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Calibration of a SPECT-CT gamma camera with child and adult thyroid-neck phantoms for in vivo monitoring of radioiodine in the exposed population in case of nuclear emergency

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A B S T R A C T

The need to quantify the uptake of ^{131}I in the thyroid of the exposed population or workers is one of the main concerns to take into account in case of nuclear or radiological emergencies. In such scenarios, due to the high volatility and rapid intake by inhalation of ^{131}I, it is very important a rapid identification of the exposed individuals to know their level of internal contamination in order to establish action protocols and countermeasures. In vivo measurements of ^{131}I in the thyroid by gamma spectrometry at Whole Body Counters (WBC) is the recommended technique, but it is difficult to manage in case of a large number of individuals potentially exposed. It is known that gamma cameras located in the nuclear medicine services are available at most hospitals and could be used as an alternative method in order to provide support in the emergency response. Thus, this work describes a methodology to calibrate this kind of equipment with anthropometric phantoms to carry out direct measurement of ^{131}I in thyroid for the quantification of internal contamination of the exposed population. A Gamma Camera (GC) of a public hospital from Madrid, H.U. La Paz, was calibrated for such purpose taking into account that a realistic geometry (10 cm distance from GC to phantom) and a rapid screening (counting time of 300 s with collimators removed) of internally contaminated individuals is necessary at early stage response. The calibration factors obtained for ^{131}I vary with thyroid size being in the range of 0.0459 to 0.0541 cps·Bq^{-1}. The minimum detectable activity (MDA) also varies with the thyroid size of the phantoms being in the range of 67 Bq to 79 Bq. An estimation of minimum detectable effective dose for children (E(70)) and adults (E(50)) has been carried out, taking into account such MDA values. Results show that, assuming a scenario of acute inhalation of ^{131}I by members of the public, this methodology allows estimating doses far below 1 mSv three days after the intake. Moreover, the validation of the methodology has been carried out by participating in an international intercomparison exercise (CATHYMARA project, EC-OPERRA 2016–2017) for the in vivo measurement of ^{131}I in thyroid to the exposed population in emergencies.

1. Introduction

Iodine-131 is a fission product with a physical half-life of 8.02 days and decays through negative beta decay with the subsequent emission of gamma and X-ray radiation from the daughter ^{131}Xe. In case of inhalation or ingestion, ^{131}I is rapidly absorbed into the blood, but about 30% is retained during a few weeks in the thyroid gland (ICRP 78). In a nuclear accident, large amounts of radioiodine may be released to the environment with the subsequent risk of contamination of the population. Accidents involving releases of radioactive iodine can be significant sources of exposure of the thyroid gland. For a given intake, the dose to the thyroid for infants is eight or nine larger than adults (UNSCEAR, 2008). After the Chernobyl accident, many citizens received thyroid doses exceeding 1 Gy due to radioiodine intakes and more than 6000 thyroid cancers (mostly in children) were attributed to radioiodine intakes (Mück et al., 2002). After the Fukushima accident, about 98% of the effective doses received by emergency workers were attributable to radioiodine intakes (UNSCEAR 2013). In such scenarios, it is very important a rapid identification of the number of people exposed and the level of internal contamination in order to establish action protocols and countermeasures. In vivo measurements of ^{131}I in the thyroid by gamma spectrometry with Germanium or NaI (Tl) detectors is the recommended technique for these issues. The use of different phantoms simulating neck and thyroid gland of members of different groups of age is crucial for a proper calibration and accurate determination of the ^{131}I activity in the thyroid, in order to estimate reliable internal doses. WBC Laboratory of CIEMAT (Fig. 1), as support laboratory of the national regulatory body in emergencies, has recently implemented a methodology consisting of the design and fabrication of age-specific thyroid-neck phantoms and the development of a calibration procedure for the in vivo monitoring of ^{131}I in the thyroid of contaminated adults and children (Pérez et al., 2018), but in case of a nuclear or radiological emergency with a very large number of individuals potentially exposed, WBC facilities may be insufficient in the

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Fig. 1. In vivo measurement of ^{131}I in thyroid at Whole Body Counter laboratory of CIEMAT.

Fig. 2. Dual-headed gamma camera from U.H. La Paz (Madrid, Spain).

Fig. 3. CIEMAT thyroid-neck phantom set.

Table 1
Dimensions for the different age-specific phantoms.

Age (y)	Perimeter (cm)	Height (cm)	Thyroid Vol (ml)	Thyroid ICRP 89 Vol (ml)
1	22	7.1	1.8	1.8
5	26	8.2	3.4	3.4
10	30	10.0	7.7	7.9
15	34	11	12	12
Female	41	12.7	17.0	17
Male	41	12.7	20.0	20

handling of such situations.

It's known that gamma cameras of the nuclear medicine services are available at most hospitals of Spain and could be used as an alternative method in order to provide support in the emergency response. These services count with trained and experienced personnel in the usage of radioactive sources such as ^{131}I, treatment of patients and specialized equipment. Therefore, gamma cameras are suitable to facilitate additional body monitoring capacity as mass screening devices in large-scale radiological incidents. This work describes a methodology to

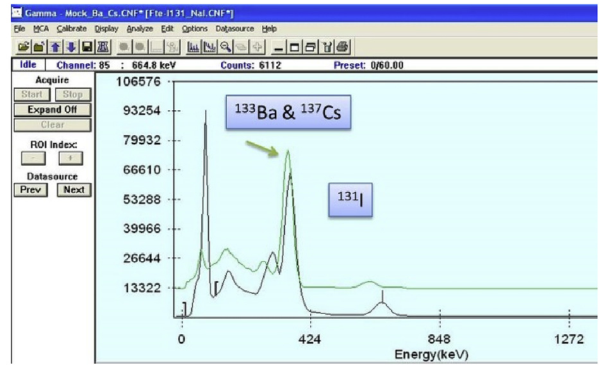

Fig. 4. Comparison of NaI detector spectra corresponding to mock ^{133}Ba and ^{137}Cs and ^{131}I.

Table 2
x/γ emissions and yields of ^{133}Ba, ^{137}Cs and ^{131}I.

Ba-133		I-131	
E (keV)	Ie (%)	E (keV)	Ie (%)
79.61	2.62	80.18	2.62
80.99	34.06		
276.39	7.16	284.30	6.14
302.85	18.33		
356.01	62.05	364.48	81.70
383.85	8.94		
Cs-137			
661.65	85.10	636.98	7.17
		722.91	1.77

Table 3
Activity (Bq) of the calibration thyroid sources.

Thyroid-Neck Phantom	ThyroidVol (ml)	^{133}Ba(Bq)
1y	1.8	9442 ± 158
5y	3.4	9438 ± 158
10y	7.7	9478 ± 159
15y	12.0	9515 ± 159
Female	17.0	9473 ± 159
Male	20.0	79820 ± 1600

Table 4
Fcal for the in vivo measurement of ^{131}I in the thyroid by a GC without collimator (Tc = 300s and 15% window centered at 356 keV).

Thyroid-Neck Phantom	Fcal (^{131}I) (cps Bq^{-1})	ΔFcal(K = 2σ) (cps Bq^{-1})
1y	0.0541	0.005
5y	0.0527	0.006
10y	0.0478	0.005
15y	0.0462	0.005
Female	0.0472	0.005
Male	0.0459	0.008

Table 5
MDA of ^{131}I in the thyroid by a GC without collimator (Tc = 300s a $d_{detector\text{-}phantom}$ = 10 cm).

Thyroid-neck Phantom	MDA (^{131}I) (Bq)
1y	67
5y	69
10y	76
15y	78
Female	77
Male	79

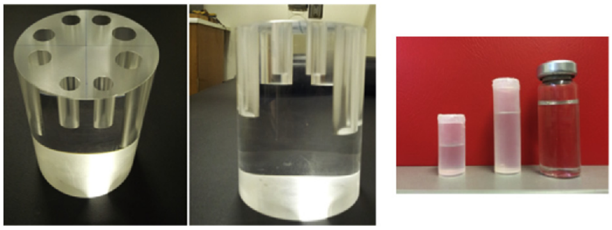

Fig. 5. Cathymara thyroid neck phantom (SCK-CEN).

calibrate this kind of equipment with anthropometric phantoms that have been designed and fabricated at CIEMAT for simulating ^{131}I activity in the thyroid in order to carry out the quantification of internal contamination of the exposed population. A gamma camera of a public hospital from Madrid (University Hospital "La Paz") was calibrated for such purpose taking into account that a realistic geometry and a rapid screening of internally contaminated individuals are necessary at the early stage response.

2. Materials and methods

2.1. Dual-head SPECT/CT gamma camera

The gamma camera is an imaging device usually used for diagnosis of diseases in nuclear medicine. It consists of one or more flat NaI (Tl) detector crystals optically coupled to an array of photomultiplier tubes in an assembly known as a "head", mounted on a gantry. The gantry is connected to a computer system that controls the operation of the gamma camera, and acquires and stores two-dimensional images of the radioisotope distribution, in a body patient, in the energy range of 70–800 keV. In order to improve the imaging resolution, different kind of collimators could be used to visualize the behavior of a gamma-emitting radionuclide in the human body, organs and tissues.

A dual-headed "Infinia" GE Healthcare gamma camera into a hybrid SPECT/CT scanner from the University Hospital La Paz (Madrid, Spain) has been utilized with calibration purposes (Gamma camera, 2006). It is based on NaI(Tl) detector crystals (thickness 3/8″) optically coupled to an array of 59 circular PMTs (head) each one connected with an ADC (analogue to digital converter). This device (without collimator) has a high detection sensitivity, allowing to determine the activity of ^{131}I incorporated in the thyroid by fitting an energy window centered at the main emission of iodine (364 keV) (Fig. 2).

2.2. Thyroid-neck phantom set

For calibration purposes, a "family" of thyroid-neck phantoms was designed and manufactured at CIEMAT, which correspond to 1, 5, 10 and 15 years old children. Each phantom consists of a Lucite cylinder with a lateral cavity where the thyroid gland simulator is introduced (Pérez et al., 2018). Each cylinder size was designed according to the age of the individual following ICRP89 recommendations (ICRP, 2002). In case of adults (male and female) a thyroid-neck phantom was manufactured by BIODEX following specifications of the ANSI N13.44 (ANSI/HPS N13.44 2014) standard and was used for adult calibration. (Fig. 3).

The thyroid glands were simulated using cylindrical vials filled with different volumes of a ^{131}I mock solution according to the age group. Table 1 shows the dimensions and thyroid volumes for children and adult phantoms.

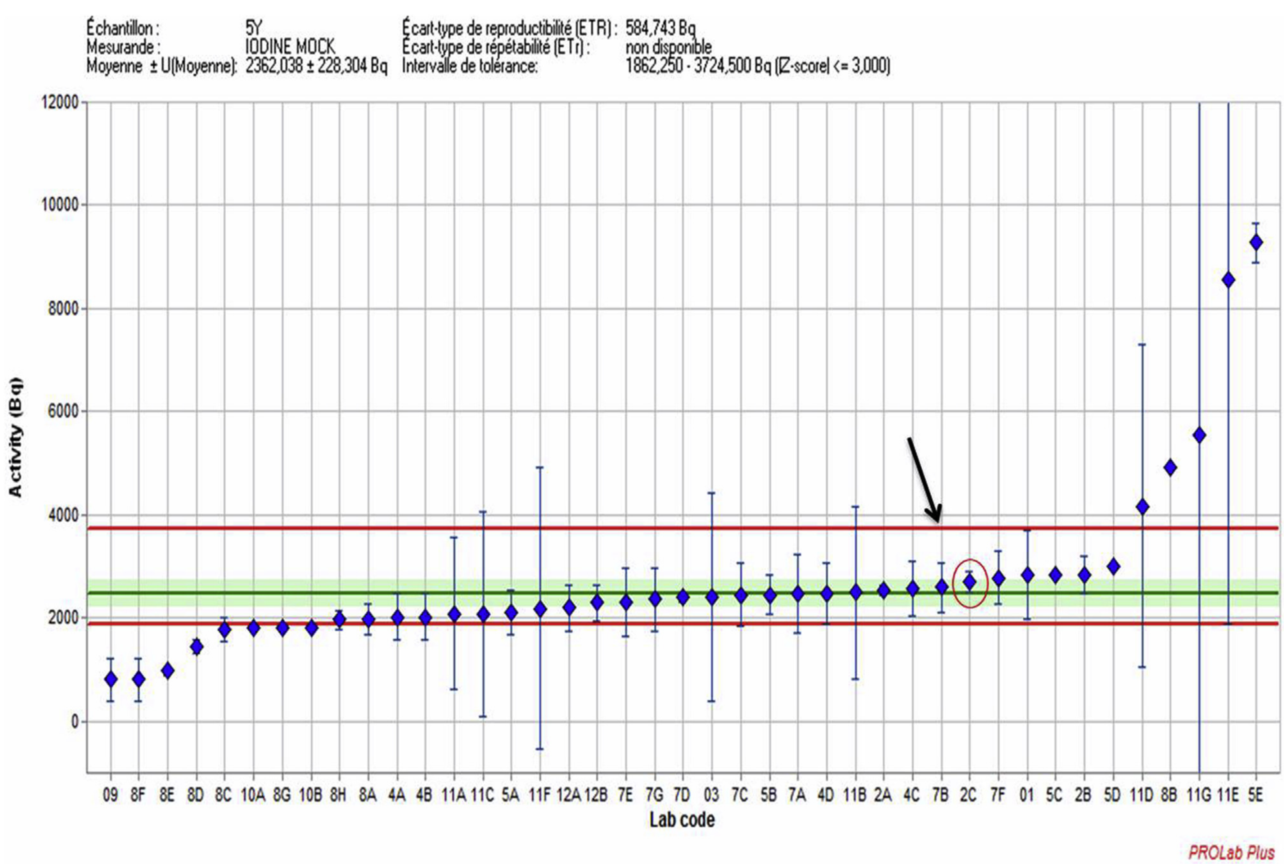

Fig. 6. Relative Bias (Br) for 5 years old phantom (Mats et al. Report of WP4 Cathymara Project).

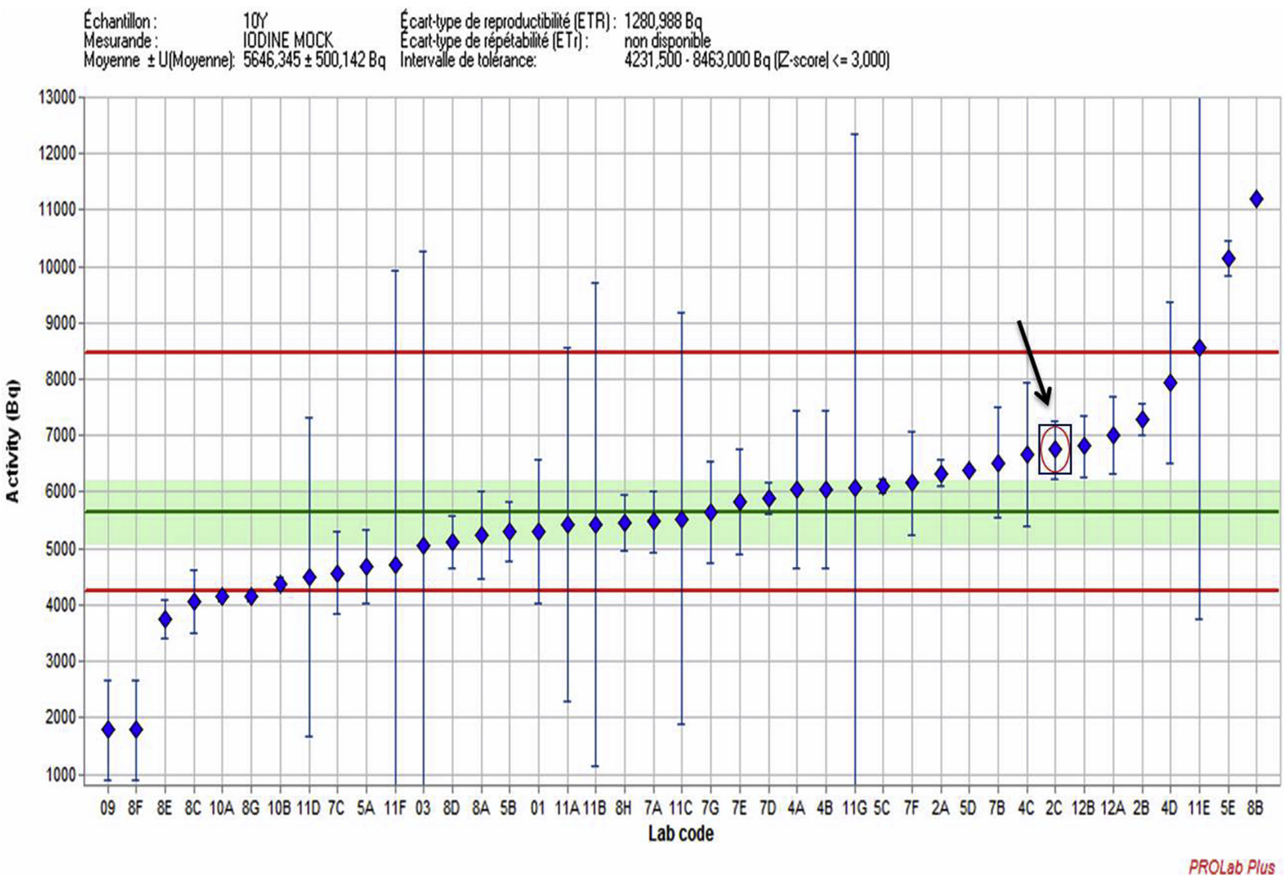

Fig. 7. Relative Bias (Br) for 10 years old phantom (Mats et al. Report of WP4 Cathymara Project).

3. Results and discussion

3.1. Calibration of a gamma camera (GC) for in vivo measurement of ^{131}I in the thyroid of the exposed population

The gamma camera was calibrated by the thyroid-neck phantom set described above. A previous study of the geometry of measurement, counting time and detector-phantom distance was carried out in order to achieve suitability to be utilized as a screening device for in vivo monitoring of ^{131}I in the thyroid of the exposed population.

3.1.1. Calibration sources

For each phantom, the thyroid gland was simulated using a cylindrical vial filled with a homogeneously distributed liquid solution of ^{133}Ba (≈90%) and ^{137}Cs (≈10%) as a surrogate of ^{131}I ($T_{1/2}$ = 8.02 days). Due to the short half-life of ^{131}I, a source of ^{133}Ba and ^{137}Cs is commonly used for calibration purpose because of the long half-life of both radionuclides ($T_{1/2}$ = 10.5y for ^{133}Ba and 30y for ^{137}Cs) and similar spectrum when comparing with ^{131}I emissions (Fig. 4). Table 2 shows the x/γ emissions of these radionuclides.

The calibration sources were manufactured and certificated by Ionizing Radiations Metrology Laboratory (LMRI) at CIEMAT (Madrid, Spain). Table 3 summarizes the Activity and uncertainty (Bq) of ^{133}Ba sources (used for GC calibration) for the different age-specific thyroid phantoms.

3.1.2. Calibration factors (cps Bq^{-1}) calculated for each children and adult geometry of measurement

Firstly, collimator of the GC was removed in order to increase the sensitivity of the measurement. The region of interest was defined as a 15% energy window centered at the main photopeak of ^{133}Ba. Therefore, this window covers both 356 keV (62.03%) and 383 keV (8.94%) photopeaks of Barium.

Taking into account that a realistic geometry and a rapid screening of internally contaminated individuals are necessary at the early stage response of an emergency, a counting time of 300 s and a distance detector surface-thyroid phantom of 10 cm were selected for thyroid measurement. Background measurements were carried out with blank phantoms (thyroid neck phantom and vial filled with distilled water) in order to subtract the background count rate from total counting for calculating thyroid calibration factors (*Fcal*). Thus, *Fcal* expressed in $cpsBq^{-1}$, is the ratio between the net area count rate N_{ROI} and the decay corrected activity of ^{133}Ba. In order to calculate *calibration factors* for ^{131}I ($F_{cal}^{I\text{-}131}$), it must be taken into account that is necessary apply a mock correction factor ($F_{C'}$) because of the GC window selected covers the 356 keV (62.03%) and 383 keV (8.94%) photopeaks of ^{133}Ba simulating the 364.5 keV (81.2%) emission of ^{131}I. $F_{C'}$ can be approximated to the ratio between such emission rates of both radionuclides ($F_{C'}$ = 0.87) (Equation (1)).

$$F_{cal}^{I-131}\left(\frac{cps}{Bq}\right) = \frac{N_{ROI}}{A^{Ba-133}\,(Bq)\cdot F_{C'}} \quad (1)$$

Table 4 shows the ^{131}I calibration factors and uncertainties for each geometry of measurement as defined above.

3.2. Sensitivity of detection of the GC for the in vivo measurement of ^{131}I in the thyroid. Minimum detectable activity (MDA) for children and adult counting geometries

According to ANSI 13.30 recommendations (ANSI/HPS N13.30: 1996/2011) the value of the Minimum Detectable Activity (*MDA*) indicates the ability of a detection system to quantify a radionuclide incorporated by an individual which has been deposited in total body or

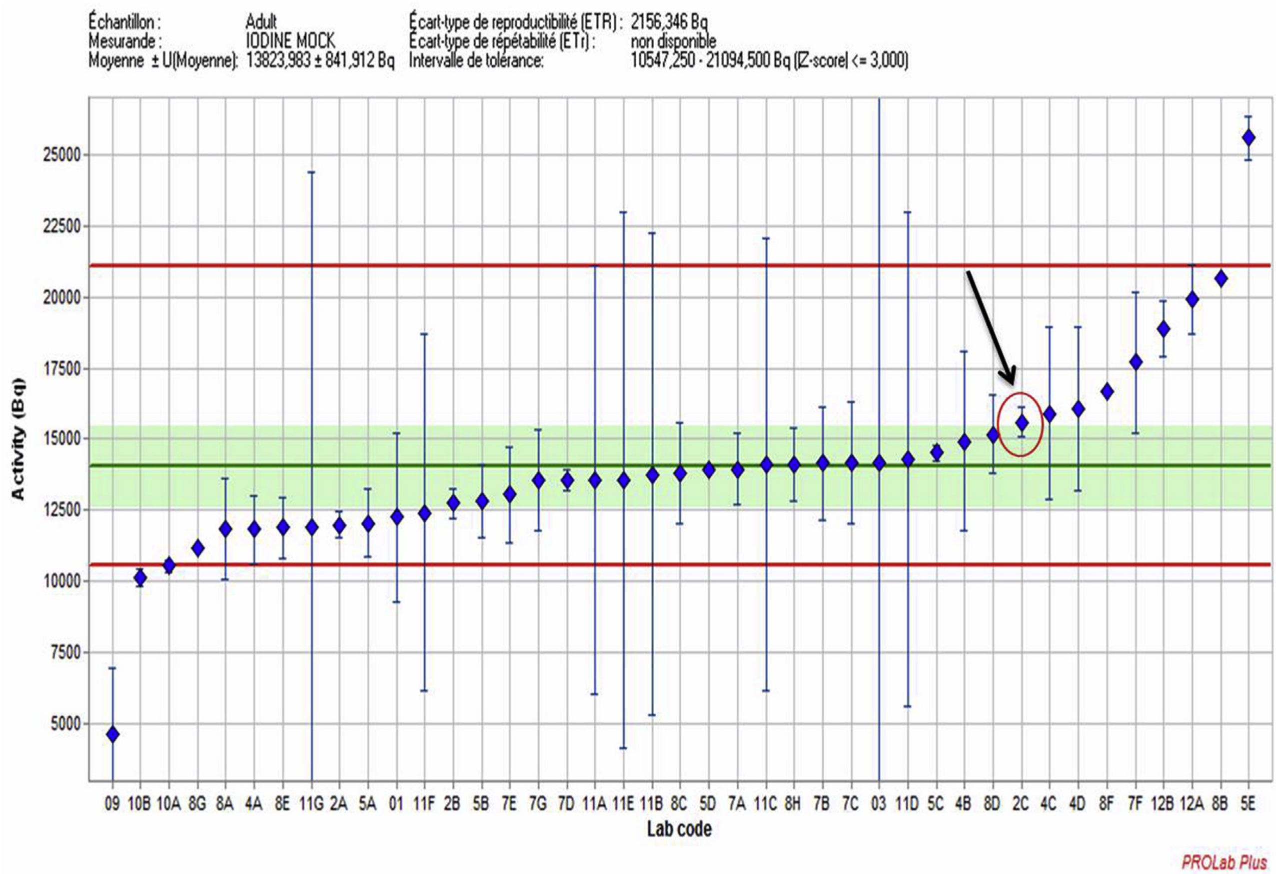

Fig. 8. Relative Bias (Br) for adult phantom (Mats et al. Report of WP4 Cathymara Project).

Table 6
Calibration Factors and MDA values from other studies using gamma cameras without collimator and d = 10 cm detector-surface distance for Adult phantoms.

Facility	Fcal Cps*Bq^{-1}	**MDA (Bq)**
Brazil (Dantas et al.,2007)	0.039 ± 0.005	81
Sweden (Ören et al.)	0.037 ± 0.003	82
Chile (Díaz-Londoño et al., 2017) GC1	0.064 ± 0.001	106
Chile (Díaz-Londoño et al., 2017) GC2	0.089 ± 0.003	104
CIEMAT- Hosp. La Paz. (Spain)	0.046 ± 0.005	79

Table 7
Committed effective doses associated with MDA values of ^{131}I in the thyroid (Tc = 300s, detector-phantom d = 10 cm) using a gamma camera for monitoring, assuming acute inhalation three days after the intake.

Thyroid-neck Phantom	MDA ^{131}I (Bq)	Commited Effective Dose E (70)children (mSv), E(50) adults (mSv) MONDAL	Commited Effective Dose (mSv) Cathymara
1y	67	5.90E-5	5.83E-5
5y	69	3.40E-5	3.38E-2
10y	76	1.80E-5	1.82E-2
15y	78	1.20E-5	1.17E-5
Female	77	7.47E-6	
Male	79	7.66E-06	

in organs. The MDA is mainly dependent on the person, the measurement geometry, the efficiency (as a calibration factor in our case of study) and the counting time (Equation (2)).

$$\mathbf{MDA(Bq)} = \frac{3 + 4{,}65 \times \sqrt{\mathbf{Bck}}}{\mathbf{Ef}\left(\frac{\mathbf{cps}}{\mathbf{Bq}}\right) \times \mathbf{Tc(s)}} \quad (2)$$

Where "*Bck*" is the background counts in the region of interest, "*Ef*" (cps/Bq) is the calibration factor for the radionuclide of interest and "*Tc*" (s) is the counting time of the measurement.

MDA may be calculated carrying out measurements of a blank person or black phantom simulating the person or a specific organ. Thus, for each counting geometry, *MDA* of ^{131}I was calculated by the measurement of the different children and adult thyroid-neck phantoms with vials filled with water, simulating blank thyroid glands at a detector surface-thyroid phantom distance of 10 cm (Table 5).

3.3. Validation of the methodology

3.3.1. Participation in the OPERRA Cathymara Project

The OPERRA/CAThyMARA project "Child and Adult Thyroid Monitoring After Reactor Accident" (European Commission, 2016–2017) focused on post-accidental monitoring strategies and assessment of thyroid doses in children and adults, resulting from intakes of radioiodine in order to improve the required capabilities, to identify gaps and to establish technical guidelines to harmonize the response in emergencies within the European Union and neighboring countries (CAThyMARA, 2019). With the objective of checking the required capabilities in case of a nuclear accident, a European intercomparison for the measurement of ^{131}I in the thyroid of the exposed population (children and adults) using non-spectrometric instruments (dosemeters, gamma cameras, radiometers, etc.) was carried out. 12 institutions (CIEMAT including) from 7 European countries took part in the exercise and 43 measurement devices were tested (Isaksson et al.,) (Isaksson et al.,).

SCK-CEN (Belgium) prepared and distributed a thyroid-neck phantom simulating the neck and the thyroid lobes for 5 years old, 10 years old children and adults, with vials filled with a mock-iodine solution of ^{133}Ba and ^{137}Cs (Fig. 5).

The participants were requested to estimate and to return the equivalent activity of ^{131}I in the thyroid phantom. The results were evaluated against criteria from the "Relative Bias" statistic parameter (Br) according to ISO 12790-1 (ISO 12790-1:2001). Following the protocol of the intercomparison exercise, five measurements were performed placing the gamma camera of La Paz Hospital without collimator in thyroid geometry conditions for each configuration of "Cathymara phantom". Results obtained for each geometry of measurement were in compliance with acceptance criteria of ISO 12790-1 Relative Bias (Br) statistic parameter (B_r in [-0.25, 0.5]) (Figs. 6–8).

3.3.2. Comparing calibration factors and MDAs from other studies

Nordic Nuclear Safety Research organized both intercalibration and intercomparison exercise in the Nordic countries for the harmonization of the in vivo thyroid measurement by non-specialized equipment (including gamma cameras) with screening purposes in nuclear or radiological emergencies (Poulsen et al.,). A set of thyroid-neck phantoms for 6 years old, 14 years old children and adults was used for calibration purposes. Several gamma cameras (with and without collimator) participated in the exercise. For gamma cameras without collimator the MDA values for ^{131}I in close geometry (detector surface-phantom distance of 0 cm) vary from 10 to 40 Bq and calibration factors, in terms of *cps Bq^{-1}*, vary from 0.04 to 0.076.

In case of thyroid monitoring for adults, B. Dantas et al. (2007) obtained a calibration factor of 0.039 cps·Bq^{-1} and a MDA value of 81 Bq for a home-made adult thyroid phantom using GC without collimator and a distance of 10 cm from the surface detector to the thyroid. Ören et al. (2016) used a dual-head gamma camera and an in-house cylindrical-conical PMMA phantom with different diameters in order to simulate different body parts and individuals of different size. Results obtained for the d = 10 cm phantom diameter (according to standard thyroid phantom diameter) with a calibration factor of 0.037cps·Bq^{-1} and a MDA value of 82 Bq for ^{131}I are also in good agreement with results obtained in this study. G. Díaz-Londoño et al. (2017) obtained MDA values about 100 Bq using both gamma cameras. Table 6 summarizes such calibration factors and MDA values comparing with results obtained in this study.

3.4. Estimation of minimum committed effective doses for the exposed population in emergency scenarios

Committed effective doses for children (E(70)) and adults (E(50)) have been estimated using MONDAL ver.3 software package developed by NIRS (2017) (Ishigure et al.,) taking into account the MDA values of ^{131}I (Table 5) assuming a scenario of acute inhalation of ^{131}I (type F) by members of the public. The values obtained confirm that three days after the intake, the in vivo measurement of ^{131}I in the thyroid using a gamma camera for the monitoring of exposed population allows estimating doses far below 1 mSv for a counting time of 300 s. In addition, by using Cathymara's "Dose per content" coefficients, the effective dose committed can be obtained directly from the measured thyroid activity (CAThyMARA, 2019). The results in both cases are similar, as shown in Table 7.

4. Conclusions

CIEMAT Whole Body Counting Laboratory has developed a calibration methodology for the in vivo measurement of ^{131}I in the thyroid of the exposed population (adults and children) using gamma cameras in case of radiological or nuclear emergency. It's proven that the usage of different calibration phantoms for adults and children allows a greater reliability in the calculation of ^{131}I activity deposited in the thyroid, improving the response in the early stage of the accident. A set of thyroid-neck phantoms for thyroid calibration were manufactured at CIEMAT using Lucite with a density and attenuation similar to soft tissue, on the basis of ICRP 89 and ANSI 13.44 recommendations, for 1, 5, 10, and 15 years old children, male and female adults. The thyroid glands were simulated using cylindrical vials filled with different volume solutions of ^{133}Ba and ^{137}Cs as ^{131}I subrogate according to the age group. MDA values for ^{131}I vary with the age of individuals, being in the range of 67–79 Bq. The calibration factors and MDA values obtained by this methodology are in good agreement with other publications on this matter.

Therefore, the methodology here presented may be used not only in emergency scenarios, but also in triage monitoring programs of the exposed workers (in vivo measurements to be performed in the nuclear medicine centers) for screening purposes (ISO 16637:2015) (ISO 16637:2016). This methodology may be also extended to others Nuclear Medicine Centers in Spain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radphyschem.2019.108668.

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