cameras

Eight models of gamma camera available in seven different facilities were evaluated in this work. Table 1 presents the models intended to be applied in internal routine monitoring.

Table 1: Gamma cameras evaluated in seven Nuclear Medicine Services.

Manufacturer	Model	Facility (NMS)
Phillips	BrightView XCT	A
GE	Millennium MG	B
GE	Discovery MN/CT 670	C
Siemens	e.cam 180	D
Elscint	Apex SPX-6	E
Siemens	Symbia	E
GE	Millennium MG	F
Siemens	e.cam 180	G

2.2.2 Neck-Thyroid Phantom

The neck-thyroid phantom (Figure 1) used for the calibration of the detectors was developed at the *In Vivo* Monitoring Laboratory of the IRD. The neck-thyroid phantom is made of polyurethane-

base tissue equivalent material. A filter paper simulating a human thyroid is spiked with a known amount of a ^{133}Ba liquid standard source [5].

It is a conventional practice to use a ^{133}Ba standard source as a surrogate for measuring ^{131}I since the energy and yield of photons emitted by ^{133}Ba are very similar to the photon emissions from ^{131}I. Furthermore, the half-life of ^{133}Ba is long (10.5 years) compared with ^{131}I (8 days), so that a certified calibration standard containing ^{133}Ba can be used for many years.

After being sealed with a plastic film, the filter paper is fixed in the proper position with an acrylic part and inserted in the neck phantom. The phantom used in this work contained originally 29771 ± 214 Bq of ^{133}Ba in 28/April/2004, certified by the *National Laboratory of Metrology of Ionizing Radiations* (LNMRI) of IRD.

Figure 1: *Neck-thyroid phantom produced in the In Vivo Monitoring Laboratory of IRD [5].*

2.2. Methods

The methodology consisted basically in determining the calibration factors for measurement of ^{131}I in the thyroid, calculation of the minimum detectable activities and the corresponding minimum detectable effective doses.

2.2.1 Calibration of the Detection System

Step 1 – Calculation of ^{131}I Equivalent Activity: The ^{133}Ba activity content in the phantom was corrected between fabrication and calibration dates. The equivalent ^{131}I activity is calculated as shown in Eq. (1) by multiplying the activity of ^{133}Ba added to the phantom by the ratio between the sum of ^{133}Ba and ^{131}I photon yields in the region of interest for the measurement, using the parameters provided in Table 2:

$$^{131}\text{I Eq Ac}_{Bq} = A\left(^{133}\text{Ba}\right) \times \frac{\Sigma\left(\gamma^{133}\text{Ba}\right)}{\Sigma\left(\gamma^{131}\text{I}\right)} \tag{1}$$

Where:

^{131}I Eq Ac = is the equivalent activity of ^{131}I, in Bq;

A (^{133}Ba) = is the activity of ^{133}Ba present in the phantom, in Bq;

Σ (γ^{133}Ba) = is the sum of emission intensities γ of ^{133}Ba; and

Σ (γ^{131}I) = is the sum of emission intensities γ of ^{131}I.

Table 2: Energy photons and emission intensity for ^{133}Ba and ^{131}I [7].

Energies γ ^{133}Ba (keV)	Emission Intensity γ
276.39	0.071
302.85	0.183
356.01	0.620
383.85	0.089
Energies γ ^{131}I (keV)	**Emission Intensity γ**
284.30	0.061
364.48	0.817

The ^{131}I equivalent activity of the phantom used in this work is in the order of 14000 Bq. This value must be corrected according to the date of calibration of the equipment.

Step 2 – Determination of Measurement Setup (Figure 2): The standard geometry consisted in positioning the phantom at 12 cm distance to the front of the Gamma-Camera (GC).

The count time was determined according to each detector sensitivity for a time after intake of 1 and 7 days, considering a weekly generic monitoring frequency, resulting in 48 monitoring periods per year.

Step 3 – Calculation of Calibration Factor (CF): The calibration factor is given by:

$$CF_{cpm/Bq} = (NC/T) / {}^{131}I \text{ Eq Ac} \qquad (2)$$

Where:

NC is the Net counts;

T is the Count Time (min); and

^{131}I Eq Ac = Equivalent activity of ^{131}I, corrected for the date of the calibration in the facility.
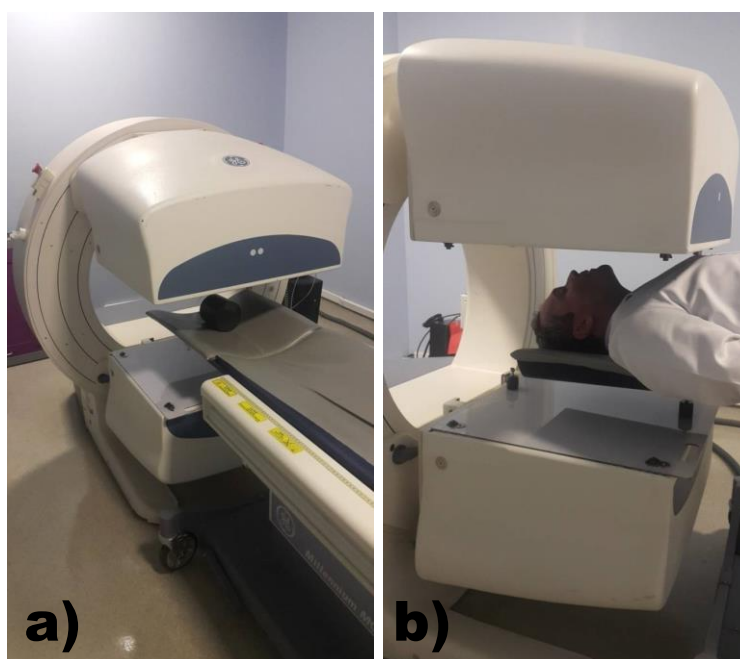

Figure 2: *Geometries used in this work.*

a) Measurement geometry for gamma-camera calibration.
b) Measurement geometry for worker monitoring.

2.2.2 Evaluation of Sensitivity

The evaluation of the sensitivity of the method for its application in routine internal monitoring is based on the calculation of the Minimum Detectable Activity (MDA), in Bq, Minimum Detectable Intake (MDI), in Bq and Minimum Detectable Effective Dose (MDED), in mSv.

The MDA of the method is given by equation 3 [8]:

$$MDA_{Bq} = (4{,}65 . \sqrt{N}) / CF . T \qquad (3)$$

Where:

N is the total counts of the background of a non-exposed subject, when the calibration is made with only one measurement; and

CF is the calibration factor, and

T is the count time (min).

The Minimum Detectable Intake (MDI), a function of the MDA and the exposure scenario, is given by:

$$MDI_{Bq} = MDA / m(t)_{inh\ or\ ing} \qquad (4)$$

Where:

MDA is the minimum detectable activity (Bq); and

m(t) is the retention fraction in the compartment of interest for inhalation or ingestion (Bq/Bq).

The last parameter to be calculated is the Minimum Detectable Effective Dose, which is based on the MDI, and is given by:

$$MDED_{Bq} = MDI_{ina/ing} \times e(g)_{ina/ing} \qquad (5)$$

Where:

MDI is the minimum detectable intake (Bq); and

e(g)_ina/ ing_ is the dose coefficient (mSv/Bq).

In order to be considered useful for internal dosimetry purposes, the technique should, at least, be able to detect an activity that would result in an annual effective dose below 1 mSv for the most likely internal exposure scenario [9]. The values of "m(t)" and "e(g)" are available in the publication 78 of the ICRP [10] and can also be generated for specific exposure scenarios and times through the software Activity Internal Dose Estimate (AIDE) [11].

The number of monitoring periods is determinant to evaluate the sensitivity of the proposed method to be applied on a routine internal monitoring in a specific NMS. This evaluation can be made by the following equation:

$$\text{Annual Sensitivity}_{mSv} = \text{MDED}_{mSv} \times n \tag{6}$$

Where:

MDED is the minimum detectable effective dose (mSv); and

n is the number of annual monitoring periods (e.g., 48 when workers are monitored once a week).

3. RESULTS AND DISCUSSION

Table 3 shows the total counts and background count results, count times, calibration dates and its respective ^{131}I equivalent activities present in the neck-thyroid phantom in the time of calibration of gamma cameras evaluated.

Table 3: Calibration parameters and counts results of the detectors analyzed.

GC Model	NMS	Count Time (min)	Counts	BG Counts	Calibration Date	^{131}I Eq Ac (Bq)
BrightView XCT	A	3	113483	37881	10/mar/17	13969
Millennium MG	B	7	255825	103282	21/jun/17	13712
Discovery MN/CT 670	C	3	31408	4050	03/ouct/17	13456
e.cam 180	D	3	69133	16853	23/mar/18	13047
Apex SPX-6	E	3	113228	36723	07/nov/18	12518
Symbia	E	2	50782	11601	07/nov/18	12518
Millennium MG	F	2	49642	8526	07/nov/18	12518
e.cam 180	G	3	16565	3544	22/may/19	11016

Table 4 shows the results for CF and MDA for each gamma camera evaluated at the different facilities using the neck-thyroid phantom. These calibrations were made in a single measurement of the neck-thyroid phantom and the background, using equation 3 to calculate the MDA.

Table 4: CF and MDA of the gamma cameras analyzed.

GC Model	NMS	CF (Cpm/Bq)	MDA (Bq)
BrightView XCT	A	1.804	167
Millennium MG	B	1.589	134
Discovery MN/CT 670	C	0.678	146
e.cam 180	D	1.336	151
Apex SPX-6	E	2.037	146
Symbia	E	1.603	149
Millennium MG	F	1.642	131
e.cam 180	G	0.359	257

The parameter MDI depends on the exposure scenario and the time elapsed between intake and *in vivo* measurement. In this work it was used the retention fraction values for 1 and 7 days between ^{131}I intake by inhalation and *in vivo* measurement (Table 5). Such values were obtained through the software AIDE. The MDED was calculated based on the MDI, considering the dose coefficient for inhalation associated to the corresponding intake scenario adopted in this study, as shown in

Table 5. The inhalation incorporation scenario was chosen because it is the most likely when handling iodine in liquid form, which is widely used in nuclear medicine therapies.

Table 5: Retention fractions and dose coefficient for inhalation obtained with the software AIDE.

m(t) (Bq/Bq)		e(g) (mSv/Bq)
1 day	**7 days**	1.98×10^{-5}
0.229	0.139	

Table 6 shows the results for MDI and MDED of the GCs evaluated, considering 1 and 7 days after intake by inhalation.

Table 6: MDI and MDED of the detectors evaluated for 1 and 7 days after intake by inhalation.

GC Model	NMS	MDI (Bq)		MDED (mSv)	
		1 day	**7 days**	**1 day**	**7 days**
BrightView XCT	A	730	1203	0.014	0.024
Millennium MG	B	587	966	0.012	0.019
Discovery MN/CT 670	C	636	1047	0.013	0.021
e.cam 180	D	658	1084	0.013	0.020
Apex SPX-6	E	637	1049	0.013	0.021
Symbia	E	652	1075	0.013	0.021
Millennium MG	F	517	940	0.011	0.019
e.cam 180	G	1122	1848	0.022	0.037

In order to evaluate the sensitivity of the detectors, it was simulated a weekly generic monitoring period, totalizing 48 annual monitoring periods. The choice of monitoring frequency depends on the routine of each NMS, it can be altered by the number of patients treated, the amount of ^{131}I activities handled and the ^{131}I physical form, for example. It was observed that the frequency required for NMS participants is lower than the generic frequency used in this study. Table 7 shows the annual sensitivities obtained for a weekly monitoring period.

Table 7: Annual sensitivities (mSv) for 48 monitoring periods per year.

GC Model	NMS	Count time (min)	Sensibility (mSv)	
			1 day	7 days
BrightView XCT	A	3	0.69	1.14
Millennium MG	B	7	0.56	0.92
Discovery MN/CT 670	C	3	0.60	1.00
e.cam 180	D	3	0.57	0.95
Apex SPX-6	E	3	0.61	1.00
Symbia	E	2	0.62	1.02
Millennium MG	F	2	0.54	0.89
e.cam 180	G	3	1.07	1.76

The gamma cameras evaluated have significant differences in manufacturing characteristics and time of operation. Some of them are in operation for about 20 years, such as the Elscint Apex SPX-6 (A) and the GE Millennium MG (B/F), while others, such as the GE Discovery MN/CT 670 are much newer. However, despite of the time of use, all gamma cameras presented enough sensitivity for occupational monitoring in a reasonable short count time. The exception is the Siemens e.cam 180 of NMS "G", which does not present enough sensitivity for the time and generic monitoring frequency simulated in this work. However, this fact does not prevent the use of this equipment for the proposed application. The sensitivity values obtained may be increased simply by optimizing two basic measurement parameters: (i) reducing distance between detector and neck-thyroid phantom and (ii) increasing measurement count time, as done with the model GE Millennium MG of NMS "B", which was 7 minutes ok. In order to avoid disturbing the routine of the NMS, it is proposed to use the minimum count time, but keeping the necessary sensitivity of the method for its application in occupational monitoring.

The counting distance (12 cm) was optimized to be the minimum distance that provides a reasonable comfort to the subject during measurement. This distance may be altered, but decreasing it may cause difficulties during the measurement procedure. Furthermore, the monitoring plan would be more effective if the measurements are schedule according to the radionuclide handling of the facility, when it is more likely to detect significant intakes by the workers.

Significant differences in sensitivity were observed between equipment of the same model of different NMS. The GE Millenium MG of NMS "B", for example, presents less sensitivity than the same model of NMS "F", which reached the minimum sensitivity required in a shorter counting time. This can be explained by the equipment maintenance conditions: the equipment of NMS "F" presents better general conditions and integrity of the crystals of its detectors. These conditions were observed through visual evaluation and the results of equipment quality control tests. The same was observed between the model Siemens e.cam 180 of NMS "D" and "G", which can also be explained by their different maintenance conditions.

It is important to emphasize that the results presented in this work are valid for a generic weekly monitoring frequency resulting in 48 monitoring periods per year. Thus, it should be kept in mind that the monitoring plan to be effectively implemented on each NMS would depend on the service routine, especially the radionuclide handling schedule.

4. CONCLUSIONS

The gamma camera performance can be evaluated by analyzing the MDA of the detection system as well as the count time required for the system to reach the minimum sensitivity to be considered useful for internal monitoring purpose. This study evaluated modern and old gamma camera models, and despite of the differences on time of manufacture between the models, all gamma cameras can be used to implement the proposed methodology. In most cases, the appropriate sensitivity was achieved setting the count time to 3 minutes, which may be reduced or increased according to the NMS routine in which the methodology is implemented. This can be considered a feasible and short count time.

It should also be highlighted that the proposed methodology is easy, simple and inexpensive, since the measurements are performed by the staff of the clinic and there is no need to purchase new equipment for the implementation of the monitoring plan.

Finaly, this study provides a methodology to be implemented in routine in order to comply with requirements established by the National Regulatoy Board for individual monitoring of workers who handle ^{131}I in Nuclear Medicine Services.

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