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CIEMAT WBC capabilities for responding in case of nuclear and radiological emergencies

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ABSTRACT

Nuclear and radiological accidents can result in internal exposures of workers (including first responders) and general population. For this reason it is necessary precise and rapid methods are developed in order to ensure capabilities for monitoring and dose assessments of internally contaminated persons. The Whole Body Counter (WBC) of the Center for Energy, Environmental and Technological Research (CIEMAT) in Madrid, Spain, has implemented techniques to determine radioiodine in the thyroid and gamma emitters throughout the body of various age groups of children and adults. In addition, the WBC laboratory has developed a new *in vivo* calibration and measurement method with germanium detectors in case of contamination of gamma emitting radionuclides in wounds at different depths.

Two detection systems have been calibrated accordingly: a Fastscan counter, consisting of two NaI(Tl) detectors, and a low-energy germanium (LEGe) detection system (four detectors), which is highly efficient at low gamma energies.

A family of Lucite thyroid neck phantoms for children and adults was designed and manufactured at CIEMAT for thyroid calibration purposes. A set of whole-body phantoms of the BOMAB type was fabricated with polyethylene, and filled with distilled water in an acid medium and with a known gamma emitter mixture for *in vivo* monitoring calibration. In addition simulators of contaminated wounds with circular pieces of Ethyl Vinyl Acetate (EVA) were provided by Institut de Radioprotection et de Sûreté Nucléaire (IRSN) from France.

Efficiency curves depending on energy are obtained in the different counting geometries, which facilitate calculating the activities of the gamma emitting radionuclides retained in the organism when monitoring real contaminated persons. In case of intake of radionuclides retained in the thyroid or in the whole body, a curve is obtained for each age specific phantom. Moreover in case of contamination in wounds a set of efficiency curves was developed depending on the contamination depth.

The detection limits (DL) of the *in vivo* measurement techniques for radionuclides have been calculated from the measurements of blank phantoms or persons according to ISO 28218 standard obtaining results for each method and age. Using the limits of detection for the estimation of the minimum committed effective dose, the values obtained were lower than 1 mSv.y^{-1}, which is below the limit for the public recommended by ICRP.

1. Introduction

In a radiological or nuclear emergency in which internal exposures are involved affecting workers and population, it is necessary to ensure internal dosimetry protocols and methods to provide reliable monitoring data and dose assessments to be used by decision makers managing the accidental situation. For this purpose, it is necessary that *in vivo* and/or *in vitro* measurements are carried out making possible to determine the retained and/or excreted activity respectively, of incorporated radionuclides. In emergency situations effective and fast methods are required, such as *in vivo* techniques for determining the activity of gamma-emitting radionuclides inside the body.

Lessons learned (Lopez et al., 2016) since the Fukushima Daiichi NPP accident suggest that procedures of *in vivo* measurement of internal contamination in exposed population can be improved, particularly in children. The Whole Body Counter (WBC) of the Center for Energy, Environmental and Technological Research (CIEMAT) in Madrid, Spain, has implemented techniques to determine the activity of radioiodine in the thyroid and gamma emitters throughout the total body in exposed population, by calibrating detector systems for different age groups of children (1, 5, 10, 15 years old) and adults (male and female). In addition, a new method for determining the activity of gamma emitters in

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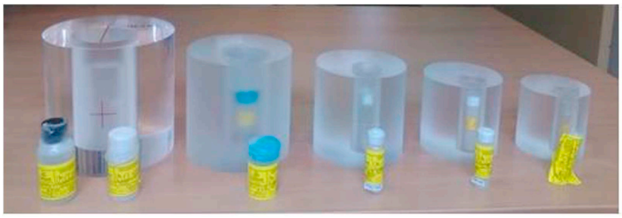

Age (years)	V thyroid (ml)
1	1.8
5	3.4
10	7.7
15	12
Adult Female	17
Adult Male	20

Fig. 1. Neck and vial phantoms with their volumes of ^{131}I.

Table 1
Pieces of BOMAB male phantom used for each age-specific whole body calibration.

	ICRP 89			BOMAB	
Age (years)	Height (cm)	Weight (kg)	Pieces used from adult male BOMAB	Height (cm)	Weight (kg)
1	76	10	Neck + 2 arms	70.1	10.6
5	109	19	Neck + 2arms + 2legs	110	19.4
10	138	32	Head + neck + abdomen + 2legs + thigh	129.9	33
15 Female	167	56	Neck + thorax + abdomen + 2arms + 2thighs	150.2	55.1
15 Male	161	53	Head + thorax + abdomen + 2thighs + 2legs	160.1	57.6
Adult Female	163	60	Neck + thorax + abdomen + arm + 2thighs + 2legs	150.1	59.3
Adult Male	176	73	Head + neck + thorax + abdomen + 2arms + 2thighs + 2legs	170	68.2

wounds has been developed to ensure internal dosimetry monitoring when the incorporation occurs through the skin. In the latter case, it usually happens in exposed workers whose work requires the use of manual machines.

2. Materials and methods

The detection systems used in this work consist of: (1) four low-energy germanium (LEGe) semiconductor detectors (by Canberra Ind.), operating in the 10–1000 keV energy range, placed inside a low radioactive background shielded room and (2) a Fastscan counter by Canberra, with two NaI(Tl) scintillation detectors located in column and operating at 100–2000 keV energy range. Both detection systems are utilized to detect and quantify internal contamination of gamma-emitting radionuclides.

The calibration phantoms for partial and total body counting systems were fabricated simulating different parts of the human body, depending on the radionuclide incorporated and its biokinetic (retention) inside the organism after intake. The phantom materials have densities and attenuation coefficients similar to human tissues and organs and they were selected taking into account the ICRU Report 44 (White et al., 2016). Thyroid neck phantoms of 1, 5, 10, 15 years old children, and of adults were made of methacrylate. Those of children were designed based on a study of children neck real dimensions in the age range from 0 to 15 years old persons and were manufactured at CIEMAT (Pérez López and López, 2018). In case of adults, a thyroid neck phantom was manufactured by BIODEX following specifications of the ANSI N13.44 (American National Standards Institute and I, 2014) standard. The vials used (see Fig. 1) as simulators of contaminated thyroid were filled with volumes of ^{131}I aqueous solutions according to ICRP 89 (ICRP, 2002).

The BOMAB HE4 phantom simulating total body of an adult male was manufactured with dimensions according to ANSI 13.35 (American National Standards Institute and I, 1999) standard; it consists of 10 pieces of polyethylene filled with distilled water in an acid medium and a radioactive cocktail. Known activities of radionuclides, such as ^{57}Co, ^{134}Cs, ^{137}Cs and ^{60}Co, were introduced proportionally to their volumes for calibration purposes. The configurations of children (1, 5, 10 years old and 15 years old) and adult female phantoms were obtained assembling different pieces of the BOMAB adult male phantom. They were assembled according to the size recommended in the ICRP publication 89 (ICRP, 2002). The pieces used in each case are shown in Table 1.

The wound calibration phantom was designed and manufactured by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) from France (see Fig. 2), consisting in Ethyl Vinyl Acetate (EVA) adipose equivalent material according to ICRU Report 44 (White et al., 2016). Each radioactive source is a circular plate (10 cm diameter, 0.2 cm depth) with a drop of radioactive material (1 cm^2) in the center, and partially-contaminated cellulose filter (surface of 5 cm of diameter). Blank phantoms similar to radioactive source were utilized in order to simulate different depths of contamination in wounds. Two sources were used for calibration purpose; the first source consists of a mixture of ^{241}Am, ^{57}Co, and ^{137}Cs and the second source of ^{133}Ba and ^{85}Sr.

In this work, three methodologies have been developed:

(1) Thyroid calibration consists in placing the neck phantom with the iodine source close to detector for measurement. Two counting geometries are considered here: one simulating the person semireclined on a sitting chair with a distance of 15 cm from the neck phantom to LEGe detector (see Fig. 6) inside a shielding room, and the other simulating a person standing up, with a 12 cm thyroid - NaI(Tl) detector distance when using the Fastscan counter. In the latter the phantom positioning depends on the calibration age (see Fig. 3). Thyroid heights considered in each case were calculated from height tables offered by the WHO (WHO, 2015) and an estimation of the height of the head depending on age.

(2) Total body calibration geometry using LEGe detector system consists in placing BOMAB phantom on a semireclined chair. The detector-phantom distance depends on the size of the phantom. A distance of 30 cm to germanium detectors for adults and for a 15-year-old young

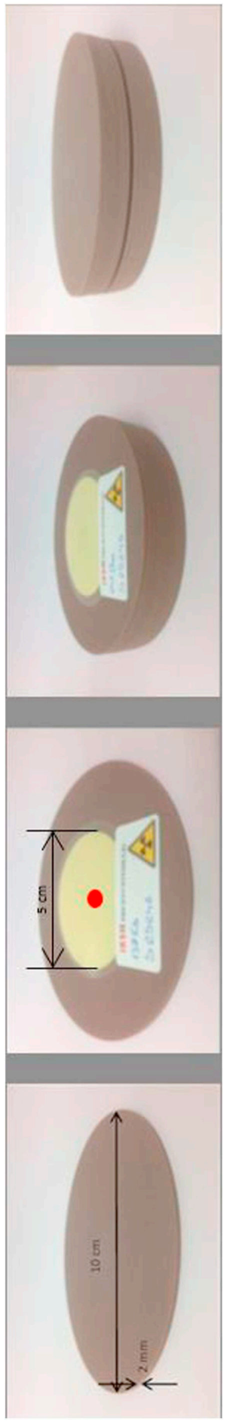

Fig. 2. IRSN wound phantom manufactured with EVA plate. Source: IRSN (France).

person is considered, and a distance of 19 cm for 10, 5 and 1 years old children (see Fig. 4). Regarding total body calibration when using a FASTSCAN counter a standing up counting geometry is preferred with 9 cm of distance to NaI(Tl) detectors (see Fig. 5).

(3) Wound calibration geometry consists in placing the wound phantom as close as possible to the LEGe detector. Measurements were made at a distance of 1 cm between the phantom and the detector (see Fig. 10).

The methodology of *in vivo* monitoring calibrations consists in the phantom being positioned in a reproducible geometry for a person, close to the detector, optimizing detector efficiency in order to get the most photon counts. The result of the measurement is a gamma spectrum that it is analyzed for identifying the emitted energies associated to radionuclides present in a person or in a phantom. When measuring a phantom with known activities of radionuclides (calibration source), the counting efficiency is calculated for each photopeak of the spectrum taking into account the net area (counts), the activity (Bq) of the radionuclide and the yield peak emission, by using equation (1).

$$Eff\left[\frac{c}{\gamma}\right] = \frac{Area\ [c]}{t\,[s]\cdot A\,[Bq]\cdot I\,[\gamma]} \tag{1}$$

The efficiencies calculated for the main energies identified in the calibration spectrum are fitted to a curve in all the energy range. This curve allows interpolating or extrapolating efficiency values for any energy, and can be used to analyze any gamma spectrum of a person measurement in the same counting geometry as the one of calibration.

3. Results

The counting geometry selected for the calibration of the detector system must be realistic and reproducible for *in vivo* measurement of real contaminated individuals.

3.1. Calibration for the in vivo measurement of ^{131}I in thyroid

The WBC of CIEMAT relied on calibration and *in vivo* measurement procedures of ^{131}I in thyroid for adults (using both Fastscan counter and LEGe detection system).

In order to extend calibration and monitoring procedures for children, measurements were made with the different age specific thyroid phantoms in the same counting geometry as the adult calibration one, with both detection systems. Age-dependent gamma spectra were analyzed with the previous adult male calibration. The resulting activities differed from the reference activity a maximum of 35% in LEGe detector and 55% in Fastscan counter for the 1-year-old child.

The graph of the results of the LEGe detector efficiency calibrations for the measurement of ^{131}I in thyroid (Pérez López and López, 2018) using phantoms of different ages are shown in Fig. 6. It is observed that the lowest efficiency value corresponds to the adult male and the highest value to the 1 year old child in the range of energies below 200 keV. The shape of the adult male calibration curve is different from the others; maximum efficiency occurs around energy of 80 keV, while the rest around 50 keV, this difference is due to different measurement conditions. It is observed that the efficiency curves differ slightly from each other depending on thyroid size. Efficiency depends on the source size; the solid angle between source and detector covers better the smaller sources.

In case of thyroid calibrations in the Fastscan counter, a single NaI (Tl) detector (upper detector or lower detector) was used, depending on the thyroid height of the individual to be measured.

Regarding the efficiency curves (see Fig. 7) it can be observed that the highest efficiencies correspond to the 5-year-old configuration. The efficiency curves for 10 years old and 15 years old configurations are alike and those of adult (male and female) are very similar. The efficiency values of a 1-year-old child are the lowest, unexpectedly,

Age (year)	H thyroid (cm)
1	61.5
5	92
10	117
15 Female	138.5
15 Male	143.5
Female	139

Fig. 3. Heights of different configurations and geometry calibration of ^{131}I in thyroid with Fastscan Counter.

compared with the results from LEGe efficiency in thyroid calibration curves. This is because the height at 1 year old neck calibration corresponds to the lower limit shield of the lower NaI(Tl) detector of the Fastscan counter, so there were fewer counts arrived to the detector (lower counting efficiency) than expected. In future calibrations, it is possible to improve this calibration using a lifter to increase the height of a child's neck of 1 year, avoiding this shielding limitation.

All the calibrations performed with ^{131}I for thyroid monitoring with both detection systems have been validated by the measurements of vials with radioactive sources of ^{133}Ba and^{137}Cs, as simulators of ^{131}I emissions. Validations consisted of carrying out five measurements of 5 and 10 years old neck phantoms and their activities were calculated with their corresponding (age dependent) efficiency curve. In addition, with the participation of CIEMAT WBC in the CATHyMARA project (Isaksson, n.d.), it was possible to measure the simulator neck phantoms of 5 and 10 years old children manufactured by SCK-CEN (Belgium) allowing the validation of the WBC-CIEMAT thyroid neck phantoms. Activity results (see Tables 2 and 3) were in compliance with acceptance criteria according to ISO 28218 (ISO, 2010) standard.

Detection limit (DL) (ISO, 2010) indicates the ability of the *in vivo* laboratory to detect a radionuclide incorporated by an individual and deposited in total body or in organs. DL is mainly dependent on the person, the measurement geometry, the counting efficiency and the counting time. In order to calculate detection limits (Pérez López and López, 2018), *in vivo* measurements of blank persons for male and female adult calibrations were performed, and measurement of blank phantoms in case of children. The measurement time with the LEGe detector system was 20 min and 5 min for Fastscan counter measurements. Results of the DL for the ^{131}I vary with the size of the thyroid, from 4.6 to 7.9 Bq with the LEGe system and from 26 to 42 Bq with the Fastscan counter.

3.2. Calibration of gamma emitters in whole body counting geometry

The WBC of CIEMAT had developed a procedure for the calibration and *in vivo* measurement of gamma emitting radionuclides deposited in total body by using a Fastscan counter for adult male geometry. In order to improve the capabilities of the laboratory, LEGe detection system and Fastscan counter have been calibrated for the *in vivo* measurement of gamma emitting radionuclides in total body for children and adults for energy detection up to 2000 keV.

The calibration measurements of the LEGe system (with four detectors) were carried out inside a shielded room of 13 cm of steel walls with low radioactive background.

Fig. 7 shows efficiency curves where smaller phantoms have the greatest efficiency due to some parts of the bigger phantoms are out of the detector solid angle.

Efficiencies values for the 15-year-old child and adult calibrations are both throughout the full energy range. In case of 1 and 5 years old children, these efficiencies show significant differences with the 10, 15 years old persons and adult efficiencies, especially at lower energies (see Fig. 8).

These calibrations were validated by the measurement of another BOMAB phantom (HE2), similar to the calibration phantom, filled with distilled water and a cocktail of ^{57}Co, ^{137}Cs and ^{60}Co (see Table 5). Five measurements of BOMAB HE2 phantom placed with the same counting geometry as the one of calibration were carried out and were analyzed with their respective age-dependent efficiency curves, fulfilling acceptance criteria according to ISO 28218 (ISO, 2010)standard.

Calibrations with the Fastscan counter were performed taking into account the height of each configuration. Supports were needed to put the pieces in a standing up configuration (see Fig. 5). In the cases of 1, 5 and 10 years old children it was decided to put the phantoms on an additional lift in order to improve their positioning as centered as possible between both lower and upper NaI(Tl) detectors, optimizing counting efficiency.

Series of measurements were performed for each age-dependent detection geometry described above. Resulted spectra were analyzed with the previous standard male adult calibration. Significant deviations were found when comparing with true activity values (i.e. 120% for ^{137}Cs activity at 1 year old child configuration).

The efficiency calibrations of the Fastscan equipment (two NaI(Tl) detectors) were carried out with two phantoms, BOMAB HE2 and BOMAB HE4 units, mainly due to the fact that the first one has simple emissions and well differentiable in the NaI(Tl) detectors, but the activity of ^{57}Co was very low, hence the BOMAB HE4 phantom was also used. Therefore, the photopeaks of BOMAB HE2 phantom were used, except for the emission of 122 keV of ^{57}Co, which was used the one from BOMAB HE4 phantom.

The efficiency curves for each phantom (Fig. 9) demonstrate similar behaviors throughout the energy range. However, the efficiency for the 1-year-old child phantom is dramatically higher, because of its small size. The others curves have less differences in efficiency, see Table 4, around 0.005 c/γ in case of the 661 keV of ^{137}Cs.

These calibrations were validated with ^{134}Cs, ^{137}Cs and ^{60}Co from BOMAB HE4 emissions (see Table 6), in the same way as it was done in the previous cases, according to ISO 28218 (ISO, 2010) standard.

The detection limits (DL) of measurement of gamma emitters in the whole body varies with phantom size and with counting time (30 min for LEGe system and 5 min for Fastscan counter) (see Tables 7 and 8). The DLs for different radionuclides are different depending on age and height of the person. For example DL for ^{137}Cs varies from 10.7 to 61.1 Bq using LEGe detector and from 49.6 to 110.0 Bq when using Fastscan counter. The detection limit for ^{99m}Tc varies from 7.0 to 39.2 Bq with

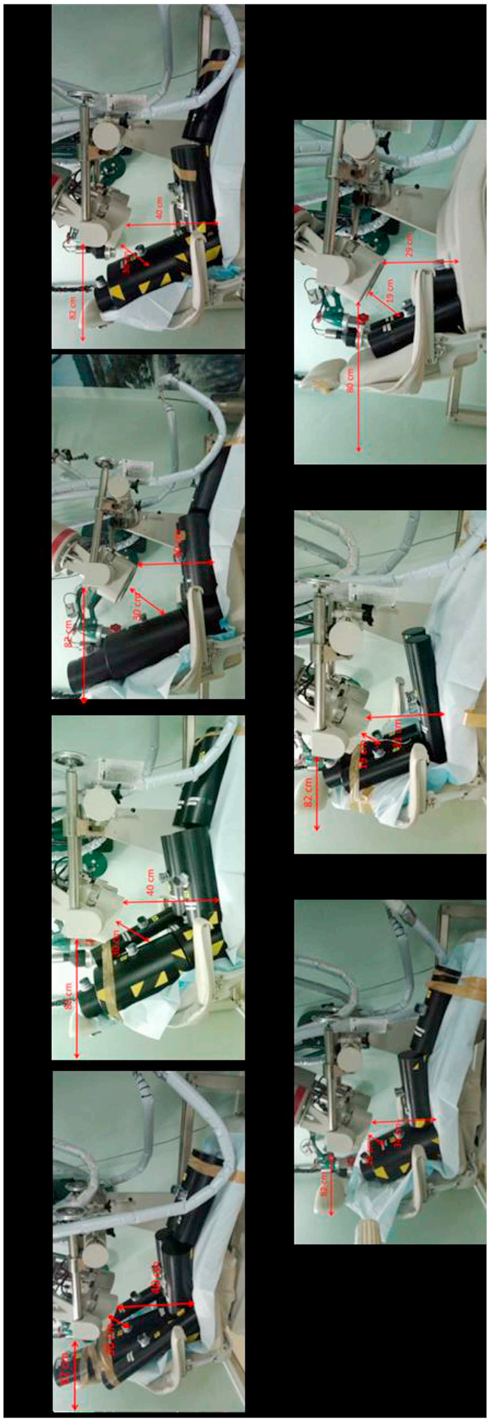

Fig. 4. Geometries of total body calibration in LEGe detection system.

Fig. 5. Configurations of total body calibration with Fastscan counter.

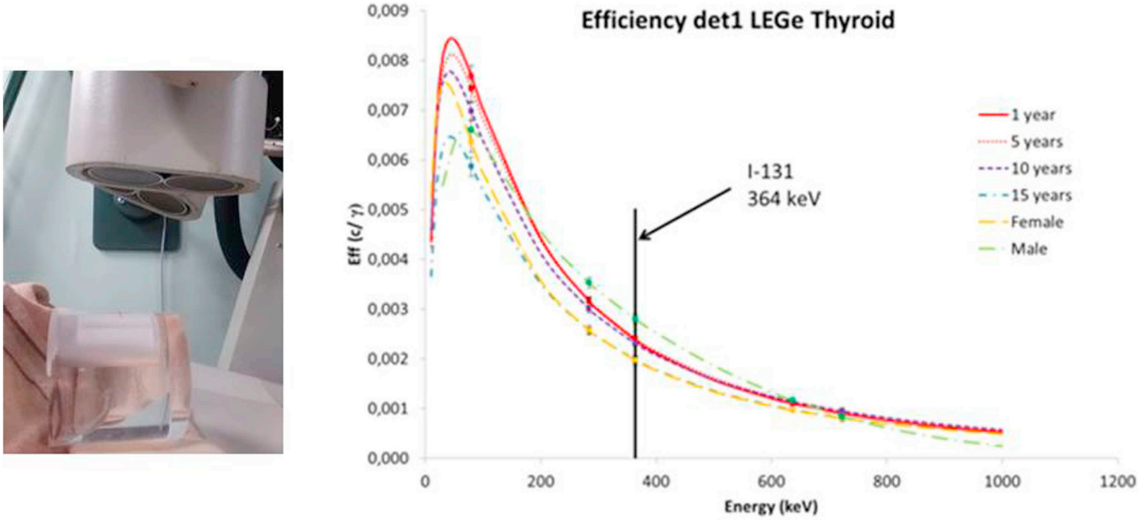

Fig. 6. Calibration geometry and efficiency curve associated to the measurement of a thyroid neck phantom with 1 LEGe detector.

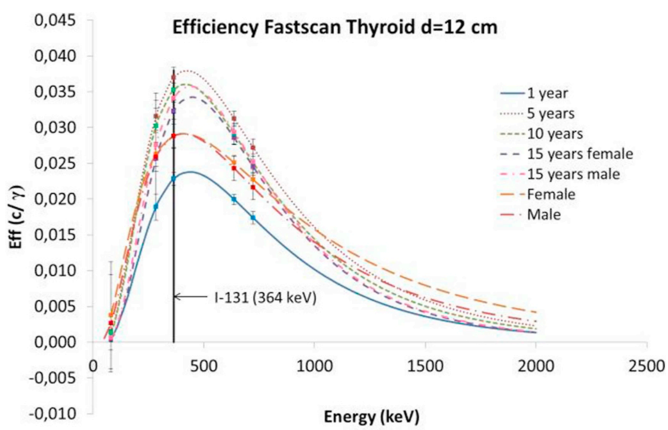

Fig. 7. Efficiency curves in function of energy in each age in Fastscan counter.

Table 2
Validation measurements for 5 and 10 years old neck phantoms with CATHyMARA project phantom for LEGe detector.

LEGe	^{133}Ba				^{137}Cs			
Age (y)	Aref(Bq)	Am(Bq)	Br	SBr	Aref (Bq)	Am(Bq)	Br	SBr
5	2536.8	2094	−0.16	0.02	291.80	91	−0.18	0.30
5	2536.8	2158			291.80	229		
5	2536.8	2197			291.80	303		
5	2536.8	2154			291.80	291		
5	2521.3	2062			291.20	277		
10	5763.4	4967	−0.17	0.02	663.00	641	−0.09	0.04
10	5734.4	4661			661.80	619		
10	5734.4	4788			661.80	590		
10	5734.4	4683			661.80	604		
10	5734.4	4768			661.80	572		

LEGe detector and from 50.8 to 127.0 Bq with Fastscan counter. All calculated detection limits ensure committed effective dose below 1 mSv y^{-1}, limit established for the public in the ICRP publication 103 (ICRP, 2007).

3.3. Calibration of gamma emitters in wounds

The efficiency calibrations for the measurement of activity (Bq) of gamma contaminants in wounds were carried out within the framework of the intercalibration and intercomparison exercise organized by the IRSN. A single detector of the LEGe detection system was utilized for calibration purpose in this new counting geometry in the energy range of 10–1000 keV.

The wound phantom allowed carrying out calibrations with activity (Bq) at different depths by positioning additional blank plates (similar as wound phantom one but without any radioactive contamination).

Results of the efficiency calibration curves for the different depths obtained are shown in Fig. 10. The curves obtained show that efficiency varies substantially at low energies (E < 250 keV), at different depths in the wound (due to self-absorption of the radionuclides in tissues). If energy > 250 keV, the efficiency variation is less significant.

The high detection sensitivity obtained with the LEGe detector allows measuring activities of few Bq of the typical gamma radionuclides of interest with a counting time of 10 min. For example, DLs of ^{137}Cs are in the range from 0.5 to 1.4 Bq depending on the contamination depth.

4. Conclusions and discussion

The WBC laboratory of CIEMAT has developed different procedures of calibration for *in vivo* measurements of potentially contaminated persons in order to improve the response in emergencies involving incorporation of X/γ emitters deposited in total body and ^{131}I in thyroid for different age groups (1, 5, 10, 15 years old and adults) and the measurement of internal contamination in wounds at different depths.

CIEMAT WBC capabilities have been expanded through the development of age specific phantoms (1, 5, 10, 15 years old children and adult male and female) for calibration purpose.

In general, efficiency calibrations depend on the positioning of the phantom and on the phantom-detector distance. In the case of the Fastscan counter measurements, the height of the phantom or the person under study also influences.

Efficiency values are, in general, greater for smaller phantoms in all energy range. In case of ^{131}I in thyroid calibrations and of gamma emitters throughout the body, there is a similarity in efficiency curves between adults and 15 years old child configurations. However, there is more discrepancy when comparing with 1 and 5 years old children efficiencies.

In the case of wounds, the most superficial wound has the highest efficiency. This *in vivo* method for the measurement of gamma emitters in wounds is unique methodology developed in Spain that allows ensuring internal dosimetry in the special situation of incorporation of internal contaminants through injured skin.

The selection of the most appropriate technique in an emergency depends on the radionuclides emitted, taking into account their gamma

Table 3
Validation measurements for 5 and 10 years old neck phantoms with CATHyMARA project phantom for Fastscan counter.

Fastscan	^{133}Ba				^{137}Cs			
Age (y)	Aref (Bq)	Am (Bq)	Br	SBr	Aref (Bq)	Am (Bq)	Br	SBr
5	2537.2	1826	0.19	0.05	291.8	203	0.27	0.08
5	2522.2	2132			291.3	193		
5	2522.2	2145			291.3	231		
5	2522.2	2056			291.3	192		
5	2522.2	2057			291.3	246		
10	5737.5	4233	0.26	0.01	662.0	588	0.12	0.04
10	5737.5	4225			662.0	611		
10	5737.5	4223			662.0	554		
10	5736.4	4232			661.9	566		
10	5736.4	4285			661.9	609		

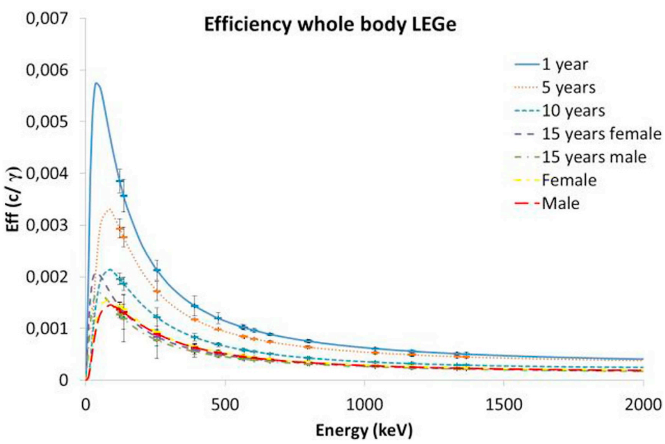

Fig. 8. Efficiency depending on the energy in total body geometry for each age specific calibration (LEGe detector system).

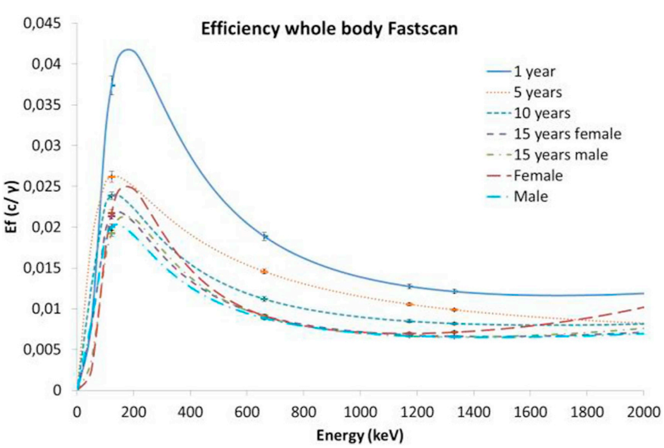

Fig. 9. Efficiency functions depending on the energy in total body geometry for each age configuration with CIEMAT Fastscan counter (2 NaI(Tl) detectors).

emission energies and their affinity organs once incorporated into the human organism.

In general, the most convenient *in vivo* monitoring procedure to follow is: firstly a rapid measurement of the internally exposed individual by NaI(Tl) detectors (Fastscan counter) which allows rapid assessment of gamma radionuclides deposited in the thyroid and throughout the body. In case of complex contaminations of gamma emitters, it is more appropriate to measure the individual with LEGe detection system due to its good spectral resolution in spite of its lower efficiency comparing with NaI(Tl) detectors and the need to perform longer counting time measurements.

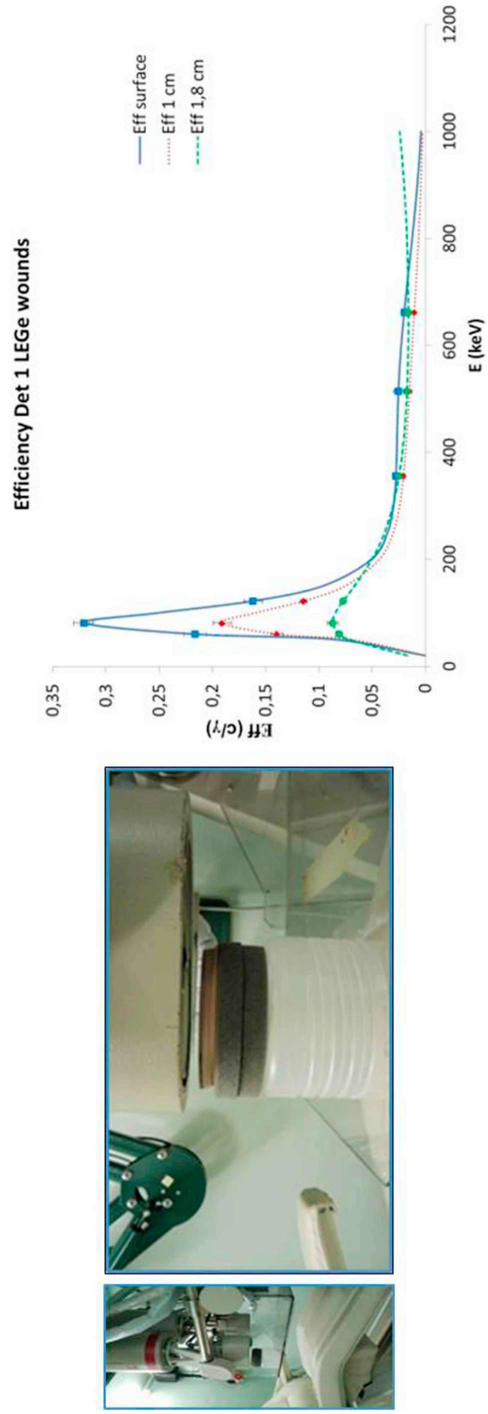

Fig. 10. Wounds calibration geometry and efficiency curves based on the depth of contamination with one LEGe detector.

Table 4
Efficiencies values for all configurations in different energies.

Energy (keV)	Effadult male	Eff adult female	Eff 15 y male	Eff 15 y female	Eff10 y	Eff 5 y 26 cm raised	Eff 1 y 59 cm raised
122	0,02000	0,02175	0,01926	0,02133	0,02385	0,02407	0,03736
661	0,00884	0,00913	0,00906	0,00914	0,01119	0,01294	0,01887
1173	0,00669	0,00697	0,00664	0,00679	0,00847	0,00932	0,01274
1332	0,00654	0,00712	0,00654	0,00662	0,00819	0,00890	0,01211

Table 5
Validation measurements for whole body phantoms in LEGe detector system.

LEGe	Co-57			Co-60			Cs-137		
Age (y)	**A ref (Bq)**	**A med (Bq)**	**Bri**	**Aref (Bq)**	**A med (Bq)**	**Bri**	**A ref (Bq)**	**A med (Bq)**	
1	96	102	0,0643	2457	2477	0,0079	3937	3907	−0,0076
1	96	130	0,3493	2457	2238	−0,0892	3937	4004	0,0170
1	96	141	0,4615	2457	2505	0,0194	3937	4038	0,0255
1	96	111	0,1569	2457	2441	−0,0068	3937	3802	−0,0343
1	96	105	0,0963	2457	2468	0,0042	3937	4087	0,0379
		Br	**0,2257**		**Br**	**−0,0129**		**Br**	**0,0077**
		SBr	**0,1721**		**SBr**	**0,0437**		**SBr**	**0,0288**
5	203	203	−0,0017	4712,66	4737	0,0052	6343	7682	0,2111
5	203,35	182	−0,1050	4712,66	4773	0,0128	6343	7636	0,2038
		Br	**−0,0534**		**Br**	**0,0090**		**Br**	**0,2075**
		SBr	**0,0730**		**SBr**	**0,0054**		**SBr**	**0,0051**
10	368	369	0,0023	8535	8462	−0,00855292	13498	12633	−0,0641
10	368	400	0,0854	8535	8996	0,054034516	13498	12702	−0,0589
10	366	320	−0,1277	8529	8644	0,013477626	13497	12923	−0,0425
10	366	359	−0,0198	8529	8488	−0,00478957	13497	13243	−0,0188
10	328	267	−0,1877	8397	6844	−0,18497082	13460	13320	−0,0104
		Br	**−0,0495**		**Br**	**−0,02616023**		**Br**	**−0,0390**
		SBr	0,1084		SBr	0,092181728		SBr	0,0238
15 M	586	761	0,2986	15122	14926	−0,0130	24266	23954	−0,0129
15 M	586	410	−0,2996	15122	12837	−0,1511	24266	24337	0,0029
15 M	586	518	−0,1151	15122	13735	−0,0917	24266	24035	−0,0095
15 M	586	581	−0,0084	15122	12319	−0,1854	24266	23347	−0,0379
15 M	586	593	0,0121	15122	14768	−0,0234	24266	23619	−0,0267
		Br	**−0,0225**		**Br**	**−0,0929**		**Br**	**−0,0168**
		SBr	**0,2178**		**SBr**	**0,0761**		**SBr**	**0,0158**
15 F	551	549	−0,0036	14327	14502	0,0122	23012	22005	−0,0438
15 F	551	510	−0,0751	14327	14338	0,0007	24763	23072	−0,0683
15 F	551	539	−0,0230	14327	14533	0,0143	24763	22560	−0,0890
15 F	551	601	0,0890	14327	14486	0,0111	24763	22458	−0,0931
15 F	551	575	0,0428	14327	14354	0,0018	24763	22813	−0,0788
		Br	**0,0060**		**Br**	**0,0080**		**Br**	**−0,0746**
		SBr	**0,0628**		**SBr**	**0,0063**		**SBr**	**0,0197**
F	596	631	0,0584	17457	16008	−0,0830	24763	24530	−0,0094
F	596	622	0,0431	17457	15619	−0,1053	24763	24296	−0,0189
F	596	485	−0,1861	17457	16104	−0,0775	24763	24257	−0,0204
F	596	687	0,1521	17457	15917	−0,0882	24763	24679	−0,0034
F	596	723	0,2130	17457	16096	−0,0779	24763	24568	−0,0079
		Br	**0,0561**		**Br**	**−0,0864**		**Br**	**−0,0120**
		SBr	**0,1522**		**SBr**	**0,0114**		**SBr**	**0,0074**
M	678	829	0,2229	17574	17841	0,0152	28218	26954	−0,0448
M	678	770	0,1366	17574	17806	0,0132	28218	27377	−0,0298
M	678	727	0,0732	17574	17653	0,0044	28218	27506	−0,0252
M	678	768	0,1331	17574	17867	0,0166	28218	26856	−0,0483
M	678	662	−0,0229	17574	17752	0,0101	28218	26689	−0,0542
		Br	**0,1086**			**0,0119**		**Br**	**−0,0405**
		SBr	**0,0908**		**SBr**	**0,0048**		**SBr**	**0,0124**

LEGe detection system has the best efficiencies below 200 keV, nevertheless Fastscan counter has the best efficiencies above 200 keV.

These methods developed by CIEMAT WBC can be used in case of nuclear and radiological emergencies. The detection limit for each radionuclide of this study allows an evaluation of the committed effective dose, E(50) [mSv], by internal exposure, below the limit of 1 mSv y^{-1}, established for the public exposures, in the ICRP publication103.

Table 6
Validation measurements for age-dependent whole body phantoms with CIEMAT Fastscan counter.

Fastscan	Co-57			Co-60			Cs-137		
Age (y)	**A ref (Bq)**	**A mes (Bq)**	**Bri**	**A ref (Bq)**	**A mes (Bq)**	**Bri**	**A ref (Bq)**	**A mes (Bq)**	**Bri**
1	710	596	−0,1607	1099	977	−0,1112	2642	2109	−0,2017
1	710	524	−0,2617	1099	992	−0,0970	2642	2412	−0,0871
1	710	523	−0,2628	1099	938	−0,1467	2642	2416	−0,0856
1	710	564	−0,2056	1099	930	−0,1537	2642	2490	−0,0574
1	710	595	−0,1620	1099	921	−0,1622	2642	2459	−0,0692
		Br	−0,2106		Br	−0,1342		Br	−0,1002
		SBr	0,0505		SBr	0,0284		SBr	0,0580
5	1371	1416	0,0321	2092	2020	−0,0340	5015	4714	−0,0599
5	1371	1457	0,0625	2092	1996	−0,0455	5015	4665	−0,0697
5	1371	1360	−0,0083	2092	2062	−0,0138	5015	4724	−0,0579
5	1371	1452	0,0586	2092	1979	−0,0536	5015	4790	−0,0447
5	1371	1370	−0,0012	2092	2015	−0,0361	5015	4835	−0,0359
	1371	Br	0,0287		Br	−0,0366		Br	−0,0536
		SBr	0,0328		SBr	0,0149		SBr	0,0133
10	2521	2004	−0,2052	3844	3527	−0,0823	9216	8314	−0,0979
10	2521	2003	−0,2056	3844	3516	−0,0851	9216	8352	−0,0938
10	2521	2573	0,0206	3844	3608	−0,0612	9216	8630	−0,0636
10	2521	2020	−0,1987	3844	3454	−0,1013	9216	8497	−0,0781
10	2521	2122	−0,1583	3844	3443	−0,1042	9216	8395	−0,0891
		Br	−0,1494		Br	−0,0868		Br	−0,0845
		SBr	0,0971		SBr	0,0173		SBr	0,0138
Male 15	5253	5549	0,0563	7068	7198	0,0183	16662	16250	−0,0247
Male 15	5253	5548	0,0561	7068	7237	0,0239	16662	16090	−0,0344
Male 15	5253	4344	−0,1731	7068	7122	0,0076	16662	16418	−0,0147
Male 15	5253	5827	0,1092	7068	7123	0,0078	16662	16443	−0,0132
Male 15	5253	4389	−0,1645	7068	7021	−0,0066	16662	16442	−0,0132
		Br	−0,0232		Br	0,0102		Br	−0,0200
		SBr	0,1347		SBr	0,0117		SBr	0,0094
Female 15 y	4067	5443	0,3383	6494	6345	−0,0229	15667	15204	−0,0296
Female 15 y	4067	5278	0,2978	6494	6436	−0,0089	15667	15137	−0,0338
Female 15 y	4067	4324	0,0632	6494	6461	−0,0051	15667	15383	−0,0181
Female 15 y	4067	4271	0,0502	6494	6469	−0,0038	15667	15199	−0,0299
Female 15 y	4067	5373	0,3211	6494	6469	−0,0038	15667	15447	−0,0141
		Br	0,2141		Br	−0,0089		Br	−0,0251
		SBr	0,1445		SBr	0,0081		SBr	0,0085
Female	5372	3894	−0,2751	7196	6756,9	−0,0610	16954	16398	−0,0328
Female	5372	4891	−0,0895	7196	6742,9	−0,0630	16954	16483	−0,0277
Female	5372	5298	−0,0138	7196	6760	−0,0606	16954	16305	−0,0383
Female	5372	5445	0,0136	7196	6671,6	−0,0729	16954	16394	−0,0330
Female	5372	3840	−0,2851	7196	6833	−0,0504	16954	16350	−0,0356
		Br	−0,1300		Br	−0,0616		Br	−0,0335
		SBr	0,1422		SBr	0,0080		SBr	0,0039
Male	6121	6197	0,0124	8199	8195	−0,0005	16954	18980	0,1195
Male	6121	6186	0,0107	8199	8185	−0,0017	16954	19216	0,1334
Male	6121	4710	−0,2303	8199	8135	−0,0078	16954	19105	0,1269
Male	6121	4522	−0,2612	8199	8309	0,0134	16954	18733	0,1050
Male	6121	4630	−0,2435	8199	8055	−0,0175	16954	18920	0,1160
		Br	−0,1424		Br	−0,0028		Br	0,1202
		SBr	0,1410		SBr	0,0113		SBr	0,0108

Table 7
Detection limits of some gamma emitters in whole body for different ages in LEGe detectors system and Fastscan.

DL (Bq) in whole body, LEGe detectors, time of measurement 1800 s											
Age (y)	**Co-57**	**Cs-134**	**Cs-137**	**Co-60**	**Ga-67**	**Ga-68**	**Y-90**	**Tc-99m**	**In-111**	**I-123**	**I-131**
1	9.7	20.0	18.7	22.7	27.2	17.4	5.23	7.17	5.73	7.09	14.2
5	14.3	26.4	25.2	30.4	30.2	25.9	15.0	15.2	15.7	18.1	27.1
10	25.1	44.1	39.6	45.1	43.5	34.4	24.4	24.4	22.7	25.4	36.6
15 Female	35.5	63.4	57.9	53.4	70.3	44.5	35.3	35.3	40.9	41.5	57.5
15 Male	39.8	66.5	61.1	54.7	80.0	47.3	38.6	39.2	45.0	45.8	61.7
Adult Female	35.5	60.1	54.6	50.3	75.7	41.5	32.7	34.2	38.6	39.4	52.8
Adult Male	36.7	60.5	54.8	50.8	79.4	41.6	33.2	35.2	39.3	40.3	53.1

Table 8
Detection limits of some gamma emitters in whole body for different ages in Fastscan counter.

DL (Bq) in whole body, Fastscan counter, time of measurement 300 s.

Age (y)	Co-57	Cs-134	Cs-137	Co-60	Ga-67	Ga-68	Y-90	Tc-99m	In-111	I-123	I-131
1	53.9	48.7	49.6	45.6	139	21.8	41.4	50.8	39.3	50.6	43.4
5	122	71.2	76.1	64.1	205	34.5	66.6	84.9	68.2	85.6	72.2
10	84.7	79.1	84.7	67.3	189	40.0	77.6	87.3	75.7	90.5	83.2
15 Female	133	98.1	106	83.6	353	131	94.9	127	96.7	123	103
15 Male	111	101	103	84	309	46.8	85.0	106	82.3	105	94.3
Adult Female	99.5	100	105	80.9	311	45.3	73.1	92.0	71.0	89.5	85.1
Adult Male	113	104	110	90.2	279	50.1	96.8	113	95.7	115	105

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