Radiation Protection Dosimetry (2018), pp. 1–6 doi:10.1093/rpd/ncy045

METHODOLOGY AT CIEMAT WHOLE BODY COUNTER FOR *IN VIVO* MONITORING OF RADIOIODINE IN THE THYROID OF EXPOSED POPULATION IN CASE OF NUCLEAR EMERGENCY

B. Pérez López*, J. F. Navarro and M. A. López
Whole Body Counter, Internal Dosimetry Service, Radiation Dosimetry Unit (CIEMAT), Avda. Complutense 40, E-28040 Madrid, Spain

*Corresponding author: begona.perez@ciemat.es

Received 29 November 2017; revised 2 February 2018; editorial decision 27 February 2018; accepted 1 March 2018

Iodine-131 is one of the main concerns from the point of view of radiological protection in a short term after a nuclear accident. The WBC Laboratory of CIEMAT has developed a methodology for *in vivo* monitoring of radioiodine in the thyroid of exposed individuals in case of emergency. Thyroid–neck phantoms of different sizes are required for calibrating the detection systems in appropriate counting geometries for the measurement of exposed population. A Low-Energy Germanium (LEGe) detector and a Fastscan Counter were calibrated using a set of thyroid phantoms fabricated by CIEMAT. Each neck phantom consists of a Lucite cylinder with a vial source of ^{131}I. Counting efficiencies depending on age and thyroid sizes were obtained to be used to determine the activity of ^{131}I in internally contaminated people. DL of ^{131}I varies with the age, being in the range of 5–8 Bq for the LEGe detector and 26–42 Bq for the Fastscan. Detection of intakes resulting in Committed Effective doses far below 1 mSv are guaranteed for thyroid monitoring in a few days after the accidental exposure assuming a scenario of acute inhalation or ingestion of ^{131}I by members of the public.

INTRODUCTION

In case of a nuclear accident large amounts of radioiodine may be released to the environment with the subsequent risk of contamination of the population. The thyroid gland is the target organ where de iodine is retained during few weeks after the intake took place. *In vivo* measurements of ^{131}I in thyroid by gamma spectrometry are recommended to quickly identify the most contaminated people in an emergency scenario. The determination of the retained activity in the thyroid and the result internal dose estimate, help to decide about taking appropriate counter measures to avoid or minimize undesirable health effects due to the ionizing radiations.

Germanium or NaI(Tl) detectors are commonly used for *in vivo* monitoring of exposed individuals at risk of incorporation of gamma emitters into the body. Radioactive sources of known activity in anthropomorphic phantoms simulating neck and contaminated thyroid gland of the individuals are required for calibration purposes. Lawrence Livermore National Laboratory (LLNL, USA) in collaboration with the European Radiation Dosimetry Group (EURADOS) organized in 2016 an international intercomparison on measurement and dose estimates of radioiodine deposited in the thyroid, using several (separate) sources of ^{131}I and ^{125}I in vials which were introduced in a ANSI neck phantom(1).

In vivo counting facilities have developed calibration and measurement procedures for monitoring workers but a gap was identified after Fukushima NPP accident regarding available calibration protocols for children(2). The use of different phantoms simulating neck and thyroid of members of different groups of age are crucial for a proper calibration and accurate determination of the ^{131}I activity in thyroid, in order to estimate reliable internal doses. The main goal of this work is to describe a methodology developed at CIEMAT Whole Body Counter (WBC) for the calibration and *in vivo* monitoring of ^{131}I in the thyroid of contaminated adults and children. Thyroid phantoms of different sizes simulating children and adults were fabricated by CIEMAT following ICRP 89 recommendations(3).

MATERIALS AND METHODS

Detection systems

CIEMAT Whole Body Counting facility counts with a Low-Energy Germanium (LEGe) detector system and a Fastscan (NaI(Tl)) Counter for *in-vivo* measurement of ^{131}I in thyroid. The active area of each LEGe detector is 3800 mm^2, with a diameter of 70 mm and a thickness of 25 mm, with a Carbon Epoxy window, 0.5 mm thick(4). The LEGe detectors are placed inside a shielded room of 13 cm steel walls lined with Pb, Cd and Cu with independent ventilation to reduce environmental background. LEGe detectors present an excellent resolution and good efficiency at low and moderate energies (10–1000 keV). One of the four LEGe is used for thyroid monitoring at a distance of 15 cm from the neck and for a counting time of 20 min (Figure 1).

The Fastscan Counter was manufactured by Canberra Industries. It includes two large sodium iodine detectors (NaI(Tl)) of 7.6 cm × 12.7 cm × 40.6 cm along the vertical axis[5]. The Fastscan whole body counter is designed to quickly and accurately monitor people for internal contamination of gamma-emitting radionuclides with energies between 100 keV and 2 MeV (Figure 2).

Both systems are operating using Genie2000 Gamma Spectrometry software[6] which provides a complete set of operating procedures to perform calibration functions, to analyze subjects and for quality assurance operations.

Design of the thyroid–neck phantom set

A 'family' of neck–thyroid calibration phantoms for children (Figure 3) was fabricated at CIEMAT (Spain). Each phantom consists of a Lucite cylinder

Figure 1. Thyroid monitoring using a LEGe detector inside a shielded room at CIEMAT WBC.

Figure 2. Fastscan counter.

with a lateral cavity where the thyroid gland simulator is introduced. Each cylinder size was designed according to the age of the individual following ICRP 89 recommendations[3]. The contaminated thyroid gland is simulated using a cylindrical vial filled with a homogeneously distributed liquid solution of ^{131}I. The selected volumes of the different thyroid glands are 1.8, 3.4, 7.7, 12 ml, which correspond to 1, 5, 10, 15-year-old children, respectively. Adult neck–thyroid phantom was designed according to ANSI 13.44[7] standard with a thyroid gland volume of 20 ml simulating reference male and 17 ml for reference female.

The neck perimeters of the different phantoms were calculated based on anatomical measurements to different ages of children. The neck thickness of the phantoms was calculated from measurements of CT studies (Table 1).

RESULTS AND DISCUSSION

Efficiency calibration for different counting geometries of *in vivo* measurement of ^{131}I in the thyroid (children and adults) were performed at the WBC of CIEMAT using Fastscan Counter and LEGe detector system. Fastscan Counter is used for a rapid measurement of thyroid activity in exposed individuals in case of radiological or nuclear emergency due to its excellent efficiency at medium and high energies. LEGe detectors are more suitable in case of complex cases of internal contamination due to their high resolution especially in a range of 10–1000 keV.

Calibration sources

In both detection systems (LEGe and Fastscan), efficiency calibration curves (counts/gamma) versus energy (keV) were obtained using ^{131}I as calibration

Figure 3. CIEMAT neck–thyroid phantom set.

Table 1. Neck phantom sizes for different ages.

Age (y)	Perimeter (cm)	Height (cm)
1	22 ± 2	7,1 ± 0,6
5	26 ± 3	8,2 ± 0,9
10	30 ± 4	10 ± 1
15	34 ± 5	11 ± 2

source for 1, 5, 10 and 15-year-old children and for the reference female. A mock-iodine of ^{133}Ba and ^{137}Cs was formerly used for the reference male calibration. All sources were manufactured and certificated by Laboratory of Ionizing Radiation Metrology (LMRI-CIEMAT) (Table 2).

Calibration of LEGe detector for measurement of ^{131}I in thyroid of adults and children

An individual detector (Det 1) of the LEGe detection system placed inside the shielded room and positioned at a detector-thyroid distance of 15 cm was calibrated by both thyroid–neck phantom and radioactive sources simulating contaminated thyroid gland for each children and adults geometry performed[8]. Figure 4 shows the counting efficiency (cps/γ) versus energy (keV) curves for the different counting geometries implemented.

The efficiency value corresponding to the main emission of ^{131}I (364 keV) is utilized in order to calculate activity in a possible intake. Table 3 shows the efficiency values for different sizes of thyroid glands.

Table 2. Activities of the calibration sources.

Date of certificate	Age (y)	*A* (kBq)	Δ*A* (kBq), *k* = 2
10/07/2015	1	29,46	0,59
10/07/2015	5	29,79	0,6
10/07/2015	10	59,5	1,2
10/07/2015	15	49,9	1,0
31/10/2014	Woman	40.6	1,2 (2.8%)
10/07/2015	Man	18,81	0,38

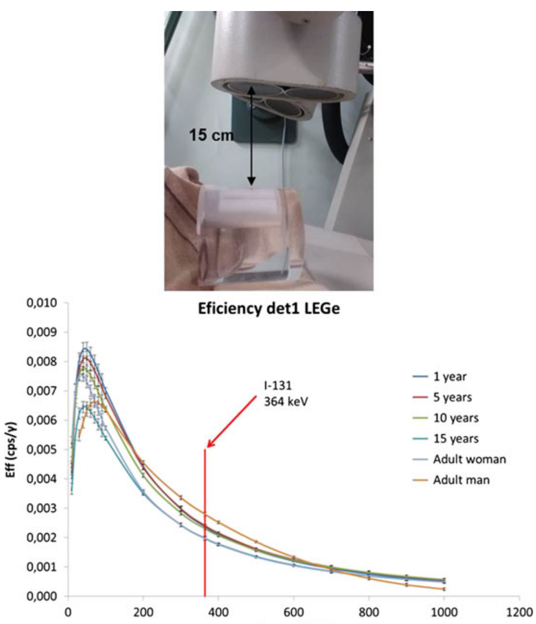

Figure 4. Counting geometry for thyroid calibration and counting efficiency versus energy for CIEMAT LEGe detector.

Calibrations of Fastscan Counter for the *in vivo* measurement of ^{131}I in thyroid (adults and children)

The calibration of Fastscan was carried out for standing up counting geometry[9]. The neck–detector distance is 12 cm. The height to the thyroid depends on the age of individuals (Table 4) according to WHO and ANSI 13.30.

Upper detector was calibrated for children aged 1 and 5 years, and upper detector for the rest of the set phantoms (Figure 5).

The maximum of efficiency curves corresponds to the energy around 400 keV, close to the main emission of ^{131}I (364 keV), which is noted in Table 5.

Validation of the ^{131}I monitoring calibration for adults and children

The validation of the thyroid calibration was carried out using the same thyroid phantom set and vials but with different radionuclides. Liquid sources of ^{133}Ba (90%) and ^{137}Cs (10%) were used for the simulation of ^{131}I emissions. Table 6 summarizes the activities and Type A uncertainties (Δ) of the different mocks used. Each vial was introduced in the corresponding neck phantom, placed at the same conditions of the

Table 3. Efficiency in LEGe detector for 364 keV.

V (ml)	Eff (cps/γ) 364 keV	Δeff (cps/γ)
1,80	0,002375	5,14E-05
3,4	0,002411	4,88E-05
7,7	0,002310	4,62E-05
12	0,001981	6,70E-05
17	0,001970	9,93E-05
20	0,002801	9,93E-05

Table 4. Source volume (ml) and ground-thyroid distance of the thyroid, CIEMAT Fastscan calibration.

V (ml)	Age (y)	*h* (cm)
1,8	1	61,5
3,4	5	92,0
7,7	10	117,0
12	15 girl	138,5
12	15 boy	143,5
17	Woman	139,0
20	Man	156,5

calibration geometry. Five measurements were performed for each phantom representing 1, 5, 10 and 15-year-old children, reference male and female adults.

A proficiency test was carried out in order to evaluate 'Relative Bias' and 'Repeatability' parameters according to ISO/IEC 28 218 Standard[10]. Results for both detection systems (LEGe and Fastscan) were in compliance with acceptance criteria of ISO 28 218 parameters, relative bias (B_r) is between [−0.25, 0.5] and repeatability (S_{Br}) is <0.4.

Sensitivity of the detection systems for thyroid monitoring. Detection limit

According to ISO/IEC 28 218[10] the value of the detection limit (DL) indicates the ability of the *in vivo* laboratory to detect a radionuclide incorporated by an individual and deposited in total body or in organs. The DL is mainly dependent on the person (tissue thickness attenuation), the measurement geometry, the efficiency and counting time. DL can be calculated from the measurement of a blank person or a blank phantom (Figure 6) as follows:

$$LD = \frac{2k_{1-\alpha}\sqrt{\left(\frac{1}{t\cdot\varepsilon}\right)^2\left(\frac{p}{2m}n_0 + \left(\frac{p}{2m}\right)^2 n_0\right)} + k^2{}_{1-\alpha}\left(\frac{1}{t\cdot\varepsilon}\right)}{1 - k^2{}_{1-\alpha}\left(\frac{u(\varepsilon)}{(\varepsilon)}\right)^2}$$

where

n_0 = # counts in the Surface B1 and B2;
p = # channels of the neck;
m = # channels in the Surface B1 and B2;
ε = efficiency;
$u(\varepsilon)$ = efficiency uncertainty; and
$k_{1-\alpha} = 1.645$.

In both (LEGe and Fastscan) detection systems DL was calculated by each counting geometry using neck phantom and blank thyroid gland in routine measurement conditions (Tables 7 and 8).

Estimation of committed doses for the exposed population in emergency scenarios

Committed effective dose for children (E(70)) and adults (E(50)) have been estimated taking into account

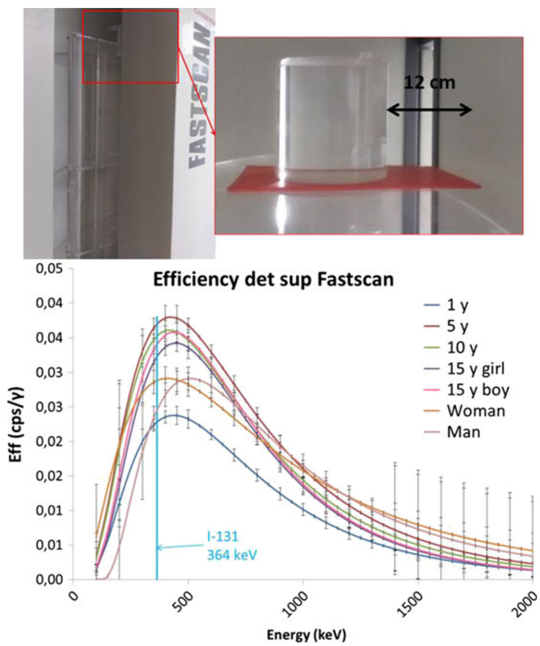

Figure 5. Counting geometry for thyroid calibration and counting efficiency versus energy for CIEMAT Fastscan Counter.

Table 5. Efficiency in Fastscan superior detector in 364 keV.

V (ml)	Eff (cps/γ) 364 keV	Δeff (cps/γ)
1,8	0,022834	8,81E-04
3,4	0,036963	1,41E-03
7,7	0,035254	1,48E-03
12	0,032312	1,19E-03
12	0,034102	2,10E-03
17	0,028840	1,69E-03
20	0,028798	1,69E-03

Table 6. Activities of the mock sources with ^{133}Ba and ^{137}Cs.

V (ml)	^{133}Ba A (Bq)	^{133}Ba ΔA (Bq)	^{137}Cs A (Bq)	^{137}Cs ΔA (Bq)
1,83	9458,8	14,8	942,11	2,89
3,43	9454,3	14,8	941,67	2,89
7,63	9493,6	14,9	945,58	2,90
12,03	9531,3	14,9	949,33	2,91
17,03	9488,7	14,9	945,09	2,90

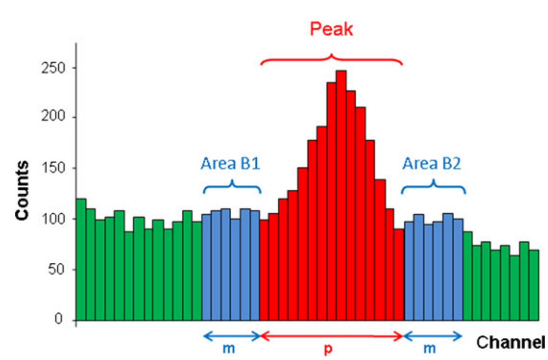

Figure 6. Detection limit (DL).

Table 7. Detection limits of ^{131}I in thyroid for different configurations of LEGe detector.

DL Detector 1 LEGe, $t = 1200$ s, $d = 15$ cm						
Age (y)	1	5	10	15	Woman	Man
DL (Bq)	6,1	4,6	5,3	6,2	7,9	6,4

Table 8. Detection limits of ^{131}I in thyroid for different configurations of Fastscan Counter.

DL Fastscan, $t = 300$ s, $d = 12$ cm							
Age (y)	1	5	10	15 girl[a]	15 boy[a]	Woman	Man
DL (Bq)	41,9	26,1	25,6	27,8	36,2	31,7	33,8

[a]They are the same phantom and their heights of measurement in the Fastscan are different, which are referenced in Table 4.

the values of DL (Bq) for ^{131}I that were obtained for both detection systems (LEGe and Fastscan) for the different counting geometries implemented. The scenarios of internal exposure considered are acute inhalation of ^{131}I type F and acute ingestion. Measurements are supposed to be performed three days after intake. Activity detected is assumed to be the same as the DL (Bq) for ^{131}I and the committed effective dose was estimated. The results confirm that three days after the intake, the *in vivo* measurement of ^{131}I in thyroid for the exposed population applying the methodology developed by CIEMAT WBC allows estimating doses about tens of microSievert for a short counting time of 300 s.

CONCLUSIONS

CIEMAT Whole Body Counting Laboratory has developed a calibration methodology for the *in vivo* measurement of ^{131}I in the thyroid of exposed population (adults and children). A Fastscan Counter and a LEGe detector inside a shielded room are used for this purpose.

A set of neck phantoms for thyroid calibration were manufactured at CIEMAT using Lucite with 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 and adult male and female. Iodine-131 was used as calibration source. Calibration efficiency values depend mainly on the source volume, neck phantom–detector distance, relative detector-source position and attenuation due to neck thickness.

Counting efficiency using Fastscan (5 min as counting time) is greater than the one for LEGe detector (20 min) for the same configuration. LEGe detector is suitable in case of complex internal contamination due to the excellent resolution of this equipment allowing the correct identification and quantification of different isotopes emitting similar gamma emissions.

CIEMAT WBC has validated this *in vivo* method for thyroid monitoring which can be applied in case of radiological or nuclear emergency involving accidental intake of ^{131}I through inhalation or ingestion by workers and members of the public of different ages. DL varies with the age of individuals, being in the range of 5–8 Bq of ^{131}I for the LEGe detector and 26–42 Bq for the Fastscan Counter. Detection of intakes resulting in committed effective doses far below 1 mSv are guaranteed for thyroid monitoring in a few days after the accidental exposure assuming an scenario of acute inhalation or ingestion of ^{131}I by members of the public.

CIEMAT WBC has participated in the 2016 EURADOS/LLNL intercomparison of thyroid monitoring and dose evaluation to validate new ANSI thyroid phantom[11] and is currently involved in the Cathymara project ‘Child and Adult Thyroid Monitoring After Reactor Accident’ (OPERRA, 7FP EURATOM, 2016–17).

ACKNOWLEDGEMENT

Eduardo Garcia Toraño and Virginia Peyres from Metrology Laboratory, Inmaculada Sierra and Carolina Hernandez from In vitro Bioassay Laboratory and Infrastructure Division of CIEMAT for their contribution in the fabrication of the thyroid–neck phantom set and the preparation of radioactive sources.

REFERENCES

1. Hickman, D. P. *et al. Thyroid phantom measurements in Joint EURADOS-LLNL intercomparison exercise*. Radiat. Prot. Dosim. **178**(2), 152–159 (2018).
2. Lopez, M. A. *et al. Lessons learned from the EURADOS survey on individual monitoring data and internal dose assessments of foreigners exposed in Japan following the Fukushima Daiichi NPP accident*. Radiat. Prot. Dosim. **170**(1–4), 402–406 (2016).
3. ICRP. *Basic anatomical and physiological data for use in radiological protection reference values. ICRP Publication 89*. Ann. ICRP **32**(3–4), 225–227 (2002).
4. López Ponte, M. A. and Bravo, T. N. *A Low Energy Germanium Detector System for lung counting at the WBC facility of CIEMAT*. Radiat. Prot. Dosim. **89**(3–4), 221–227 (2000).
5. Canberra. *Manual Fastscan Counter* (2004).
6. Canberra. *Manual Genie/Abacos 2000* (1999).
7. American National Standards Institute. I., *ANSI/HPS N13.44–2014. Thyroid Phantom Used in Occupational Monitoring* (2014).
8. Pérez López, B. and Navarro Amaro, J. F. *Determinación in-vivo de I-131 en tiroides mediante el sistema*

LEGe Detector 1., CIEMAT/DR/DPI/08/13, Editor. 2013, CIEMAT.
9. Pérez López, B. and Navarro Amaro, J. F. *Determinación in-vivo de I-131 en tiroides mediante los sistemas NaI(Tl) y Fastscan*, CIEMAT/DR/DPI/07/13, Editor. 2013, CIEMAT.
10. ISO. *ISO 28218: Radiation protection—performance criteria for radiobioassay*, ISO, Editor. 2010. p. 45.
11. Etherington, G. *et al*. *CAThyMARA report: technical guidelines for radioiodine in thyroid monitoring*. OPERRA Deliverable D5.31 (2017).