Comparison of surface contamination monitors for in vivo measurement of $^{131}$I in the thyroid

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Abstract. The routine handling of radiopharmaceuticals in nuclear medicine represents a significant risk of internal exposure to the staff. The IAEA recommends the implementation of monitoring plans for all workers subject to a risk of exposures above 1 mSv per year. However, in Brazil, such recommendation is practically unfeasible due to the lack of a sufficient number of qualified internal dosimetry services over the country. This work presents an alternative based on a simple and inexpensive methodology aimed to perform in vivo monitoring of $^{131}$I in the thyroid using portable surface contamination probes. Results show that all models evaluated in this work present enough sensitivity for the evaluation of accidental intakes.

1. Introduction
According to the information available at the Brazilian Nuclear Energy Commission (CNEN) [1], there are approximately 430 authorized nuclear medicine clinics in regular operation in Brazil, resulting in a significant number of occupationally exposed workers who handle routinely a wide variety of radionuclides in the form of unsealed sources. Such professional activity represents a risk associated to the possibility of intake via inhalation and ingestion and the subsequent internal exposure. Currently, the most frequently used radionuclides in the field of nuclear medicine are $^{99m}$Tc, $^{131}$I, $^{123}$I, $^{201}$Tl and $^{18}$F. $^{131}$I is widely used for diagnosis and therapy and is considered the most critical radionuclide in terms of internal exposure of the workers because of its high dose coefficient. The use of other radionuclides is being studied worldwide and can be a subject of radiological protection concern in a near future.

In spite of a consensus that external exposure is predominant, significant intakes may occur simultaneously in nuclear medicine practice. However, depending of the exposures scenario, and 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 [2]. It is a responsibility of the Radiation Safety Officer (RSO) of the facility to manage the Radiation Protection Programme and, based on monitoring results, to implement the necessary measures to keep exposure levels as low as possible. It should also be highlighted that the application of radiation protection principles in a routine pattern relies on a shared responsibility among the RSO and the occupationally exposed workers [3].

The evaluation of internal occupational exposures requires the use of specific methodologies which allow identification and quantification of intakes as well as the estimation of committed effective doses of the workers [4]. Currently, in Brazil, qualified laboratories are not available in all regions of the country to offer internal dosimetry services. Thus, it would represent a high cost to the medical
institutions if the CNEN would apply the need for the implementation of internal monitoring programmes according to national radiation protection requirements [5].

This work describes a simple and convenient alternative aiming to implement a low-cost internal monitoring programme applied to workers who handle unsealed sources of $^{131}$I used mainly for therapy purposes in nuclear medicine facilities. Such professionals are frequently exposed to height activities of $^{131}$I and consequently, present higher risks of intake. The methodology uses portable surface-contamination monitors, a type of equipment available in all nuclear medicine facilities since it is of obligatory use according to the CNEN requirements.

2. Materials

2.1. Neck-thyroid phantom

The neck-thyroid phantom (figure 1) used for the calibration of the detectors for the measurement of $^{131}$I in the thyroid was developed at the In Vivo Monitoring Laboratory of IRD. The neck phantom is made of polyurethane-base tissue equivalent material. A filter paper simulating a human thyroid is contaminated with a known amount of $^{133}$Ba liquid source. After being sealed with a plastic film, the filter paper is contained in an acrylic part and inserted in the neck phantom. It is conventional practice to use sources of $^{133}$Ba as a surrogate for measuring $^{131}$I since the energy and yield of photons emitted by $^{133}$Ba are very similar to photon emissions from $^{131}$I (table 1). 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.

![Figure 1. Neck-thyroid phantom developed and produced in the In Vivo Monitoring Laboratory of IRD [6].](image)

| Energies $^{133}$Ba (keV) | Emission Intensity $^{133}$Ba |
|---------------------------|------------------------------|
| 276.39                    | 0.071                        |
| 302.85                    | 0.183                        |
| 356.01                    | 0.620                        |
| 383.85                    | 0.089                        |

| Energies $^{131}$I (keV)  | Emission Intensity $^{131}$I |
|---------------------------|------------------------------|
| 284.30                    | 0.061                        |
| 364.48                    | 0.817                        |
2.2. Portable surface contamination monitors
The table 2 presents a list of sixteen equipment evaluated in this work that were been previously calibrated at the Laboratório Nacional de Metrologia das Radiações Ionizantes (LNMRI-IRD) and at the Laboratório de Ciências Radiológicas (LCR-UERJ).

| Trade Mark  | Model      | Quantity | Type          |
|-------------|------------|----------|---------------|
| Eberline    | E-120      | 1        | Geiger-Muller |
| Prólogo     | PSN-7013   | 1        | Geiger-Muller |
| Berthold    | LB-124 Scint | 1      | Scintillator  |
| IEN         | MIR-7026   | 2        | Geiger-Muller |
| MRA         | GP-500     | 1        | Geiger-Muller |
| Polimaster  | PM 1400    | 1        | Geiger-Muller |
| Thermo Scient.| RadEye B20  | 1      | Geiger-Muller |
| Tech. Associates | PUG-7A     | 1      | Geiger-Muller |
| Dosimeter   | 3007A      | 1        | Geiger-Muller |
| Ludlum      | Model 3    | 3        | Geiger-Muller |
| Thermo Scient. | Identifinder | 1  | Scintillator  |
| SE International | Inspector Exp | 1 | Geiger-Muller |
| Saphimo     | Mini Trace | 1        | Geiger-Muller |

3. Methods
3.1. Calibration of the monitors
The calibration procedure was conducted as follows:

Step 1: The $^{133}\text{Ba}$ activity content of the phantom was corrected taking into account the time elapsed between fabrication and calibration dates and the half-life of $^{133}\text{Ba}$. The $^{131}\text{I}$ equivalent activity was then calculated according to equation (1)

$$At \text{ Eq } ^{131}\text{I} Bq = A (^{133}\text{Ba}) \times \frac{\Sigma (\gamma^{133}\text{Ba})}{\Sigma (\gamma^{131}\text{I})}$$  \hspace{1cm} (1)

Where:

At Eq $^{131}\text{I}$ = Equivalent activity of $^{131}\text{I}$;

$A (^{133}\text{Ba})$ = Activity of $^{133}\text{Ba}$ (Bq) present in the phantom;

$\Sigma (\gamma^{133}\text{Ba})$ = Sum of emission intensities $\gamma$ of $^{133}\text{Ba}$; and

$\Sigma (\gamma^{131}\text{I})$ = Sum of emission intensities $\gamma$ of $^{131}\text{I}$.

Step 2: The measurement setup was established as shown in Figure 2, and the phantom count rate was recorded over five sequential measurements at standard geometries of 0 and 3 cm between the detector front face and the phantom surface.
Step 3: A blank phantom was measured in five sequential counts in the same setup for background account.

Step 4: The calibration factors were calculated for the standard geometry according to equation (2):

$$CF_{cpm/Bq} = \frac{cpm}{A_{calib}}$$

Where:

- $cpm$ = net count rate (total cpm of phantom subtracted by background count rate); and
- $A_{calib}$ = $^{131}$I equivalent activity content of the phantom.

3.2. Evaluation of sensitivity

The evaluation of the sensitivity of the method for its application in routine internal monitoring is based on the calculation of three parameters: (i) Minimum Detectable Activity (MDA); (ii) Minimum Detectable Intake (MDI) and; (iii) Minimum Detectable Effective Dose (MDED).

The MDA of the method is calculated as follows [7]:

$$MDA_{Bq} = \frac{4.65 \times \sigma_{bg}}{CF}$$

Where: $\sigma_{bg}$ = Standard deviation of the BG (counts) in one minute; and $CF$ = Calibration Factor (cpm/Bq).
The MDI is a function of the MDA and depends on the exposure scenario and time, in days, elapsed between intake and in-vivo measurement. In this work MDI and MDED where calculated for retention fractions “m(t)” values of 1 and 7 days. The Minimum Detectable Intake (MDI) is calculated as follows:

\[
\text{MDI}_{Bq} = \frac{\text{MDA}}{m(t)_{\text{inh or ing}}}
\]

Where: MDA = Minimum Detectable Activity (Bq); and 
\(m(t)\) = 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, based on the MDI, considering the dose coefficients associated to the corresponding intake scenario adopted in the simulation. It is calculated as follows:

\[
\text{MDED}_{mSv} = \text{MDI}_{\text{inh or ing}} \times e(g)_{\text{inh or ing}}
\]

Where: MDI = Minimum Detectable Intake (Bq); and 
\(e(g)_{\text{inh or ing}}\) = Dose coefficient (mSv/Bq).

The values of “m(t)” and “e(g)”, presented in table 3, are available in the Publication 78 of the ICRP [9] and may also be generated for specific exposure scenarios and times after intake through the software AIDE [10]. Figure 3 illustrates an example of the AIDE software main screen.

Table 3. Retention fractions and dose coefficients generated with the software AIDE.

| m(t) (Bq/Bq) | 1 day  | 7 days | e(g) (mSv/Bq) |
|--------------|--------|--------|---------------|
|              | Inh    | Ing    | Inh           | Ing            |
| 1 day        | 0.229  | 0.252  | 0.229         | 0.252          |
| 7 days       | 1.98x10^{-5} | 2.17x10^{-5} |               |

Figure 3. AIDE software main screen.
In order to be considered useful for internal monitoring purposes, the technique should, at least, be able to detect an activity that would result in an effective dose below 1 mSv per year for the most likely internal exposure scenario [8]. Such evaluation is based on the annual projection of MDED considering the sensitivity of the method and frequency of monitoring adopted. The evaluation is carried out by adopting a generic monitoring routine, being realistic with handling procedures routine of $^{131}$I in nuclear medicine facilities where radioiodine therapy is performed. The routine is set to a worker that handles $^{131}$I once a week for 11 months throughout the year, resulting in a total of 48 monitoring periods. The evaluation of applicability is obtained by the following equation:

$$\text{PCED}_{\text{mSv}} = \text{MDED}_{\text{inh or ing}} \times N$$  \hspace{1cm} (6)

Where: PCED = Projected Committed Effective Dose for 1 year; MDED = Minimum Detectable Effective Dose; and N = number of monitoring periods throughout 1 year.

4. Results

Two thyroid phantoms, with distinct $^{133}$Ba activities, were used in this work. Phantom #1 and #2 contain, respectively, 15211 Bq (10/06/2011) and 4531 Bq (17/09/2013). The calculation of $^{131}$I equivalent activities, as described above, resulted in the following values in the date of the calibration of the monitors: Phantom #1: 16684 Bq and Phantom #2: 4970 Bq.

Tables 4 and 5 present the results of the counts, calibration factors, minimum detectable activities, minimum detectable intakes for each detector and phantom used in each calibration geometry of 0 and 3 cm respectively. Detector count rates were recorded in cpm for harmonization purposes since some models present output in cpm and others in cps (values in cps were multiplied by 60). The values of MDI correspond to an intake by inhalation considering the time of 1 day elapsed between intake and measurement.

Table 4. Results of the calibration performed at the geometry of 0 cm.

| Detector    | Phantom used | Counts (cpm) | CF (cpm/Bq) | MDA (Bq) | MDI (Bq) |
|-------------|--------------|--------------|-------------|----------|----------|
| PM 1400     | #1           | 226          | 0.0173      | 783      | 3421     |
| MIR-7026    | #1           | 238          | 0.0183      | 4097     | 17890    |
| RadEye B20  | #1           | 339          | 0.0261      | 1677     | 7323     |
| PUG-7A      | #1           | 433          | 0.0334      | 3611     | 15769    |
| 3007A       | #1           | 333          | 0.0257      | 3140     | 13711    |
| Model 3 #1  | #1           | 433          | 0.0334      | 1196     | 5224     |
| Model 3 #2  | #1           | 333          | 0.0258      | 3975     | 17359    |
| Model 3 #3  | #1           | 329          | 0.0255      | 1557     | 6798     |
| Identifinder| #1           | 53048        | 4.1366      | 347      | 1516     |
| Inspector Exp | #1       | 306          | 0.0261      | 1964     | 8575     |
| Mini Trace  | #1           | 428          | 0.0365      | 1329     | 5802     |

Figure 4 shows the results of MDA the geometry of 3 cm, as a parameter for sensitivity comparison. It is possible to observe a significant difference of sensitivity between the LB-124 Scint and Identifinder compared with other detectors evaluated. This is related to the fact that these two models are scintillation detectors, made of ZnS:Ag (zinc sulphide doped with silver) and NaI (sodium iodide doped with thallium), respectively. Because of its intrinsic characteristics, scintillators detectors are significantly more sensitive to photons Geiger Miller detectors.
Table 5. Results of calibration performed at the geometry of 3 cm.

| Detector       | Phantom used | Counts (cpm) | CF (cpm/Bq) | MDA (Bq) | MDI (Bq) |
|----------------|--------------|--------------|-------------|----------|----------|
| E-120          | #1           | 100          | 0.0069      | 6708     | 29294    |
| GP-500         | #2           | 73           | 0.0153      | 3782     | 27347    |
| PSN-7013       | #2           | 48           | 0.0100      | 3844     | 16788    |
| MIR-7026 #1    | #2           | 33           | 0.0069      | 6094     | 18476    |
| LB-124 Scint   | #2           | 4020         | 0.8439      | 232      | 1014     |
| PM 1400        | #1           | 102          | 0.0078      | 1755     | 7664     |
| MIR-7026 #2    | #1           | 125          | 0.0096      | 7218     | 31519    |
| RadEye B20     | #1           | 174          | 0.0133      | 3237     | 14136    |
| PUG-7A         | #1           | 262          | 0.0202      | 5942     | 25948    |
| 3007A          | #1           | 200          | 0.0154      | 5097     | 22258    |
| Model 3 #1     | #1           | 116          | 0.0089      | 4396     | 19197    |
| Model 3 #2     | #1           | 160          | 0.0124      | 7430     | 32446    |
| Model 3 #3     | #1           | 146          | 0.0113      | 3615     | 14120    |
| Identifinder   | #1           | 25811        | 2.0127      | 714      | 3117     |
| Inspector Exp  | #1           | 151          | 0.0128      | 3992     | 17434    |
| Mini Trace     | #1           | 171          | 0.0146      | 3322     | 14505    |

Figure 4. Comparison of detectors MDA for the geometry of 3 cm.

In internal dosimetry, the evaluation of sensitivity of detection system is performed based on MDA value, with the following limits calculated on the basis of this initial parameter and the possible exposure scenarios.
Tables 6 and 7 present the values of MDED calculated according to the methodology described previously. These values correspond to the geometries of 0 cm and 3 cm, considering times of 1 and 7 days elapsed between intake and measurement.

Table 6. Minimum Detectable Effective Doses for 1 and 7 days after intake. Measurements performed at the geometry of 0 cm.

| Detector       | MDED (mSv) – 0 cm |       |       |
|----------------|-------------------|-------|-------|
|                | 1 day             | 7 days|       |
|                | Inh               | Ing   | Inh   | Ing   |
| PM 1400        | 0.068             | 0.067 | 0.112 | 0.110|
| MIR 7026       | 0.354             | 0.353 | 0.584 | 0.577|
| RadEye B20     | 0.145             | 0.144 | 0.239 | 0.236|
| PUG-7A         | 0.312             | 0.311 | 0.514 | 0.509|
| 3007A          | 0.271             | 0.270 | 0.447 | 0.442|
| Model 3 #1     | 0.103             | 0.103 | 0.170 | 0.169|
| Model 3 #2     | 0.344             | 0.342 | 0.566 | 0.560|
| Model 3 #3     | 0.135             | 0.134 | 0.222 | 0.219|
| Identifinder   | 0.030             | 0.030 | 0.049 | 0.049|
| Inspector Exp  | 0.170             | 0.169 | 0.280 | 0.277|
| Mini Trace     | 0.115             | 0.114 | 0.189 | 0.187|

Table 7. Minimum Detectable Effective Doses for 1 and 7 days after intake. Measurements performed at the geometry of 3 cm.

| Detector       | MDED (mSv) – 3 cm |       |       |
|----------------|-------------------|-------|-------|
|                | 1 day             | 7 days|       |
|                | Inh               | Ing   | Inh   | Ing   |
| E-120          | 0.580             | 0.578 | 0.956 | 0.945|
| GP-500         | 0.541             | 0.549 | 0.892 | 0.882|
| PSN-7013       | 0.332             | 0.331 | 0.548 | 0.542|
| MIR 7026 #1    | 0.366             | 0.364 | 0.603 | 0.596|
| **LB-124 SCINT** | **0.020**       | **0.020** | **0.033** | **0.033**|
| PM 1400        | 0.152             | 0.151 | 0.250 | 0.247|
| MIR 7026 #2    | 0.624             | 0.622 | 1.028 | 1.017|
| RadEye B20     | 0.280             | 0.279 | 0.461 | 0.456|
| PUG-7A         | 0.514             | 0.512 | 0.846 | 0.837|
| 3007A          | 0.441             | 0.439 | 0.726 | 0.718|
| Model 3 #1     | 0.380             | 0.379 | 0.626 | 0.619|
| Model 3 #2     | 0.642             | 0.640 | 1.058 | 1.047|
| Model 3 #3     | 0.313             | 0.311 | 0.515 | 0.509|
| Identifinder   | 0.062             | 0.061 | 0.102 | 0.101|
| Inspector Exp  | 0.345             | 0.344 | 0.569 | 0.563|
| Mini Trace     | 0.287             | 0.286 | 0.473 | 0.468|
In tables 6 and 7, it can be observed that there are not much significant difference between values of MDED calculated assuming inhalation or ingestion. This fact is related to the biokinetic and dosimetric models of $^{131}$I and reduces the uncertainty on internal dose estimations.

The figure 5 shows the results of MDED in decreasing order of sensitivity for geometry of 3 cm, which all detectors were evaluated.

Table 8 shows the values of projected committed effective dose for 1 year, calculated by applying the methodology described previously.

![Figure 5. MDED values for 1 and 7 days after the $^{131}$I intake, in descending order of sensitivity, for geometry of 3 cm.](image)

**Table 8.** Projected Committed Effective Dose for the geometry of 0 cm

| Detector          | Projected Committed Effective Dose (mSv) | 1 day | 7 days |
|-------------------|------------------------------------------|------|-------|
|                   | Inhalation | Ingestion | Inhalation | Ingestion |
| PM 1400           | 3.3 | 3.2 | 5.4 | 5.3 |
| MIR 7026 #2       | 17.0 | 17.0 | 28.1 | 27.7 |
| RadEye B20        | 7.0 | 7.0 | 11.5 | 11.3 |
| PUG-7A            | 15.0 | 15.0 | 24.7 | 24.4 |
| 3007A             | 13.0 | 13.0 | 21.5 | 21.2 |
| Model 3 #1        | 5.0 | 4.9 | 8.2 | 8.1 |
| Model 3 #2        | 16.5 | 16.4 | 27.2 | 26.9 |
| Model 3 #3        | 6.5 | 6.4 | 10.7 | 10.5 |
| Identifinder      | 1.4 | 1.4 | 2.4 | 2.4 |
| Mini Trace        | 5.5 | 5.5 | 9.1 | 9.0 |
| Inspector Exp     | 8.2 | 8.1 | 13.4 | 13.3 |
Considering the scenario where the *in vivo* measurement is performed 1 day after the intake, Detector Berthold LB-124-SCINT presented the highest sensitivity among all models evaluated in this work (0.96 mSv at geometry 3 cm) and is the only one suitable for application in routine occupational monitoring.

Figure 6 shows a comparison of the detectors performance at geometry 0 cm, including detector LB-124SCINT at geometry 3 cm. The monitoring frequency must be established so that lost dose fractions in each single measurement projected over a period of 1 year does not exceed 1 mSv. In the evaluation performed in this work, the detectors should present MDEDs below 0.02 mSv which is the fraction of 1 mSv in 48 monitoring periods over 1 year.

![Figure 6](image)

**Figure 6.** Comparison of detectors performance in terms of Projected Committed Effective Doses (mSv). Scenario: Measurement Geometry 0 cm; Intake via inhalation; In vivo measurement performed 1 and 7 days after the intake.

5. Conclusions

This work demonstrated technical and economic viability of using surface contamination detector for the control of internal exposures of workers in the practice of nuclear medicine. However it has been observed significant differences in sensitivity among the models evaluated. At the standard geometry of 3 cm, the detector Berthold LB-124 SCINT has shown to be the most sensitive, presenting a MDED of approximately 0.02 mSv, for a monitoring scheme supposing an in vivo measurement performed one day after intake by inhalation or ingestion, and approximately 0.03 mSv if the measurement is performed seven days after the intake.

Such performance is related to the higher sensitivity of detectors using ZnS:Ag scintillation crystals, resulting in a higher efficiency for photons if compared to a Geiger-Müller detetor.

It was also observed that the Ludlum Model 3 #2, which is the oldest model included in this comparison presented the lowest sensitivity, being able to detect approximately 0.64 and 1.05 mSv for one and seven days after the intake respectively at the geometry of 3 cm.
However, even considering the differences in sensitivity it can be stated that practically all detectors are suitable for application in special in vivo monitoring of the thyroid at the geometries of 0 and 3 cm.

This conclusion relies on the fact that all models presented enough sensitivity at 0 cm, as far as the in vivo measurement is performed up to seven days after the intake. In such monitoring scheme the MDA results in committed effective doses below the registry level of 1 mSv.

On the other hand, at the geometry of 3 cm, Ludlum Model 3 #2 and MRA-MIR 7026 #2 did not present enough sensitivity for measurements performed seven days after the intake, with MDED slightly above 1 mSv.

Based on the results obtained in this work, for occupational routine monitoring, only model Berthold LB-124-SCINT attended the sensitivity criterion, showing enough sensitivity at geometry 3 cm provided that the measurement is performed 1 day after the intake.

Identifinder detector has not reached the minimum sensitivity required, considering the calibration conditions established in this work. However, it is possible to optimize the procedure by increasing the count time so that a lower MDA, and consequently a higher sensitivity, is obtained, allowing its application for routine monitoring.

Thus, it can be concluded that the use of portable monitors is a suitable and inexpensive tool for thyroid monitoring in the case of suspicion of accidental intakes in nuclear medicine clinics, radiopharmaceutical production plants or any facility where occupationally exposed workers handle significant activities of $^{131}$I.

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