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Abstract

The 2020 updated Strategic Research Agenda (SRA) of the European Radiation Dosimetry Group (EURADOS), recommends improving the calibration of in vivo monitoring techniques for children, particularly in case of radiological emergencies. Consequently, members of the WG7 task group on Internal Dosimetry for Emergency have organized and carried out an intercomparison exercise at the Whole Body Counter Laboratory of CIEMAT aimed at comparing different age-dependent thyroid neck phantoms for in-vivo monitoring of ^{131}I in the thyroid, specifically targeting children and adults.

Seven laboratories, BfS (Germany); SCK CEN (Belgium), SURO (Czech R.), IRSN (France), STUK (Finland), CIEMAT (Spain) and QST (Japan) have participated in the exercise.

Before starting the exercise, a technical questionnaire for gathering information and a protocol of measurements were agreed by members of the task group. Measurements were carried out with a Broad Energy germanium detector (BEGe) and three geometries of measurements were agreed for comparing efficiency values at short (2 cm), medium (10 cm) and long (15 cm) detector-phantom distance. A fixed counting time (600 s) was selected for calculating detection limits with blank vials.

Prior to the beginning of the measurement campaign, the participants answered a technical questionnaire with a detailed description of their phantoms, dimensions of the vials for thyroid simulation, radioactive sources, calibration and measurement procedures, etc. The intercomparison measurements, all the data collected in the technical questionnaire and the results of the measurements (efficiency calibration curves and detection limits) were shared with the participants for agreement.

The provided information confirmed significant variations in the design of the phantoms and their characteristic such as overlying tissue thickness, thyroid volume, tissue-equivalent material and dimensions of vials simulating thyroid lobes. Such differences highlight the necessity of harmonization in this field.

Regarding the intercomparison measurements, a comparative study has been conducted on the efficiency values obtained for each age group in the three defined geometries. The results revealed significant variability in the efficiency values, particularly at short and medium detector-phantom distances, where discrepancies can reach up to 50%.

Following this intercomparison it seems important to establish a consensus regarding the design of reference age-dependent thyroid phantoms in order to standardize calibration and measurement procedures for enhanced accuracy and harmonization.

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1. Introduction and context

The accidents at the Chernobyl and Fukushima Daiichi nuclear power plants showed that thyroid cancer, particularly in children, was the main concern when evaluating the health effects associated to internal exposures in these emergency situations. In such scenarios, Iodine-131 is noteworthy because it is one of the major components of the release and extended half-life (8.02 days) when comparing to other radioactive iodine isotopes, makes it a focal point of concern (Pröhl *et al.*, 2002). Furthermore, in case of inhalation or ingestion, about 30% is retained during a few weeks in the thyroid gland (ICRP, 2015). The presence of radioactive iodine raises the potential for an elevated risk of developing thyroid cancer not only in adults but also in children. After the Chernobyl accident, more than 6000 thyroid cancers (mostly in children) were attributed to radioiodine intakes (UNSCEAR, 2008). After the Fukushima accident, about 98% of the effective doses received by emergency workers were attributable to radioiodine intakes (UNSCEAR, 2013).

The assessment of doses due to accidental intakes of ^{131}I in the short term after an accident in a nuclear reactor, is based on the monitoring of individuals affected by the emergency situation, including workers, first responders and members of the public. Direct in-vivo measurement of radioiodine in thyroid is usually the preferred method for assessing intake (EC Directorate-General for Energy, Radiation Protection n° 188). This can be accomplished using spectroscopic instruments commonly equipped with either sodium iodide detector (NaI(Tl)) or high-purity germanium detectors (HPGe), typically used in whole-body counters. These detectors allow for the quantification of gamma emissions from ^{131}I , enabling a reliable estimation of the radionuclide's activity within the thyroid. While NaI(Tl) detectors offer a cost-effective and portable solution with sufficient sensitivity for screening measurements, HPGe detectors provide superior energy resolution, which is particularly useful in distinguishing ^{131}I from other gamma-emitting radionuclides (Qadr, 2020).

To obtain reliable values of the committed doses related to accidental intakes, detectors have to be properly calibrated, using thyroid phantoms and calibration radioactive sources simulating the internal contamination in thyroid of individuals of different ages. The variation in thyroid gland size among individuals in different age groups is noteworthy. Hence, employing age-dependent phantoms for calibration purposes could reduce the uncertainties of measurement and, consequently, enhance the dose assessment. Regarding radioactive sources, due to the short half-life of ^{131}I ($T_{1/2} = 8.02$ days), ^{133}Ba ($T_{1/2} = 10.5$ years) or a mixture of ^{133}Ba and ^{137}Cs ($T_{1/2} = 30.1$ years) are commonly used for calibration purposes because of their longer half-life and similar spectrum when comparing as ^{131}I photon emissions (Figure 1) (Table 1).

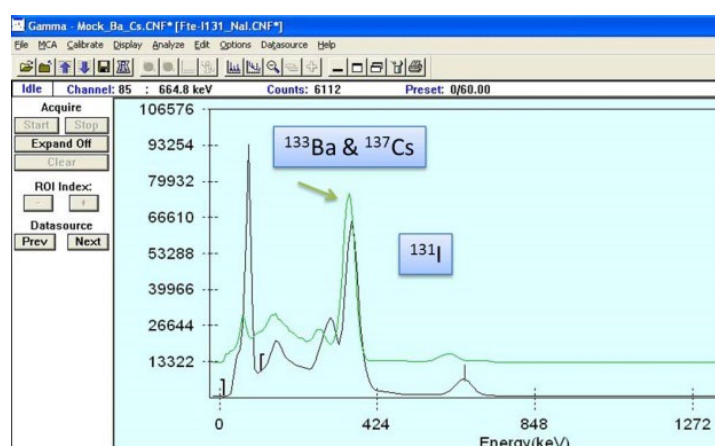


Figure 1. Comparison of NaI(Tl) detector spectra corresponding to mock ^{133}Ba & ^{137}Cs and ^{131}I

Table 1. Photon emissions and yield for ^{131}I and ^{133}Ba & ^{137}Cs

^{131}I ($T_{1/2} = 8.01$ d)		^{133}Ba ($T_{1/2} = 10.51$ y)		^{137}Cs ($T_{1/2} = 30.07$ y)	
E (keV)	Ie (%)	E (keV)	Ie (%)	E (keV)	Ie (%)
80.18	2.62	80.99	34.06		
284.30	6.14	276.398	7.164	283.53	0.00058
		302.85	18.33		
364.49	81.7	356.017	62.05		
		383.85	8.94		
636.98	7.17	160.613	0.645	661.66	85.1

The substitution of ^{131}I with ^{133}Ba and ^{137}Cs for calibration purpose can be justified in both spectroscopic and non-spectroscopic equipment. In the case of spectroscopic instruments, it is sufficient to consider the energies and emission probabilities of the primary emissions of ^{131}I (364.5 keV) and ^{133}Ba (356 keV), which is why some laboratories use only this isotope for calibration. On the other hand, for non-spectrometric equipment, a mixture of ^{133}Ba and ^{137}Cs in an appropriate ratio must be used to simulate the spectrum of ^{131}I across the entire emission energy range (from 80 to 637 keV). Additionally, the higher emission probability of barium X-rays compared to those of iodine must be considered. The CATHYMARA project (Broggio *et al.*, 2019) addressed these issues to evaluate the accuracy and reliability of thyroid dose measurements in both adults and children, with spectroscopic (Lebacqz *et al.*, 2019) and non-spectroscopic devices (M. Isaksson *et al.*, 2019). It is important to highlight that gamma cameras, based on NaI(Tl) detector crystals, allow the creation of energy windows around a photopeak. Therefore, ^{131}I or ^{133}Ba as surrogate of ^{131}I , can be used for their calibration to perform in vivo measurements of radioiodine in the thyroid of exposed population (children and adults). Gamma cameras not only demonstrate excellent sensitivity but also high precision in activity quantification, with negligible dependence on the model used (Dantas et al., 2007, Navarro et al., 2019).

In vivo monitoring laboratories usually use adult thyroid phantoms for the calibration of the detectors for the measurement of ^{131}I in thyroid of exposed workers. The ANSI adult phantom (ANSI/HPS N13.44, 2014) can be considered as a reference phantom for adult monitoring. However, when measurements need to be conducted on children of different ages, it is essential to account for the differences in thyroid volume between adults and children. These values vary from a few cm^3 in young children to approximately 20 cm^3 in adults. Furthermore, there are no established specific standards for designing age-dependent phantoms. Only a few laboratories manufacture age-dependent phantoms to be used in emergency situations when exposure of members of the public may take place.

The 2020 updated Strategic Research Agenda (SRA) of the European Radiation Dosimetry Group (EURADOS), recommends improving the calibration of in vivo monitoring techniques for children, particularly in case of radiological emergencies (Harrison *et al.*, 2021). In this regard, it is essential to focus on the development and validation of age-scaled reference calibration phantoms, alongside the optimization of counting geometries and detection sensitivity, to ensure more accurate and reliable measurements. An action has been carried out by the WG7 Task Group “Internal Dosimetry for Emergency”, in the frame of the research program of the European Radiation Dosimetry Group (EURADOS e.V.). This action, coordinated by CIEMAT (Spain), aims to compare age-dependent thyroid phantoms available around the world, using the same detection system for calibration purposes, in order to obtain age-dependent counting efficiency values for different geometries of measurements.

2. General Organisation of the Intercomparison exercise

The intercomparison exercise for different age-dependent neck thyroid phantoms (children and adults) has been carried out at the WBC laboratory from CIEMAT using the same detection system (Broad Energy Germanium Detector) in order to achieve a better analysis of the differences among the phantoms from the participating laboratories. Prior to commencing the exercise, invitation letters were sent to in vivo measurement laboratories worldwide that might be interested in participating, under the condition that they could provide not only adult but also children thyroid phantoms (Annex I). Technicians from each participating laboratory were invited to visit the CIEMAT facilities to carry out the intercomparison measurements themselves. If they were unable to attend, the realisation of these measurements was delegated to the CIEMAT technicians.

Along with the invitation letter, a technical questionnaire was also sent to the laboratories for gathering information about their availability for performing measurements, phantoms, calibration sources, detectors, geometries of measurement, sensitivity of detection, etc. (Annex II).

Seven laboratories were enrolled to participate in the exercise (Table 2). Unfortunately, other interested laboratories did not have the required thyroid phantoms for children and therefore could not be enrolled.

Table 2. List of the participating laboratories

Institution	City	Country	Contact person
SCK CEN (Belgian Nuclear Research Centre)	Mol	Belgium	J. Boeckx (*) A.L. Lebacqz
SÚRO (National Radiation Protection Institute)	Prague	Czech Republic	V. Rovenska (*) P. Fojtik
STUK (Radiation and Nuclear Safety Authority)	Helsinki	Finland	T. Torvela
IRSN (Institut de Radioprotection et de Sûreté Nucléaire)	Fontenay-aux-Roses	France	T. Beaumont D. Broggio
BfS (Bundesamt für Strahlenschutz)	Neuherberg	Germany	S. Helbig O. Meisenberg
CIEMAT (Contador de Radiactividad Corporal)	Madrid	Spain	J.F.Navarro B.Pérez
QST (National Institutes for Quantum Science and Technologies)	Chiba	Japan	M. Kowatari

(*) Measurements performed by technicians from participating laboratories.

As presented in section 4, a measurement protocol was designed and agreed with the participants. Due to the global COVID crisis, there were delays in the implementation of the scheduled measures. The intercomparison started in July 2021 and finished in January 2023. After that, all the data collected in the technical questionnaire and the results of the measurements were compiled for analysis and agreed with participating laboratories.

3. Materials and Methods.

3.1 Detection System at the CIEMAT whole body counter laboratory.

The facility, where the measurement system is located, consists of a shielded chamber having low radioactive background with inner dimensions of 2.43 m x 2.43 m x 1.97 m, with 13 cm steel walls lined with Pb (5 mm), Cd (1 mm) and Cu (1 mm) allowing to reduce the environmental background and then improving the sensitivity of detection.

The detection system consists of a broad energy germanium detector BEGe (Figure 2) with an excellent resolution and good efficiency in the energy range of 10 keV to 2000 keV. The BEGe detector has a diameter of approximately 91 mm, a thickness of 31 mm, and an active surface area of 6500 mm². Detection efficiencies and energy resolutions are optimized in the 3 keV to 662 keV energy range. Therefore, it is suitable for in-vivo measurements of radioiodine in the thyroid. It has a thin window made of "Carbon Epoxy", which is typical for low-background applications. The detector is encapsulated in low-radioactive background materials (copper, steel, etc.) which significantly reduce Compton scattering. Each detector is connected to an independent cryostat that cools the system to a constant temperature of 77 K. Each detector is connected to a DSA-LX covering an energy range between 0 and 1000 keV.

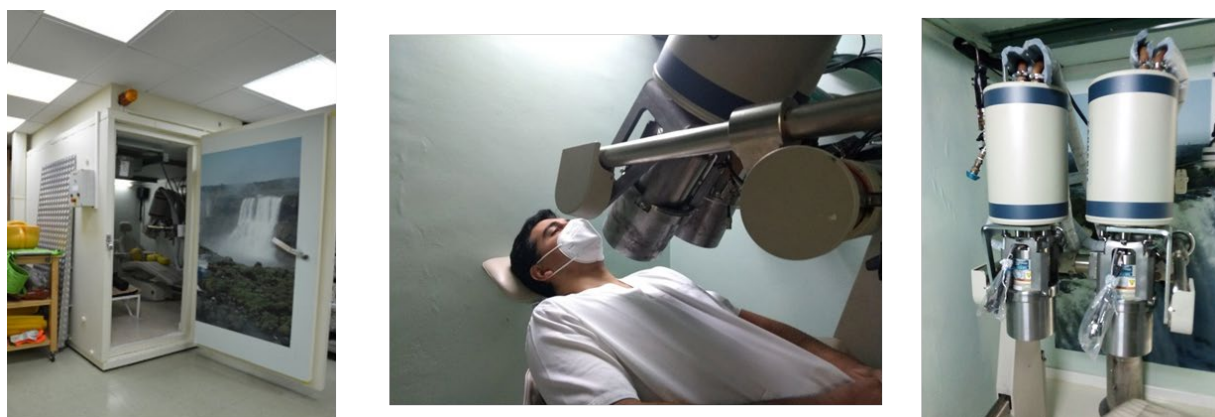


Figure 2. Thyroid measurement detection system (BEGe) at the CIEMAT WBC Laboratory

3.2 Age-Dependent Thyroid Neck Phantoms

The participating laboratories in the intercomparison exercise were encouraged to send to CIEMAT WBC laboratory their thyroid neck phantoms and radioactive calibration sources for calibration purposes, as well as blank vials filled with distilled water for calculating detection limits, following a previously agreed-upon schedule. As shown in Table 3, all the participants have one or more adult phantom, however not all of them have settings for each age group of both children and teenagers.

Table 3. Age-dependent thyroid neck phantom configurations from the participating laboratories

Institution	Age-dependent phantoms	Overlying tissue thickness (mm)	Calibration sources	Active thyroid volume (ml)	References
SCK CEN (Belgium)	1-y-old; 5-y-old (child) 10-y-old; 15-y old (teenager) adult (small, medium, large) Plexiglas (PMMA) (ICRP, 1975) (Karachalias, 2013)	8 mm (1y) 10 mm (5y) 12 mm (10y) 14 mm (15y) 19 mm (adult)	^{133}Ba Pairs of vials	1.7 ml to 19 ml ICRP89	
SÚRO (Czech R.)	3-6y-old child (low, high) (*) 11-15y-old teenager (low, high) Adult (low, medium, high) Styren (*) low and high represent individuals who are less or more robust within the same age group	3 mm (3-6y)low 12 mm (3-6y)high 4,5 mm (11-15y)low 11,5 mm (11-15y)high 5,5 mm low adult 15,5 mm medium adult 22,5 mm large adult	^{133}Ba Pairs of vials	4,8 ml to 20,2 ml ICRP89	
STUK (Finland)	6-y-old child; Adult (std male) high-density polyethylene (HDPE)	6,2 mm (6y) 9.1 mm (adult)	^{133}Ba Pairs of vials	3,8 ml (6y) 17,7ml (adult) ICRP 89	
IRSN (France)	5-y-old child, 10-y-old; 15-y old teenager; Adult (standard male) (Beaumont <i>et al.</i> , 2017)	4 mm (5y) 4,5 mm (10y) 4,8 mm (15y) 5 mm (adult)	^{133}Ba 3D-print thyroid	3.24 ml 7.52 ml 11.43 ml 19.05 ml (ICRP 89) Phantoms (translucent resin - VeroClear) and filled	 

BfS (Germany)	Phantom 1: three pairs of holes are used for simulating children and standard adult. Phantom 2: two pairs of holes for simulating large adults PMMA (ICRP, 1975)	4,5 to 10 mm young people age 4 to 15 y 11 mm to 29 mm adults	^{133}Ba Pairs of vials	20 ml  children& adults	
CIEMAT (Spain)	1-y-old; 5-y-old (child) 10-y-old; 15-y old (teenager) Adult (standard male & female) Lucite (PMMA) (Pérez et al., 2018)	2,1 mm (1y) 3 mm (5y) 4,2 mm (10y) 5,4 mm (15y) 5 mm (adult)	^{133}Ba ^{137}Cs Single vials	1,8 ml to 20 ml ICRP 89	
QST (Japan)	3-months-old child; 5-y-old child; Adult (standard male) PMMA filled with distilled water	15 mm (3th month) 13,5 mm (5y) 35 mm (adult)	^{133}Ba Single vials and point source	1 ml vial or point source 	

All laboratories involved in the intercomparison have submitted detailed information on their calibration phantoms and the manufacturing process. This information is presented in the subsequent subsections of this chapter.

3.2.1 SCK CEN thyroid phantoms.

The neck phantom for simulating adults (Figure 3) consists of a cylinder of diameter 130 mm and height 120 mm, made of plexiglas (Staf RX® PMMA G), with three pairs of holes to accommodate the pairs of vials that represented different thyroid sizes (small, medium and large adult). The thickness of the material between the holes and the phantom's peripheral surface was selected based on age and body composition to realistically represent the overlying tissue layer of the human neck. In the same way, another neck phantom (Figure 4) with a diameter of 100 mm and height 120 mm was used, with four pair of holes for simulating 15-years-old teenager, 10-years-old teenager, 5-years-old child and a 1-year-old child (Karachalias, 2013).



Figure 3. Thyroid neck phantom for adults (3 different configurations)

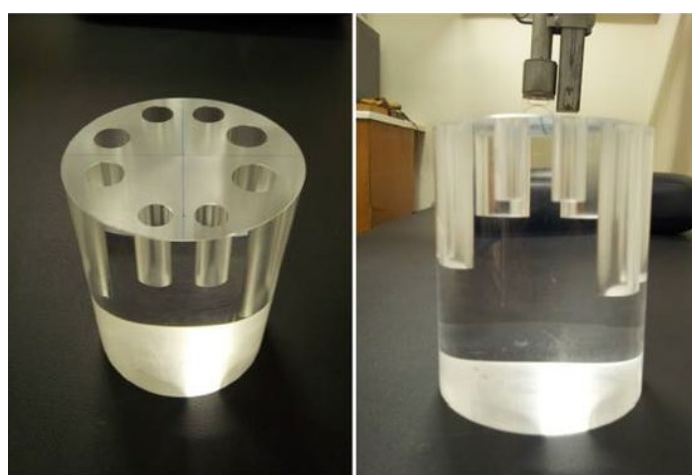


Figure 4. Thyroid neck phantom for children and teenagers (1-y, 5-y, 10-y and 15-y)

A pair of vials filled with a radioactive solution of ^{133}Ba was prepared for each age group for simulating the two lobes of a contaminated thyroid gland (the isthmus was considered to be negligible) (Figure 5). The choice of vials was made according to availability and in a way that the shape of each lobe was as realistic as possible (active height larger than the lobe diameter). Values for the thyroid mass are based on extensive statistical studies according to ICRP recommendations (ICRP, 2002). Water was used as matrix, having almost the same specific gravity as the thyroid gland. Thyroid volumes were derived from the thyroid mass using the specific gravity of 1.05 g/ml given by ICRP (Table 4). Additionally, blank vials with distilled water were prepared for calculating detection limits.

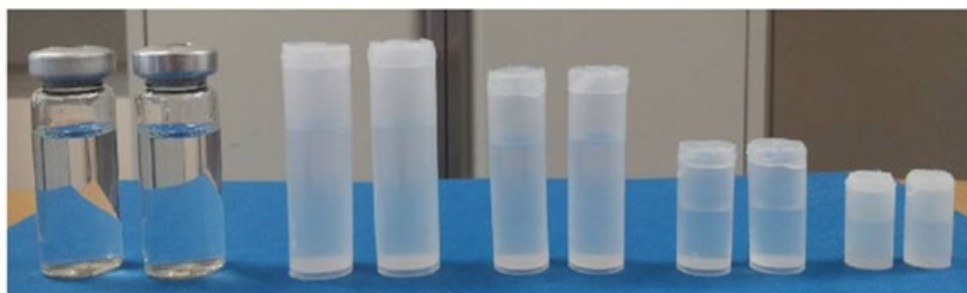


Figure 5. Vials for simulating different thyroid sizes (children & adults)

Table 4. Thyroid volume derived from the thyroid mass for different SCK-CEN phantoms

	1-y phantom	5-y phantom	10-y phantom	15-y phantom	ADULT phantom
Volume	1.7 ml	3.2 ml	7.5 ml	11.4 ml	19.0 ml

To represent the depth of the thyroid gland in a realistic way, the thickness of the overlying tissue layer (T) was gradually increased from that of a 1-year-old child to that of adults (adult1, adult2 and adult3 correspond to different degrees of corpulence) (Figure 6). The selection of these thickness values for the overlying tissue layer is based on studies published by ICRP (ICRP, 1975) and the IAEA (IAEA, 1996)

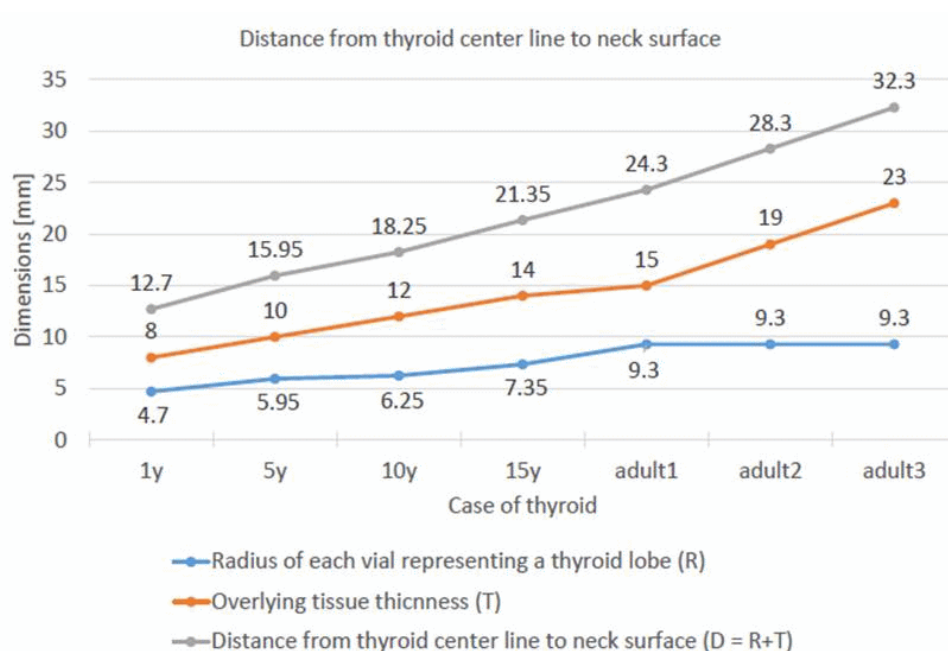


Figure 6. Overlying tissue thickness (T) for all neck-thyroid phantom configurations

A cross section of a neck phantom is depicted in figure 7 including the radius R of each hole (thyroid lobe), the thickness of the overlying tissue layer (T).

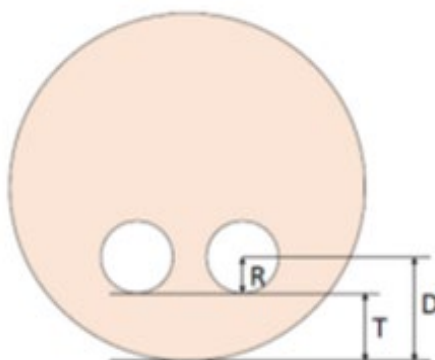


Figure 7. Cross section of a neck phantom

3.2.2 BfS thyroid phantoms.

The BfS neck phantoms for simulating children, teenagers, standard adults (Figure 8A) and large adult configurations (Figure 8B) consist of PMMA cylinder of 120 mm diameter and 220 mm height. The choice of phantom dimensions is based on ICRP publications (ICRP 23, 30 & 38 report) as a basis and a thesis done at Johann Wolfgang Goethe University (S. Helbig, personal communication, July 2025). The BfS phantom set is not age-dependent. It's based on the distance between source and neck/phantom surface that could establish a relation between this distance and the age of the measured person.

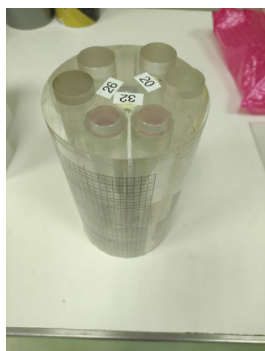


Figure 8A. Bfs children, teenagers and adult phantom

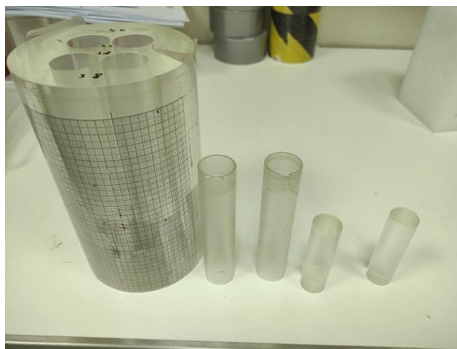


Figure 8B. Bfs large adult phantom

As shown in the figure 9 (relate to figure 8A phantom), three pairs of holes are used for simulating gland thyroid in order to represent different configurations from children and standard adult. In the same way, (Figure 8 B), two pairs of holes are used for simulating thyroid gland from large adults.

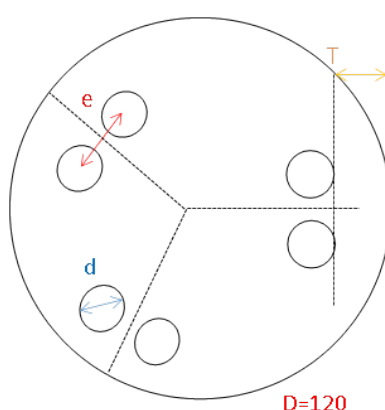


Figure 9. Definition of "e", "d" and "T" parameters (mm)

Table 5 shows dimensions of the thyroid phantoms according to the parameters defined above. $T + d/2$ (20, 26, 32, 38, 44 mm) represents the "thyroid depth" for calibration). In emergency situations BfS use the 20-mm-calibration for children. The thickness of the overlying tissue layer (T) is derived from ICRP 23 (ranged from 5 to 29 mm) (ICRP, 1975). A tissue thickness of 5 cm to 1 cm is specified for young people aged 4 to 15. The selected thyroid volume is based on the ICRP 23 and the mean mass and density specified there. The ICRP 23 report specifies an average mass of 17 g for adult

females and 20 g for adult males. According to the literature, the density is between 1.036 g/cm^3 and 1.066 g/cm^3 . The thickness of the overlying tissue (T) and the thyroid values are also derived from ICRP 23.

Table 5: Dimensions of the thyroid phantoms

Parameter	Size (mm)				
T + d/2	20	26	32	38	44
e	32	32	32	32	32
d	30				
T	5	11	17	23	29

Two active vials (10 ml volume each of them) for simulating both lobes of the thyroid gland with ^{133}Ba for calibrating all the configurations (Figure 10).



Figure 10. ^{133}Ba active vials

3.2.3 SURO thyroid phantoms.

The SURO neck phantoms for simulating children, teenagers, and adults consist of three proprietary age-dependent phantoms (three age-groups) made of Styrene with a pair of holes to insert two removable cylindrical radioactive sources for simulating thyroid lobes (Figure 11). For calibration purposes, a radioactive solution of ^{133}Ba has been used to provide different activities for each age group. The material of the sources is PMMA (Vial) and silicone rubber (filling).



Figure 11. SURO 3-6-y (low, high), 11-15-y (low, high), adult (low, medium, high)

Dimensions and positioning of the phantom and sources are presented in Table 6

Table 6. SURO Phantoms: dimensions & source positioning

Central position of sources					
SURO Phantom	Position	Rear depth (mm)	Center depth (mm)	Front depth (mm)	Source diameter (mm)
3 - 6 Y	low	19.0	11	3	15
80 mm diameter; 120 mm high	high	28	20	12	15
11-15 Y	low	21.5	13	4.5	16
100 mm diameter; 140 mm high	high	28.5	20	11.5	16
Adult	low	26.5	16	5.5	20
130 mm diameter; 160 mm high	medium	36.5	26	15.5	20
	high	43.5	33	22.5	20

Additionally, SURO has provided a Vintage Nuclear Chicago adult thyroid phantom (from 1960s) with a very realistic thyroid gland made of tissue equivalent material filled with a mixture of ^{133}Ba and ^{137}Cs still with measurable activity (not used in this study) (Figure 12).



Figure 12. Vintage Nuclear Chicago adult thyroid phantom

3.2.4 STUK thyroid phantoms.

STUK laboratory provides two modelled anthropometrical neck thyroid phantoms for reference to a 6-year-old child (T1 phantom) and adults (T3 phantom). The neck tissue model is made of high-density polyethylene (HDPE), the density of which is 0.95 g/cm^3 (Figure 13). The phantoms are activity models to be used with an anthropomorphic whole-body phantom of the respective body size, adult or child.



Figure 13. T1 & T3 Thyroid neck phantoms with source vessels.

Each neck phantom contains two cylindrical radionuclide sources symmetrically positioned on the ventral side of the neck, mimicking the two lobes of the human thyroid gland. The radionuclide source material was fabricated by precipitation with ion-exchange resin and sealed in cylindrical HPDE vessels. The sources contain ^{133}Ba radionuclide, which simulates the incorporation of ^{131}I homogeneously distributed in the thyroid gland tissue. According to the manufacturer, the linear attenuation factor of the active source matrix for gamma radiation is 3% lower than that of soft biological tissue at 400 keV, but 7–20% lower in the gamma energy range of 100–500 keV. The assembly and dimensions of the neck phantoms and source vessels are shown in Figure 14.

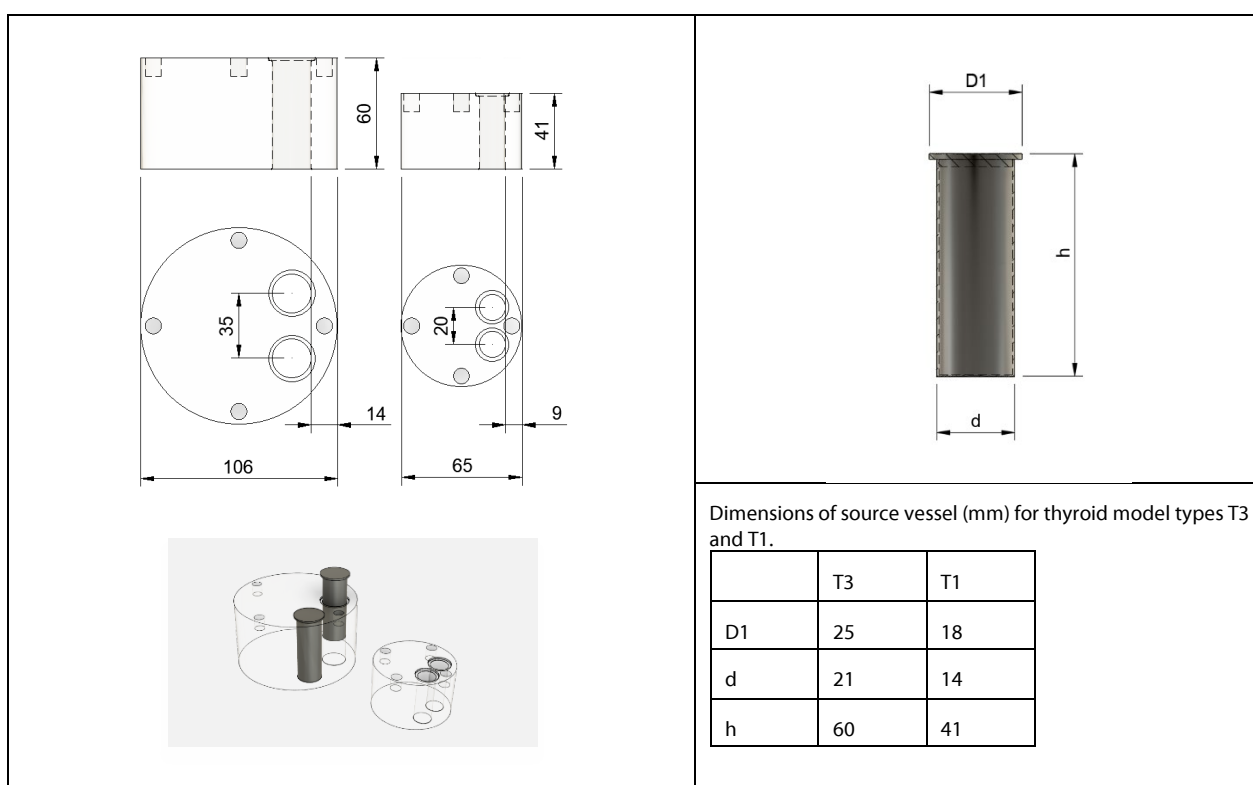


Figure 14. Type T3 (adult) and T1 (child) thyroid neck model assembly and dimensions.

The specific values of the thyroid model parameters are presented in Table 7.

Table 7. Values of thyroid model parameters (T1 & T3)

Parameter	Values of thyroid model parameters (mm)			
	TYPE 1 (6-y-old)		TYPE 3 ADULT	
	Single lobe	Both lobes	Single lobe	Both lobes
Mass (g)	2.0	4.0	9.3	18.6

3.2.5 IRSN thyroid phantoms.

IRSN developed a set of age-specific thyroid phantoms for 5, 10, 15 years old children and for the adult (Beaumont et al 2017). The phantoms have been designed with a Computer Aided Design (CAD) software and printed using a PolyJet 3D printing technology. A translucent resin (VeroClear) was used to manufacture phantoms as it allowed to mimic the adipose tissue attenuation properties. The phantoms have been designed following the ICRP thyroid volume recommendations (ICRP 2002). A mathematical model was used for the thyroid shape, it includes two ellipsoidal lobes and an isthmus cut by the trachea (Ulanovsky et al., 1997). The thyroid-neck distance, called overlying tissue thickness, was fixed after a literature review. The set of phantom includes thyroid inserts and full age-specific necks including the spinal cord and cervical spine, as shown on Figure 15.

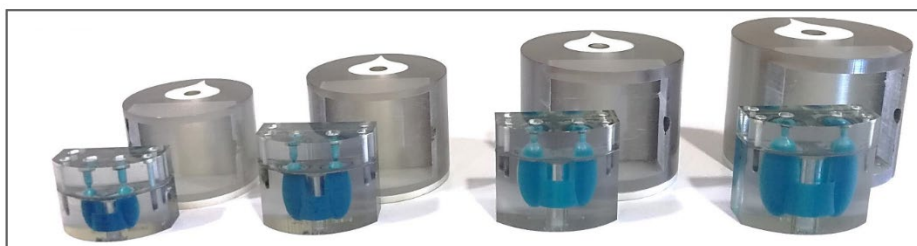


Figure 15. IRSN age dependent neck thyroid phantoms, from left to right, the thyroid volumes correspond to 5-, 10-, 15- year-old children and adult.

The main dimensions are reported in Table 8. The thyroid phantoms were filled with a ^{133}Ba radioactive solution which contains 4% of hydrochloric acid.

Table 8. Dimensions of the thyroid-neck phantoms

	5- year -old	10- year- old	15-year-old	Adult Male
Thyroid volume (cm ³)	3.24	7.52	11.43	19.05
Overlying tissue thickness (mm)	4.0	4.5	4.8	5.0
Trachea diameter (cm)	0.7	0.8	1.1	1.4
Neck radius (cm)	3.8	4.4	5.2	5.4

3.2.6 CIEMAT thyroid phantoms.

CIEMAT has a family of phantoms (Figure 16) consisting of five configurations corresponding to an adult phantom, and four phantoms for children with different ages, it means, 1, 5, 10 and 15 years old. All phantoms are made of Lucite. Each one consists in a solid cylinder, with a side drilled hole where a cylinder piece with the same material and a hole where the vial is hosted. Opposite to this side, the cylinder is truncated for improving stability when it is lying. The dimensions of each thyroid-neck phantom are presented in Table 9.

Table 9. Dimensions of the CIEMAT thyroid neck phantom set

Age (y)	Neck diameter (mm)	Neck height (mm)	Thyroid volume (ml)
1	71.0 ± 0.5	71.0 ± 0.5	1.8
5	82.0 ± 0.5	82.0 ± 0.5	3.4
10	95.0 ± 0.5	96.0 ± 0.5	7.7
15	108.0 ± 0.5	109.0 ± 0.5	12.0
Adult Female	127.0 ± 0.5	127.0 ± 0.5	17.0
Adult Male	127.0 ± 0.5	127.0 ± 0.5	20.0

Overlying tissue layer is different for each phantom, gradually increased with the age.



Figure 16. Age-dependent thyroid neck phantom set CIEMAT WBC

Vials are thyroid simulators. They are different sizes depending on the age and based on ICRP 89 report. Aqueous solution in acid medium fulfils each vial. The sources are ^{133}Ba and ^{137}Cs which gamma emissions are very closed to ^{131}I ones. (Perez et al., 2018)

3.2.7 QST thyroid phantoms.

As shown in figures 17a, 17b & 17c, the QST age-dependent thyroid neck phantoms consist of three different configurations corresponding to 3-months-old child (70 mm diameter, 54 mm height), 5-years-old child (75 mm diameter, 60 mm height) and adult (110 mm diameter, 90 mm height). Phantoms are made of tissue equivalent plastic material (PMMA), filled with distilled water and with a source holder for introducing a radioactive point source or a 1 ml vial for simulating contaminated thyroid gland. A radioactive solution of ^{133}Ba or a radioactive point source are utilized for calibration purposes. The activity and volume of the vials (1 ml) are identical for all age-dependent configurations. The thickness of the overlying tissue layer was gradually increased.



Figure 17a. QST 3th-month newborn phantom



Figure 17b. QST 5-year-old phantom



Figure 17c. QST adult phantom

3.3 Software for gamma spectrometry analysis.

The BEGe detector is connected to a DSA-LX covering an energy range between 0 and 1000 keV. Apex in vivo® (Mirion Apex) built on Genie™ 2000 spectroscopy software, was used to analyse the spectra. A screenshot of the interface is shown in Figure 18.

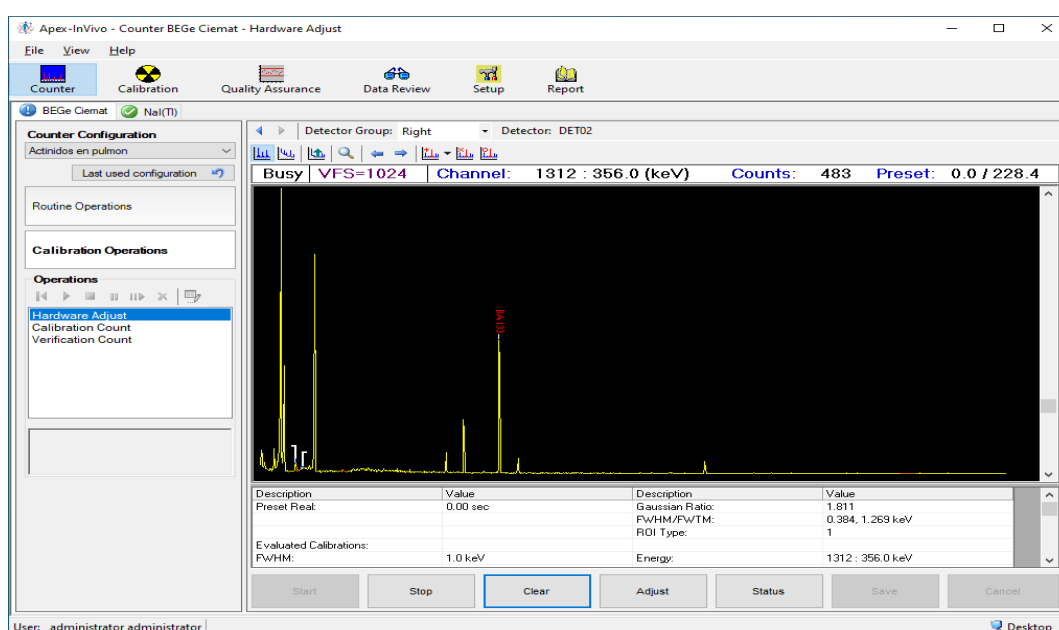


Figure 18. Mirion Apex Built on Genie™ 2000 spectroscopy software. Canberra Inc.

4. Protocol of measurements.

For performing intercomparison measurements, a protocol was designed and agreed with the participating laboratories. Each of them sent their thyroid phantoms, radioactive sources and blank vials at the Whole Body Counter laboratory of CIEMAT following a previously agreed-upon schedule. Technicians from each participating laboratory were invited to CIEMAT to conduct the measurements taking into account the special regulations and restrictions adopted due to the COVID crisis). If a laboratory declined the invitation, the measurements would instead be conducted by CIEMAT technicians. Three geometries of measurements were agreed for comparing efficiency values at short (2 cm), medium (10 cm) and long (15 cm) detector-phantom distances. Efficiency calibration for the main emission of ^{133}Ba (356 keV) was performed for each geometry of measurement and age-dependent thyroid phantom. The efficiency values were expressed according to Eq. 1 as the ratio of photons detected in the full-energy peak relative to the number emitted per unit time.

$$\varepsilon_p(E) = \frac{N_p}{A \cdot I_\gamma \cdot t} \quad (\text{Eq. 1})$$

Where:

$\varepsilon_p(E)$: is the peak efficiency at energy E .

N_p : is the number of counts in the photopeak.

A : is the activity of the source (in becquerels, Bq).

I_γ : is the gamma emission intensity (fraction or probability of emission at energy E).

t : is the counting time (in seconds).

The counting time for calculating efficiencies could be adapted depending on statistics of measurements in order to decrease uncertainties.

In order to calculate minimum detectable activity (MDA) (Currie et al., 1968), blank phantom measurements were carried out with blank vials as surrogate of the non-contaminated thyroid. A fixed counting time of two minutes was agreed for comparing values. A specific excel sheet was created and distributed for each participant for collecting all information concerning the intercomparison measurements (Annex III; Annex IV).

5. Results of the intercalibration exercise.

5.1 Technical Questionnaires.

Before conducting the exercise, a technical questionnaire for gathering information was distributed to all participating laboratories.

- Information was requested regarding laboratory management (contact persons, technicians responsible for measurements, availability to send thyroid neck phantoms to CIEMAT).
- Description of age-dependent neck-thyroid phantoms
 - manufacturer, materials, dimensions,
 - age-dependent neck-thyroid phantoms available,
 - dimensions of the vials for thyroid simulation,
 - calibration sources, measurement geometries, detection systems, spectroscopy software, etc.

This section gives a summary of the main data provided by the participants:

Table 10 shows the different age-dependent neck thyroid phantom configurations for each participant. All the labs have one or more settings for adults. However, not all laboratories have all settings for children in different age groups.

Table 10. Age-specific neck thyroid phantom configurations

Laboratory	3th month phantom	1 y phantom	3-6 y phantom	5 y phantom	6 y phantom	10 y phantom	11-15 y phantom	15 y phantom	ADULT Phantom
BfS (Germany)			Yes						Yes No specified
IRSN (France)				Yes		Yes		Yes	Yes Std Male
SCK CEN (Belgium)		Yes		Yes		Yes		Yes	Yes Small Medium Large
STUK (Finland)					Yes				Yes Std Male
SURO (Czech R.)			Yes Low High				Yes Low High		Yes Low, Medium High
CIEMAT (Spain)		Yes		Yes		Yes		Yes	Yes Std Female Std Male
QST (Japan)	Yes			Yes					Yes Std Male

Tables 11 and 12 present a detailed overview of neck diameters and heights corresponding to various participant configurations.

Table 11. Neck diameter (mm) for all the age-specific neck thyroid phantoms

Laboratory	3th month phantom	1y phantom	3-6 y phantom	5y phantom	6y phantom	10y phantom	11-15y phantom	15y phantom	ADULT phantom
BfS (Germany)		120							120
IRSN (France)				76		88		104	108
SCK CEN (Belgium)		100		100		100		100	130
STUCK (Finland)					65				110
SURO (Czech R.)			80				100		130
CIEMAT(Spain)		71		82		95			127
QST (Japan)	70			75					110

Table 12. Neck height (mm) for all the age-specific neck thyroid phantom

Laboratory	3th month phantom	1y phantom	3-6 y phantom	5y phantom	6y phantom	10y phantom	11-15y phantom	15y phantom	ADULT Phantom
BfS (Germany)			200						200
IRSN (France)				54		66		77	84
SCK CEN (Belgium)		120		120		120		120	140
STUK (Finland)					41				60
SURO (Czech R.)			120				140		160
CIEMAT(Spain)		71		82		100		110	127
QST (Japan)	54	60							90

The overlying tissue thickness may be one of the most critical factors to consider in phantom design. The variations in values noted within identical age groups could potentially influence the calculated efficiency values. Table 13 shows the different values for each age-dependent phantom corresponding to each participating laboratory.

Table 13. Overlying tissue layer (mm) for all the age-specific neck thyroid phantom

Laboratory	3th month phantom	1y phantom	3-6 y phantom	5y phantom	6y phantom	10y phantom	11-15y phantom	15y phantom	ADULT Phantom
BfS (Germany)		(*)							
IRSN (France)				4		4.5		4.8	5
SCK-CEN (Belgium)		8		10		12		14	15 small 19 medium 23 large
STUCK (Finland)					6.2				9.1
SURO (Czech R.)			3 low 12high				4.5 low 11.5 high		5.5 low 15.5 medium 22.5 high
CIEMAT (Spain)		2.1		3		4.2		5.4	5
QST (Japan)	15			13.5					35

(*) The overlying tissue layer thickness (T) is derived from ICRP 23 (ranged from 5 to 29 mm) (Figure 9). Tissue thicknesses of 5 cm and 11 cm are specified for individuals aged 4 and 15, respectively.

Another significant parameter, that could impact the efficiency, is the thyroid volume across different age groups (Table 14). Several laboratories utilize volumes according to ICRP 89 document or values that closely align with it. However, other laboratories keep the same volume for all age groups.

Table 14. Active thyroid volume (ml) for all the age-specific neck thyroid phantom

Laboratory	3th month phantom	1 y phantom	3-6 y phantom	5 y phantom	6y phantom	10 y phantom	11-15y phantom	15 y phantom	ADULT phantom
BfS (Germany)		20							
IRSN (France)				3.2		7.5		11.4	19.0
SCK CEN (Belgium)		1.7		3.2		7.5		11.4	19.0
STUCK (Finland)					4 g -> 3.8ml				18.6 g -> 17.7 ml
SURO (Czech R.)			2x2.4				2x5,1		2x10.1
CIEMAT(Spain)		1.8		3.4		7.7		12	20
QST (Japan)	1ml or point source			1ml or point source					1ml or point source

Additionally, the method of simulating the thyroid and the activity of the sources used for the different phantoms have been studied. As shown in the graphs below, five laboratories used different source geometry to simulate thyroid contamination for each age group whereas two laboratories used the same radioactive sources for all their phantoms, both in children and adults (Figure 19).

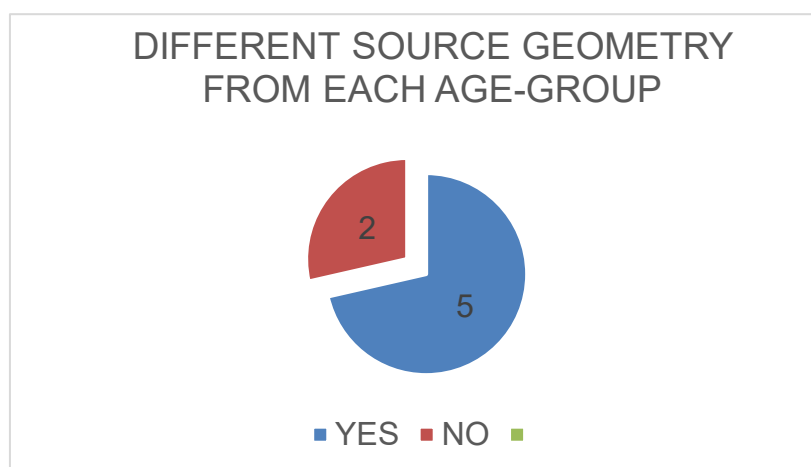


Figure 19. Number of laboratories using different source geometry for different age group

Additionally, five laboratories employ two vials to depict both thyroid lobes of the thyroid gland, whereas two laboratories using a single vial for simulating the thyroid gland (Figure 20).

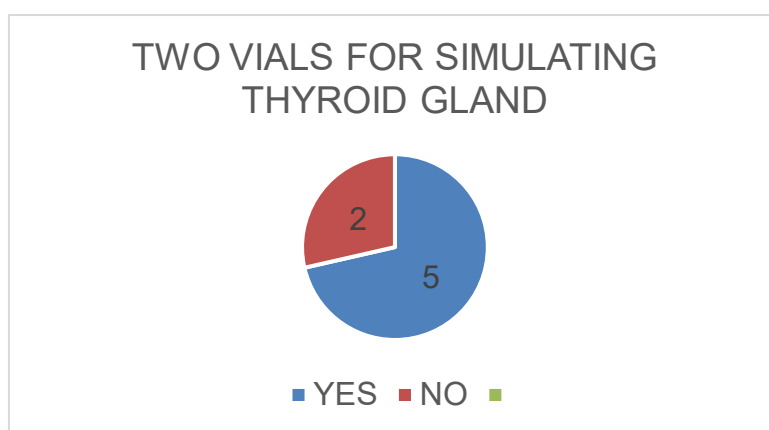


Figure 20. Number of laboratories simulating the thyroid gland using two vials.

5.2 Age-dependent thyroid phantoms: Efficiency values from each participating laboratory

Each of the participating laboratories provided their thyroid phantoms, as well as the radioactive calibration sources. For each neck thyroid configuration, efficiency values (ϵ_p) for the main emission of ^{133}Ba (356 keV) were evaluated at the three detector-phantom distances (d) of measurement agreed (short, medium and high) are presented below (Figures 21 to 27)

5.2.1 SCK CEN.

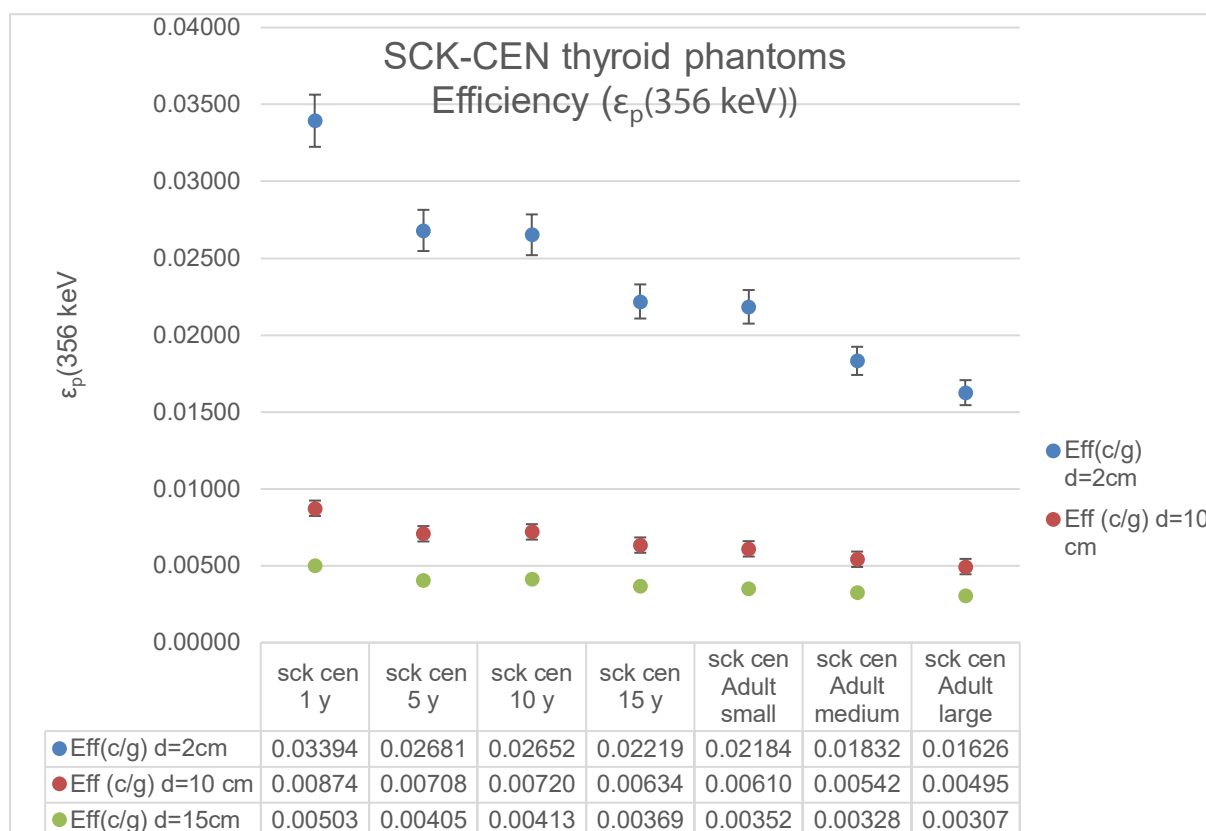


Figure 21. Efficiency values at short, medium and long detector-phantom distance

5.2.2 BfS.

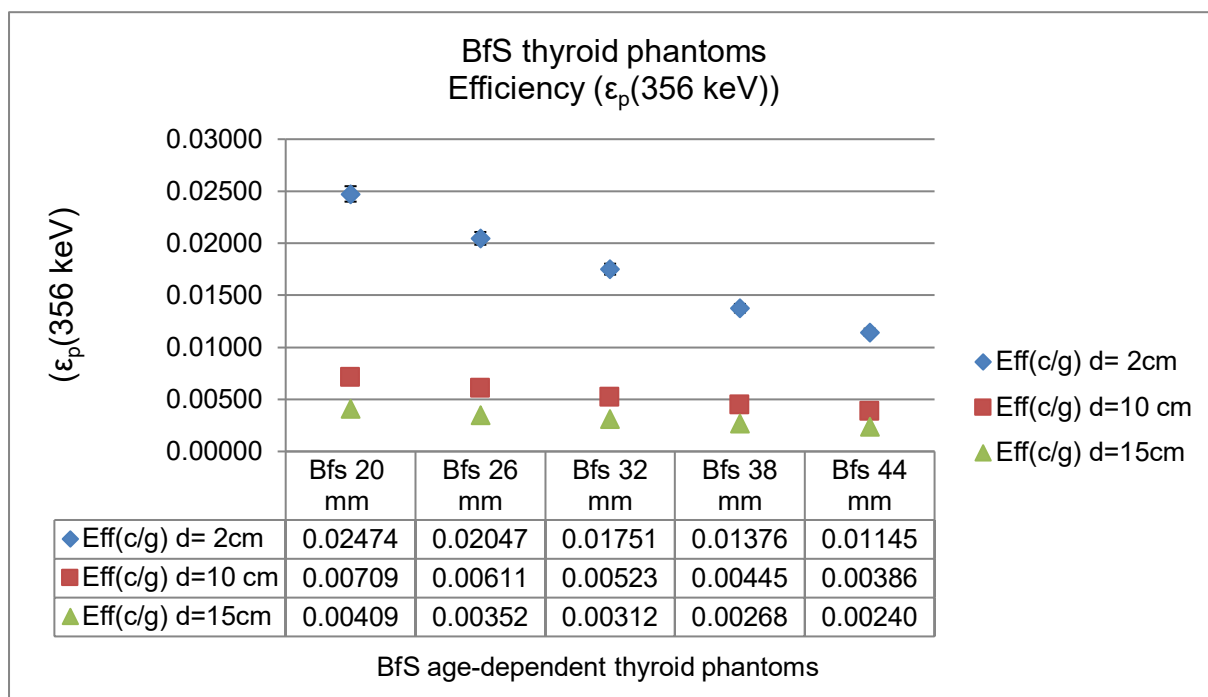


Figure 22. Efficiency values at short, medium and long detector-phantom distance

5.2.3 SURO

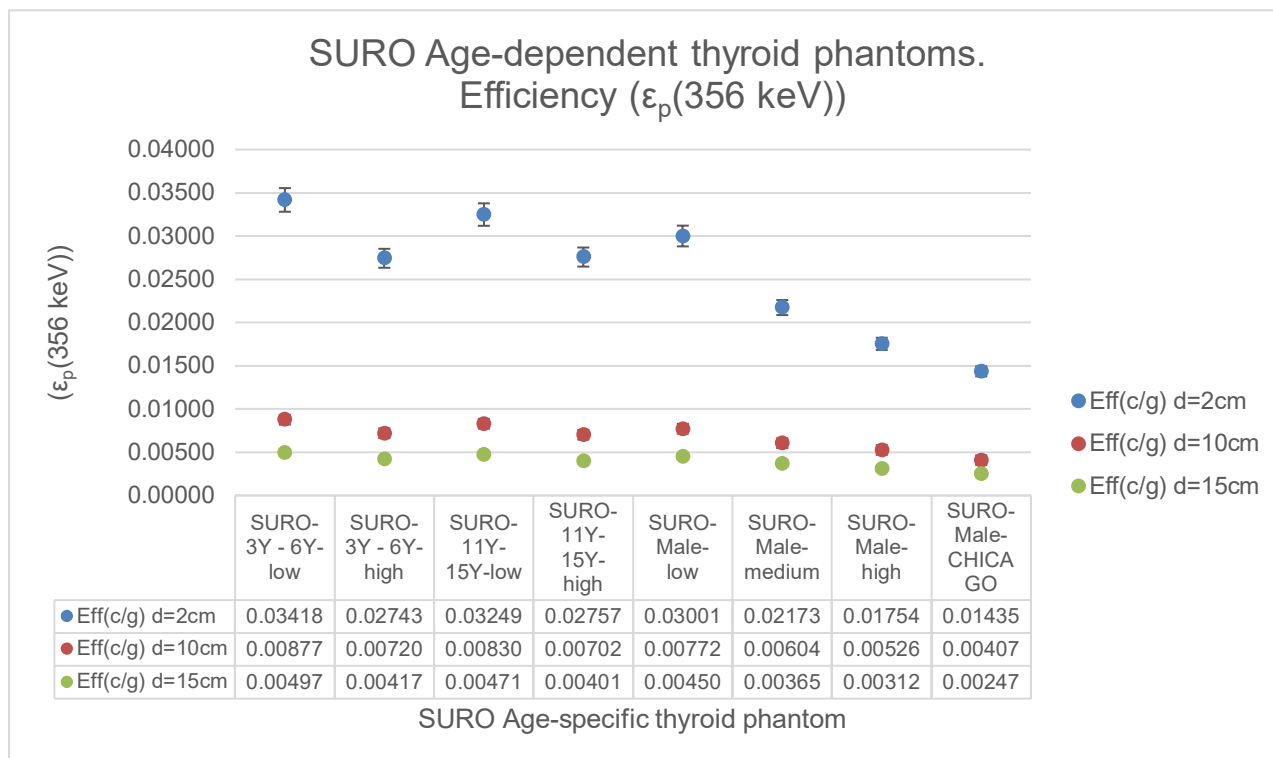


Figure 23. Efficiency values at short, medium and long detector-phantom distance

5.2.4 STUK

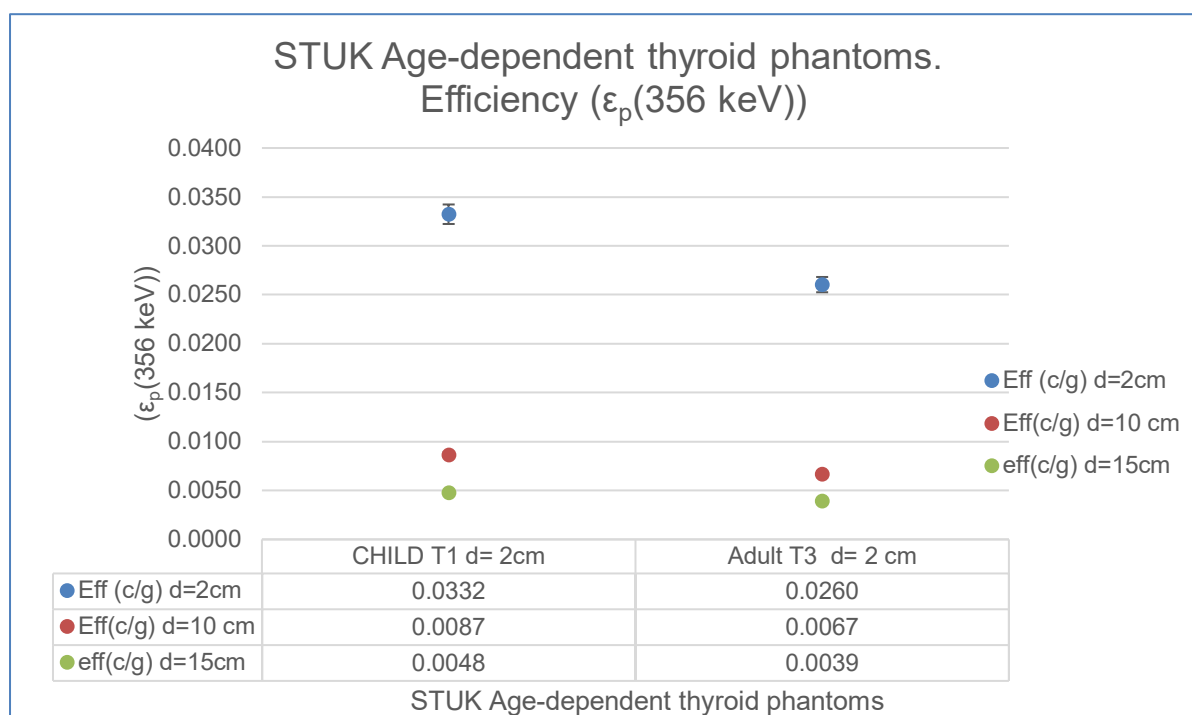


Figure 24. Efficiency values at short, medium and long detector-phantom distance

5.2.5 IRSN

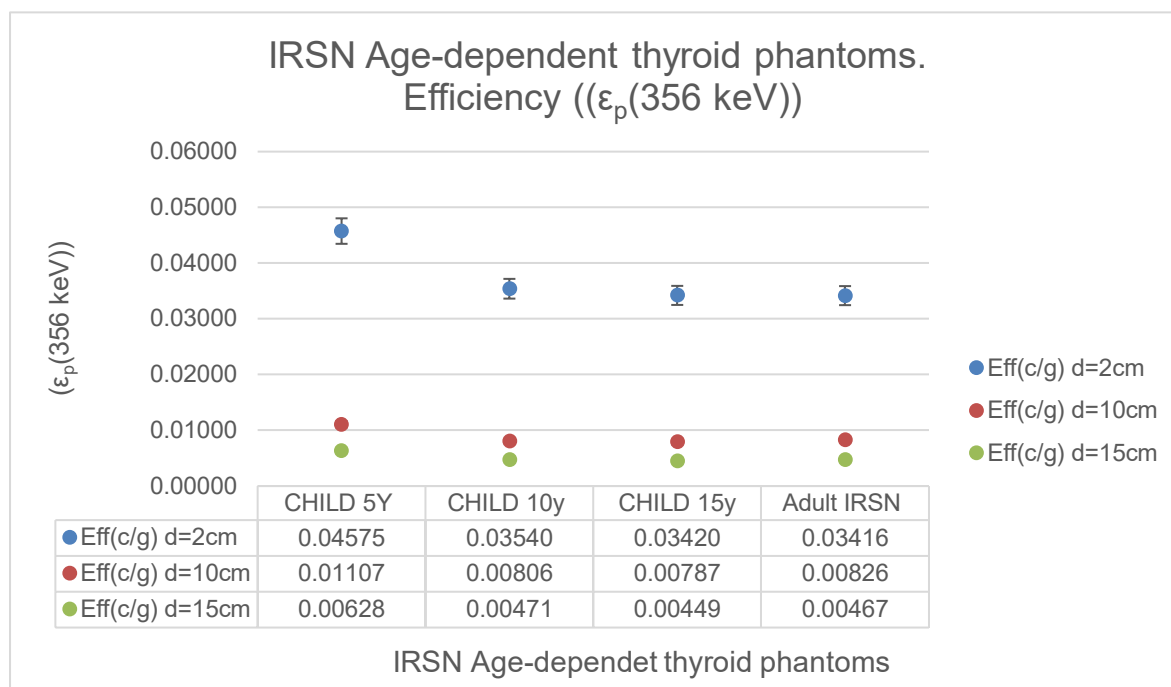


Figure 25. Efficiency values at short, medium and long detector-phantom distance

5.2.6 CIEMAT

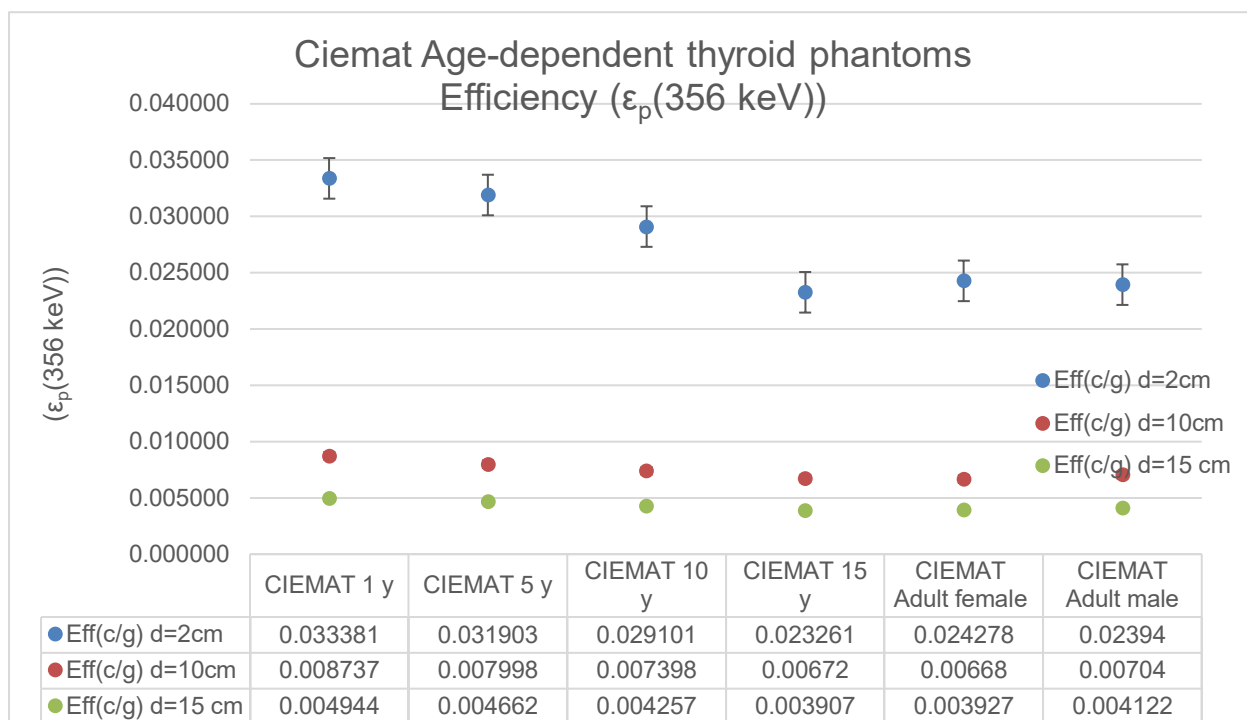


Figure 26. Efficiency values at short, medium and long detector-phantom distance

5.2.7 QST

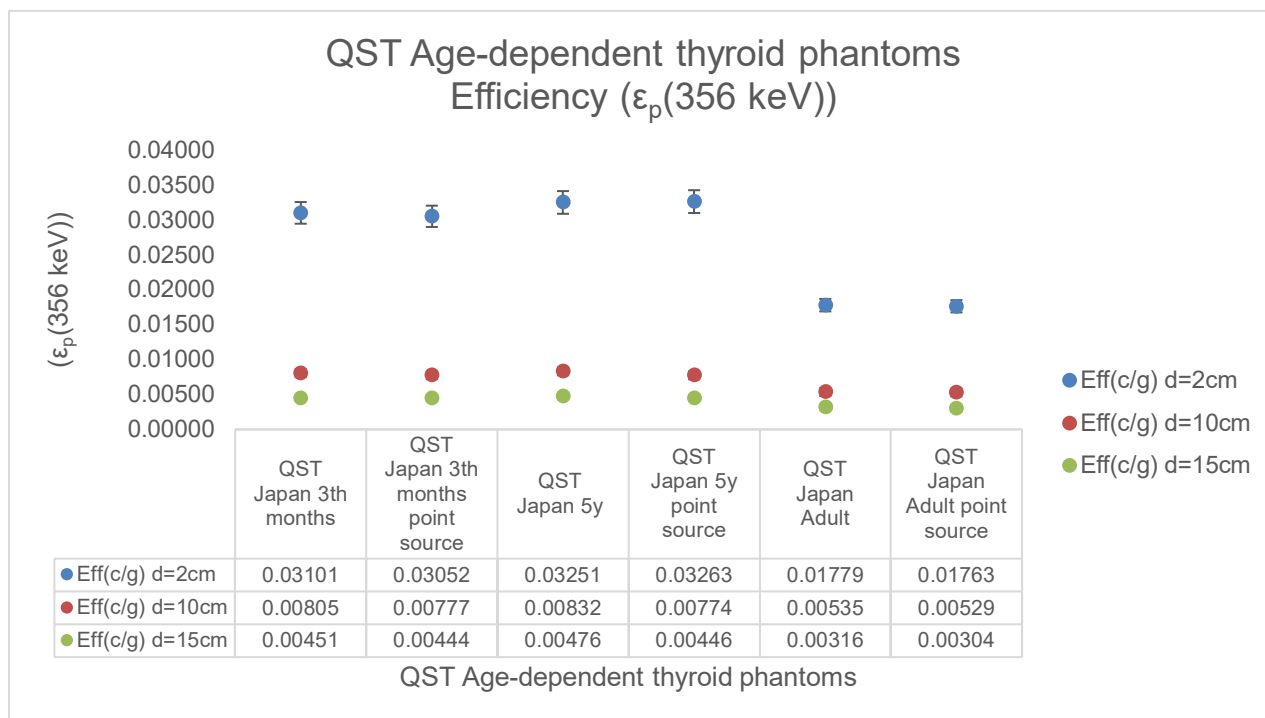


Figure 27. Efficiency values at short, medium and long detector-phantom distance

5.3 Detection limits

The minimum detectable activity (MDA) represents the lowest level of activity that can be reliably distinguished from background radiation with a given level of confidence. (Currie, 1968). It is a key parameter in radiation measurements, as it defines the sensitivity limit of a detection system and influences the reliability of quantitative analyses. Understanding and accounting for MDA in thyroid simulations ensures that measurements remain within acceptable uncertainty limits, ultimately improving the comparability of results between different laboratories. Detection sensitivity is highly dependent on the detection system, environmental background, efficiency, measurement counting time and the target individual or phantom used. In this study, following the established protocol, blank phantom measurements were carried out with blank vials as surrogate of the non-contaminated thyroid. A fixed counting time of 600 seconds was agreed for comparing values. The MDA values for ^{133}Ba , expressed in becquerel (Bq), corresponding to the participating laboratories which sent blank vials are presented below (Figures 28 to 32).

5.3.1. SCK CEN

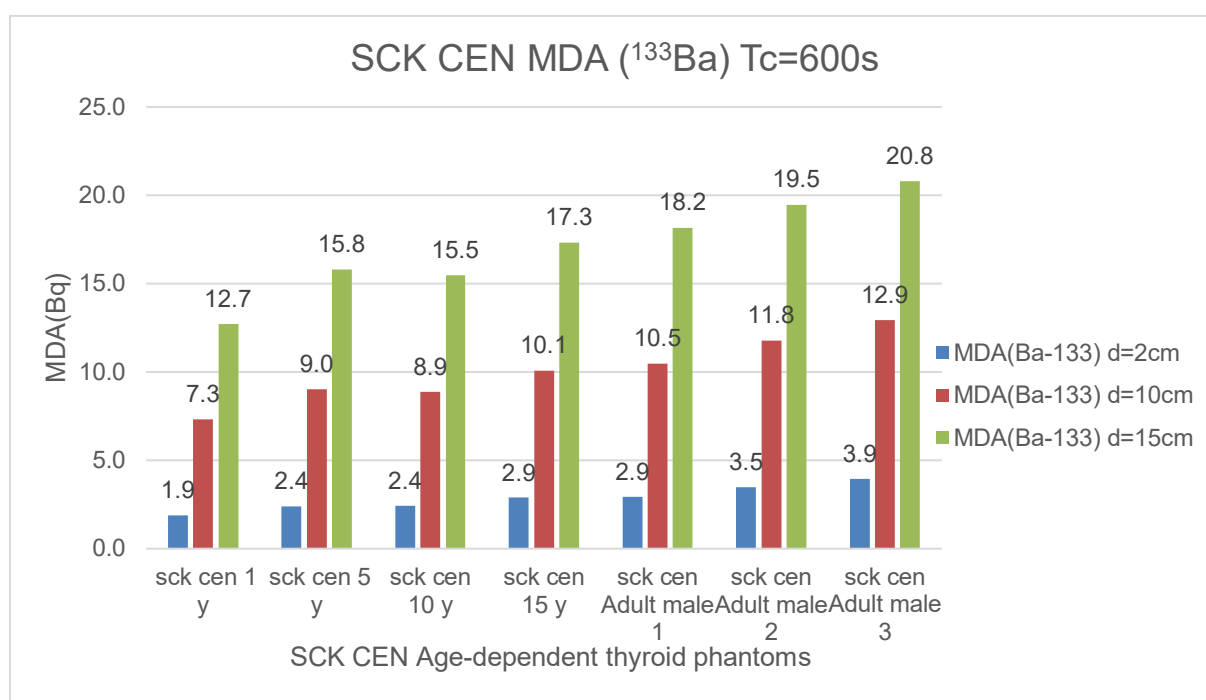


Figure 28. MDA values at short, medium and long detector-phantom distance

5.3.2. SURO

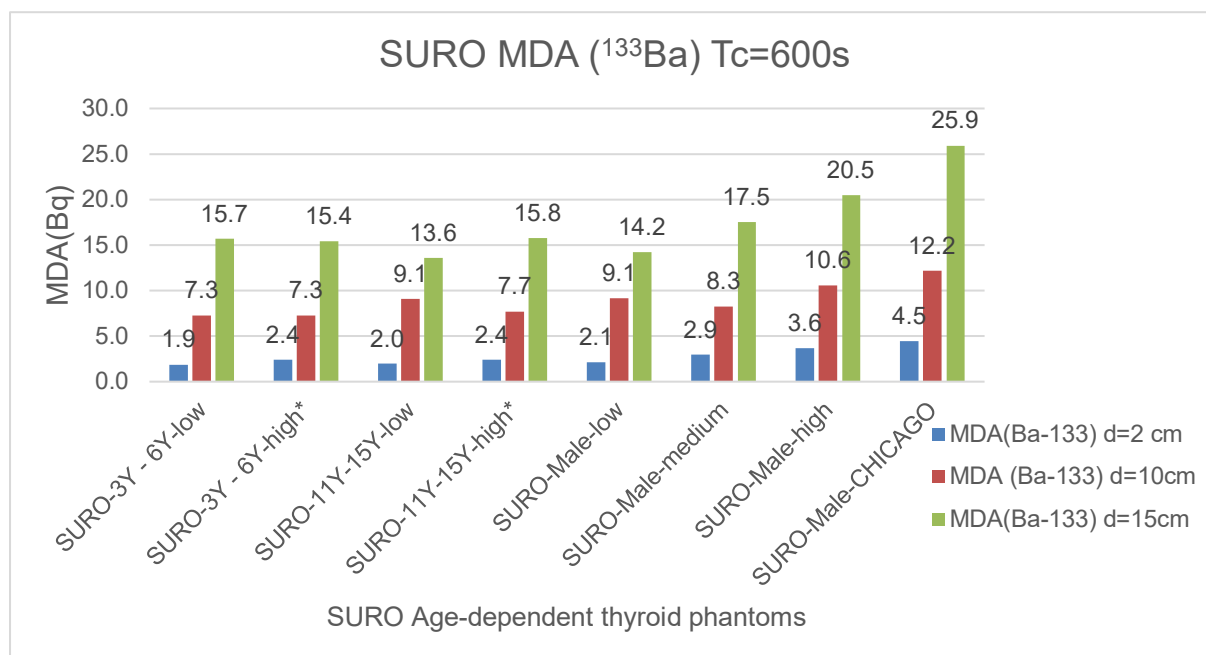


Figure 29. MDA values at short, medium and long detector-phantom distance

5.3.3. STUK

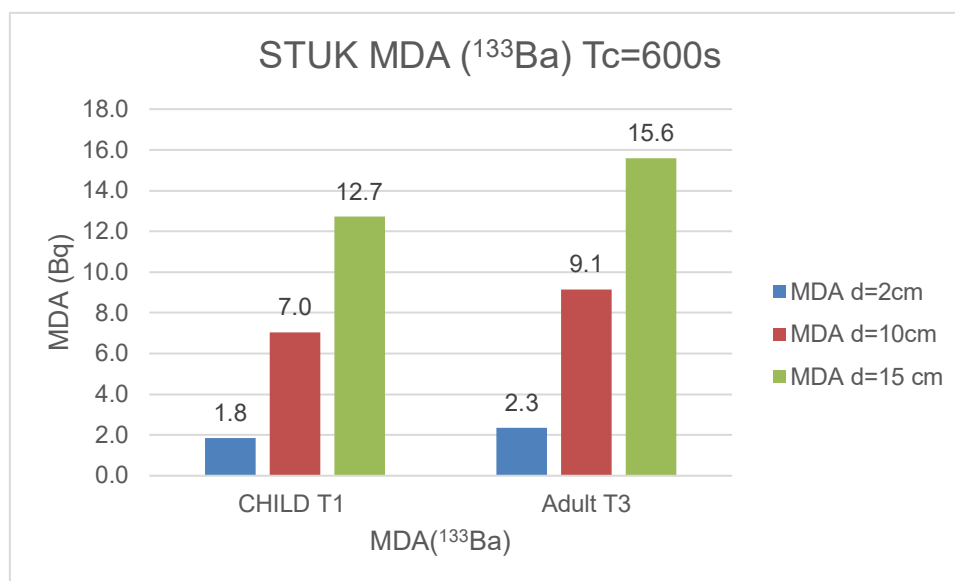


Figure 30. MDA values at short, medium and long detector-phantom distance

5.3.4. CIEMAT

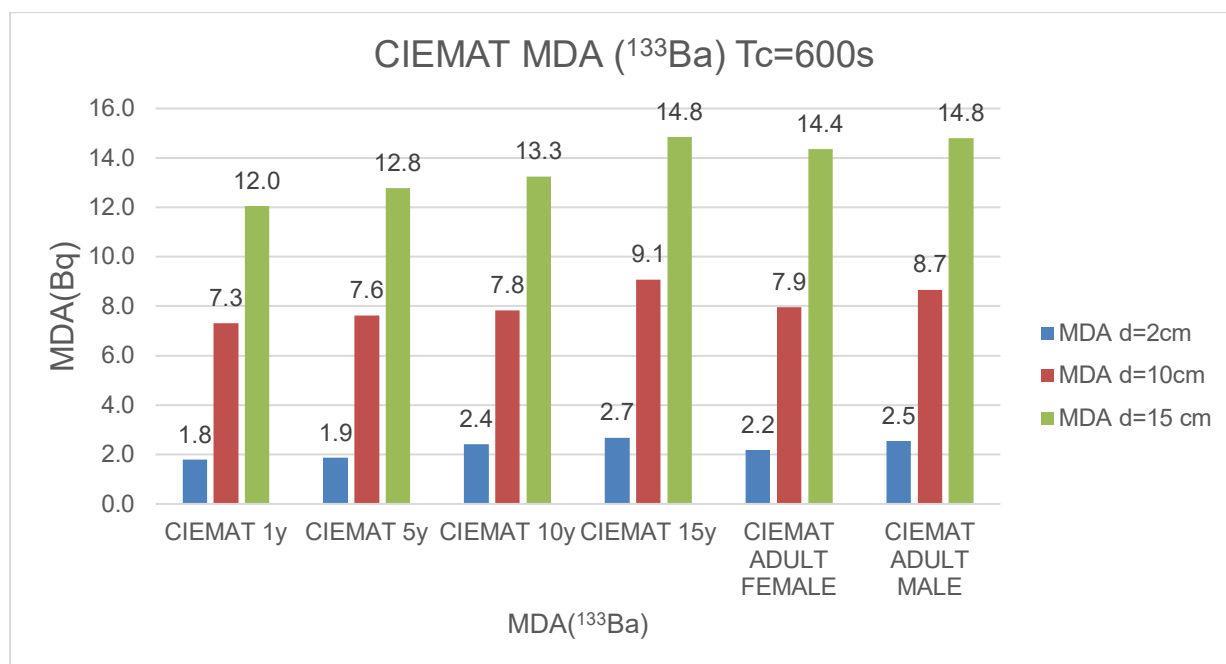


Figure 31. MDA values at short, medium and long detector-phantom distance

5.3.4. QST

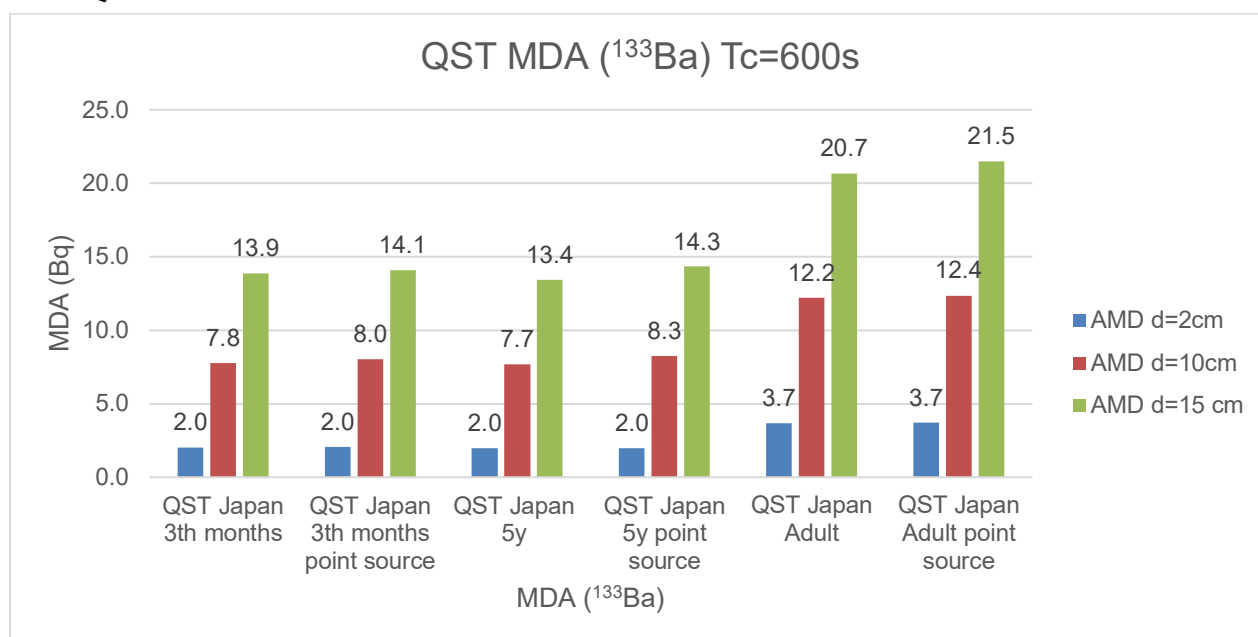


Figure 32. MDA values at short, medium and long detector-phantom distance

6. Comparative Analysis of Results and Conclusions

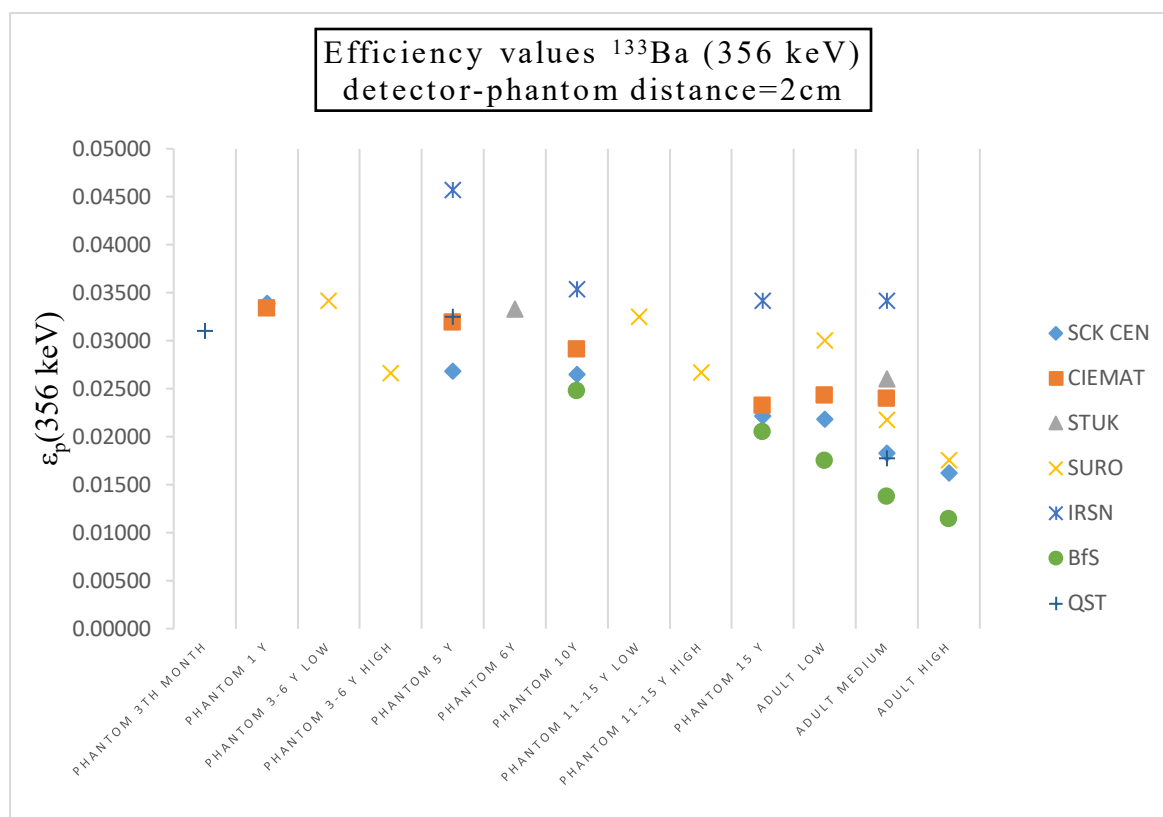
6.1. Efficiency values and uncertainties for each age-dependent thyroid phantom from the participating laboratories.

The efficiency values and uncertainties (coverage factor $k = 2$) for the main emission of ^{133}Ba (356 keV), expressed as the ratio between photons detected in the full-energy peak relative to the number of emitted per unit time, are presented below (Tables 15 to 17 and Figures 33 to 35).

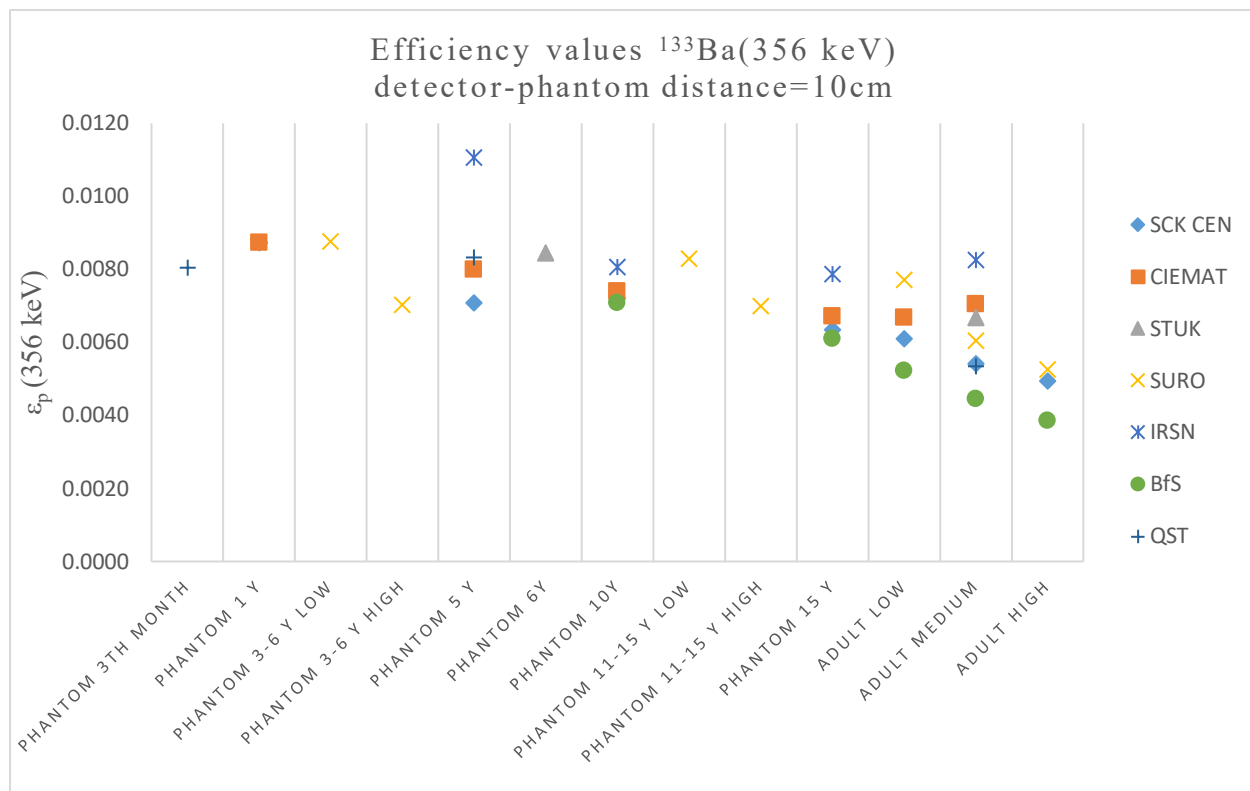
As illustrated in Table 15 and Figure 33, for short detector-phantom distance ($d = 2\text{cm}$), efficiency values decrease when increasing age for all the participants. These results confirmed that the efficiency decreases when increasing thyroid volume (i.e. with age) where discrepancies can reach up to 50 %. In this regard, the results are in good agreement with other studies (Gómez-Ros *et al.*, 2019). This effect is more significant at short (Figure 33) than at medium and long detector-phantom distances (Tables 16 and 17: Figures 34 and 35) where discrepancies diminish as the distance increases. Such results confirm that to enhance the assessment of ^{131}I incorporation in the thyroid, it is advisable to develop age-dependent calibration phantoms. (Broggio *et al.*, 2019).

Table 15. Efficiency and uncertainty values, $\varepsilon_p(356\text{ keV})$, at $d = 2\text{cm}$

Phantom	SCK CEN	CIEMAT	STUK	SURO	IRSN	BFS	QST
3rd month							$0,0310 \pm 0,0009$
1 y	$0,0339 \pm 0,0022$	$0,0334 \pm 0,0008$					
3-6 y low				$0,0342 \pm 0,0008$			
3-6 y high				$0,0267 \pm 0,0005$			
5 y	$0,0268 \pm 0,0018$	$0,0319 \pm 0,0007$			$0,0457 \pm 0,0009$	$0,0247 \pm 0,0007$	$0,0325 \pm 0,0010$
6y			$0,0333 \pm 0,0010$				
10y	$0,0265 \pm 0,0004$	$0,0291 \pm 0,0007$			$0,0354 \pm 0,0007$		
11-15y low				$0,0325 \pm 0,0008$			
11-15y high				$0,0267 \pm 0,0005$			
15 y	$0,0222 \pm 0,0014$	$0,0233 \pm 0,0005$			$0,0342 \pm 0,0007$	$0,0205 \pm 0,0006$	
adult low	$0,0218 \pm 0,0003$	$0,0243 \pm 0,0006$		$0,0300 \pm 0,0007$		$0,0175 \pm 0,0005$	
Std adult	$0,0183 \pm 0,0003$	$0,0239 \pm 0,0006$	$0,0260 \pm 0,0008$	$0,0217 \pm 0,0005$	$0,0342 \pm 0,0007$	$0,0138 \pm 0,0004$	$0,0178 \pm 0,00057$
adult high	$0,0163 \pm 0,0002$			$0,0175 \pm 0,0004$		$0,0115 \pm 0,0003$	

Figure 33. Efficiency values for ^{133}Ba (356 keV): detector-phantom distance = 2cmTable 16. Efficiency and uncertainty values, $\epsilon_p(356 \text{ keV})$, at $d=10\text{cm}$

Phantom	SCK CEN	CIEMAT	STUK	SURO	IRSN	BFS	QST
3rd month							$0,0081 \pm 0,0002$
1 y	$0,0087 \pm 0,0006$	$0,0087 \pm 0,0008$					
3-6 y low				$0,0088 \pm 0,0002$			
3-6 y high				$0,0070 \pm 0,0001$			
5 y	$0,0071 \pm 0,0005$	$0,0080 \pm 0,0007$			$0,0111 \pm 0,0002$	$0,071 \pm 0,0002$	$0,0083 \pm 0,0003$
6y			$0,0084 \pm 0,0003$				
10y	$0,0072 \pm 0,0001$	$0,0074 \pm 0,0007$			$0,0081 \pm 0,0002$		
11-15y low				$0,0083 \pm 0,0002$			
11-15y high				$0,0070 \pm 0,0001$			
15 y	$0,0063 \pm 0,0004$	$0,0067 \pm 0,0002$			$0,0079 \pm 0,0002$	$0,0061 \pm 0,0002$	
adult low	$0,0061 \pm 0,0001$	$0,0067 \pm 0,0002$		$0,0077 \pm 0,0002$		$0,0052 \pm 0,0002$	
Std adult	$0,0054 \pm 0,0001$	$0,0070 \pm 0,0002$	$0,0260 \pm 0,0008$	$0,0060 \pm 0,0002$	$0,0083 \pm 0,0002$	$0,0045 \pm 0,0001$	$0,0054 \pm 0,0002$
adult high	$0,0049 \pm 0,0001$			$0,0053 \pm 0,0001$		$0,0039 \pm 0,0001$	

Figure 34. Efficiency values for ^{133}Ba (356 keV): detector-phantom distance = 10cmTable 17. Efficiency and uncertainty values, $\varepsilon_p(356 \text{ keV})$, at $d=15\text{cm}$

Phantom	SCK CEN	CIEMAT	STUK	SURO	IRSN	BFS	QST
3rd month							$0,0045 \pm 0,0001$
1 y	$0,0050 \pm 0,0003$	$0,0049 \pm 0,0001$					
3-6 y low				$0,0050 \pm 0,0001$			
3-6 y high				$0,0041 \pm 0,0001$			
5 y	$0,0040 \pm 0,0003$	$0,0047 \pm 0,0001$			$0,0111 \pm 0,0001$	$0,0041 \pm 0,0001$	$0,0048 \pm 0,0001$
6y			$0,0046 \pm 0,0002$				
10y	$0,0041 \pm 0,0001$	$0,0043 \pm 0,0001$			$0,0081 \pm 0,0001$		
11-15y low				$0,0047 \pm 0,0001$			
11-15y high				$0,0041 \pm 0,0001$			
15 y	$0,0037 \pm 0,0002$	$0,0039 \pm 0,0001$			$0,0079 \pm 0,0001$	$0,0035 \pm 0,0001$	
adult low	$0,0035 \pm 0,0001$	$0,0039 \pm 0,0001$		$0,0045 \pm 0,0001$		$0,0031 \pm 0,0001$	
Std adult	$0,0033 \pm 0,0001$	$0,0041 \pm 0,0001$	$0,0038 \pm 0,0001$	$0,0037 \pm 0,0001$	$0,0083 \pm 0,0001$	$0,0027 \pm 0,0001$	$0,0032 \pm 0,0001$
adult high	$0,0031 \pm 0,0001$			$0,0031 \pm 0,0001$		$0,0024 \pm 0,0001$	

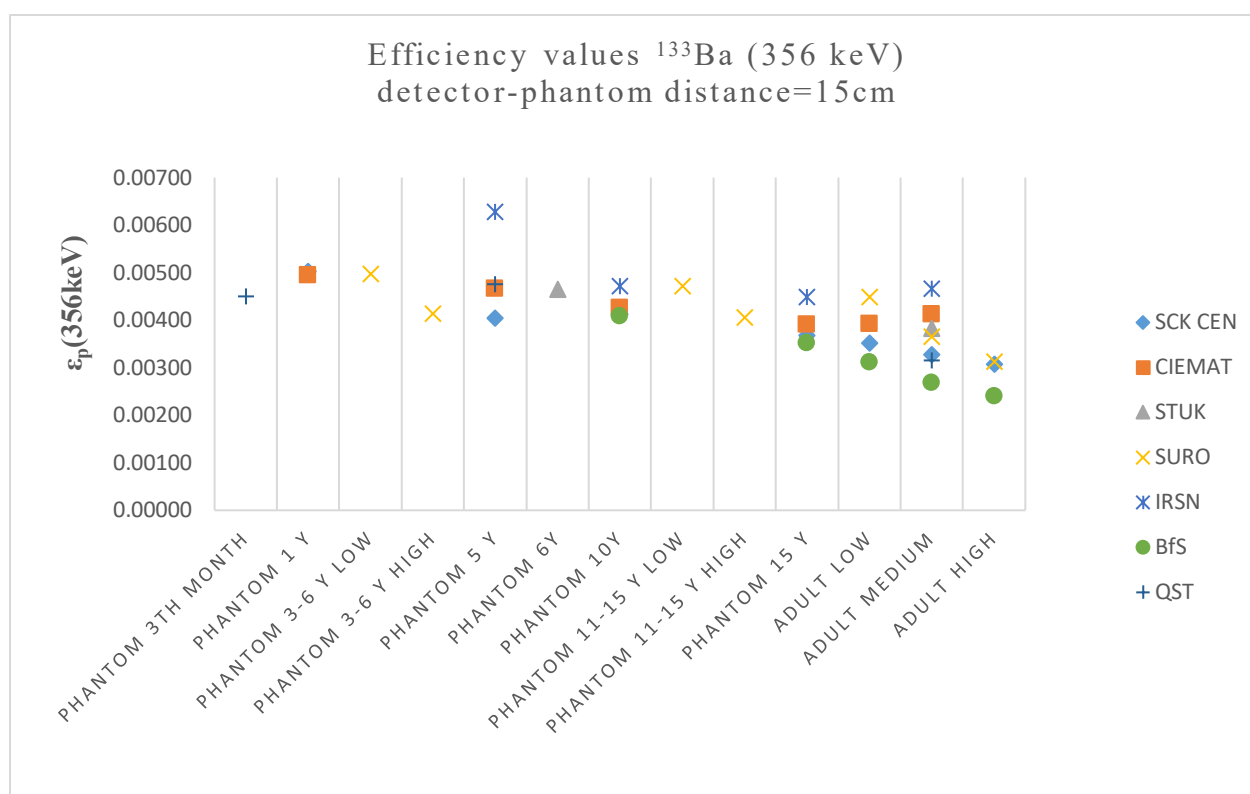


Figure 35. Efficiency values for ^{133}Ba (356 keV): detector-phantom distance = 15cm

6.2. Comparative analysis on the efficiency values obtained by the participants for each age group.

A comparative study was conducted on the efficiency values obtained by the participants for each age group. In order to improve the comparative study and considering that each laboratory had different age groups thyroid phantoms, the representative phantoms for 5-year-old and 6-year-old children were unified into the "3–6-year-old" age group. Similarly, the age groups of 11-year-old children and 15-year-old teenagers were consolidated into the "11–15-year-old" category. In the case of the 1-year-old and 10-year-old age groups, the results are presented separately, although only a few laboratories have provided these configurations. In the case of adults, the comparative study was conducted exclusively for the standard adult phantoms. The efficiency values for each age group are represented in the graph from highest to lowest. Additionally, with the aim of analyzing the causes behind the differences among phantoms representing the same age group, a study has been conducted on parameters that may have a significant influence on efficiency, such as the active thyroid volume (ml) and the overlying tissue thickness (mm) of the thyroid phantoms.

6.2.1. 3-6-year-old age group

As shown in Figure 36, the efficiency values for the "3-6 years" age group exhibit significant variation at the short detector-phantom distance ($d = 2$ cm), with discrepancies reaching up to 47%. These discrepancies slightly decrease as the distance between the detector and the thyroid phantom increases, dropping to 36% at $d = 10$ cm and 34% at $d = 15$ cm.

As shown in Figure 37, overlying tissue thickness and active thyroid volume corresponding to each age specific configurations of the participating laboratories have been represented. In general,

higher efficiency values (i.e. see “IRSN” and “SURO low” values) are associate with lower overlying tissue thickness but this effect doesn’t follow a regular pattern (i.e. see “QST”, “STUK” values) because other parameters such as thyroid volume, thyroid shape for simulating both lobes of the thyroid gland, tissue-equivalent material, etc. could influence the variations of the values as well.

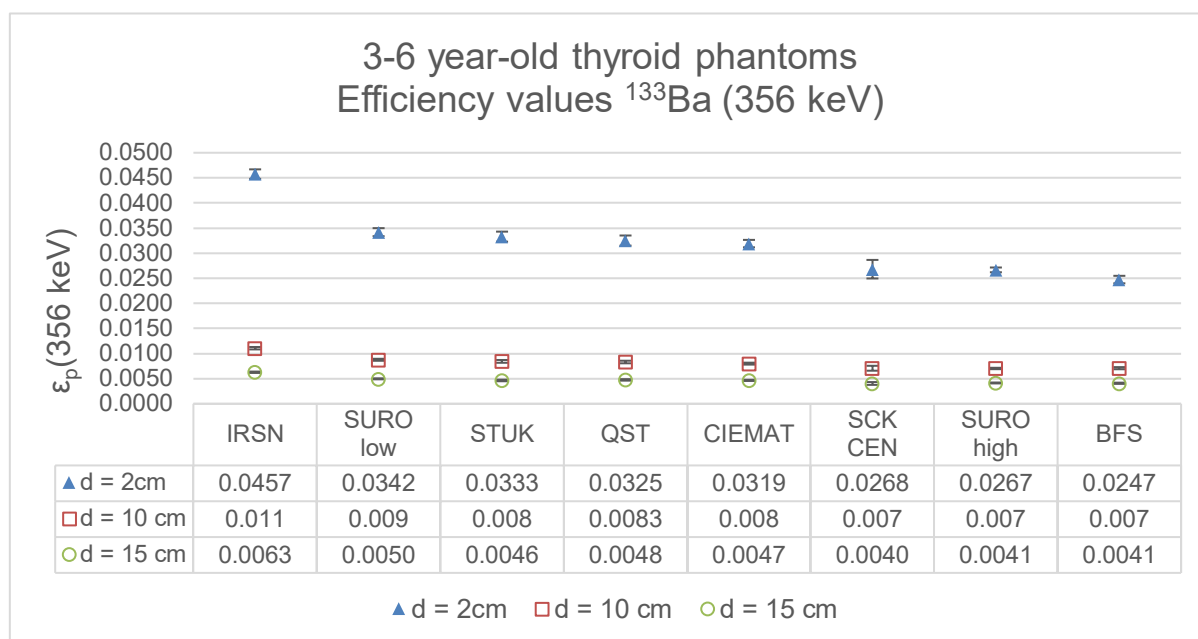


Figure 36. ^{133}Ba Efficiency values for “3-6-year-old” thyroid phantoms

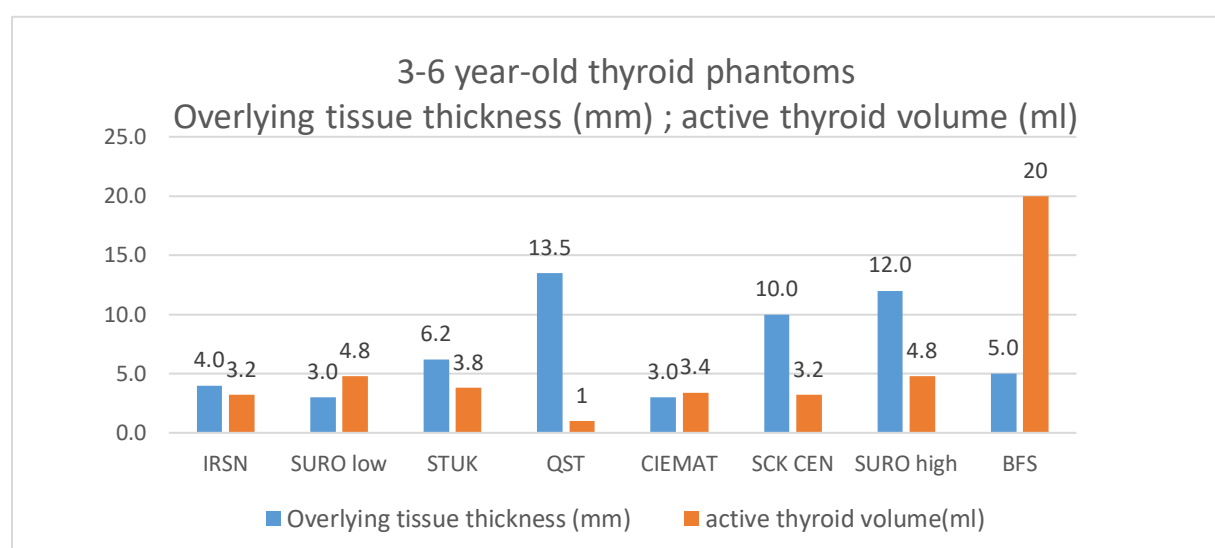


Figure 37. Overlying tissue thickness and active thyroid volume for “3-6-y” thyroid phantoms

6.2.2. 11-15-year-old age group.

As shown in Figure 38, the efficiency values for the “11-15 years” age group vary significantly at the short detector-phantom distance ($d = 2$ cm), with discrepancies reaching up to 40%. These discrepancies decrease as the distance between the detector and the thyroid phantom increases, dropping to 23% at $d = 10$ cm and 22% at $d = 15$ cm. As shown in Figure 39 it could be assumed the

same conclusion than the last paragraph. Higher efficiency values (i.e. see “IRSN” and “SURO low” values) are associated with lower overlying tissue thickness but this effect doesn’t follow a regular pattern.

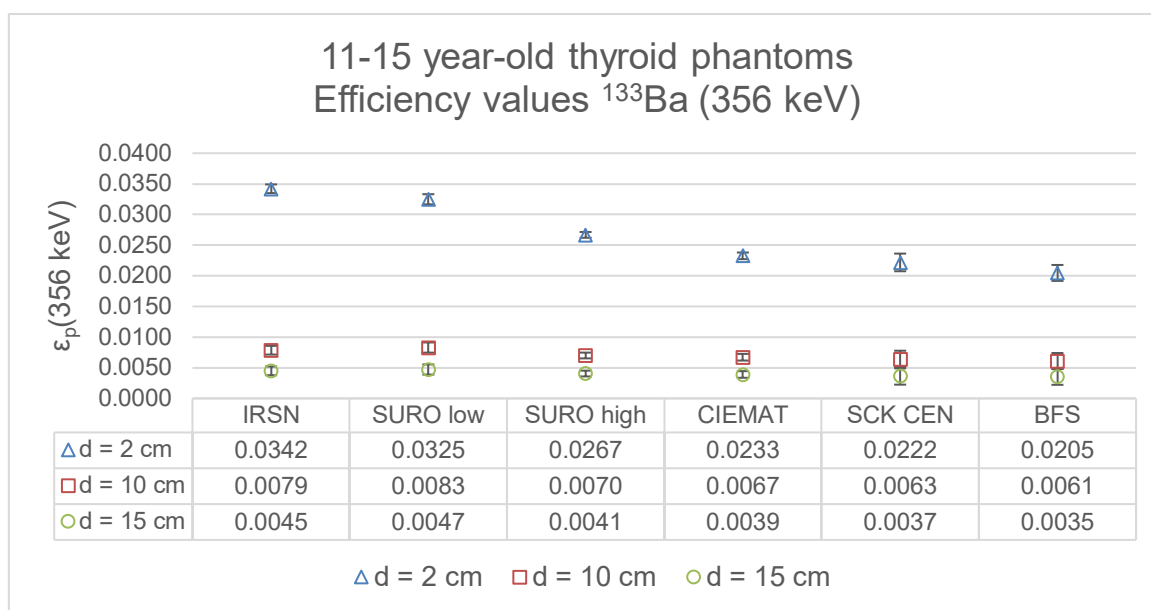


Figure 38. ^{133}Ba Efficiency values for “11-15-year-old” thyroid phantoms

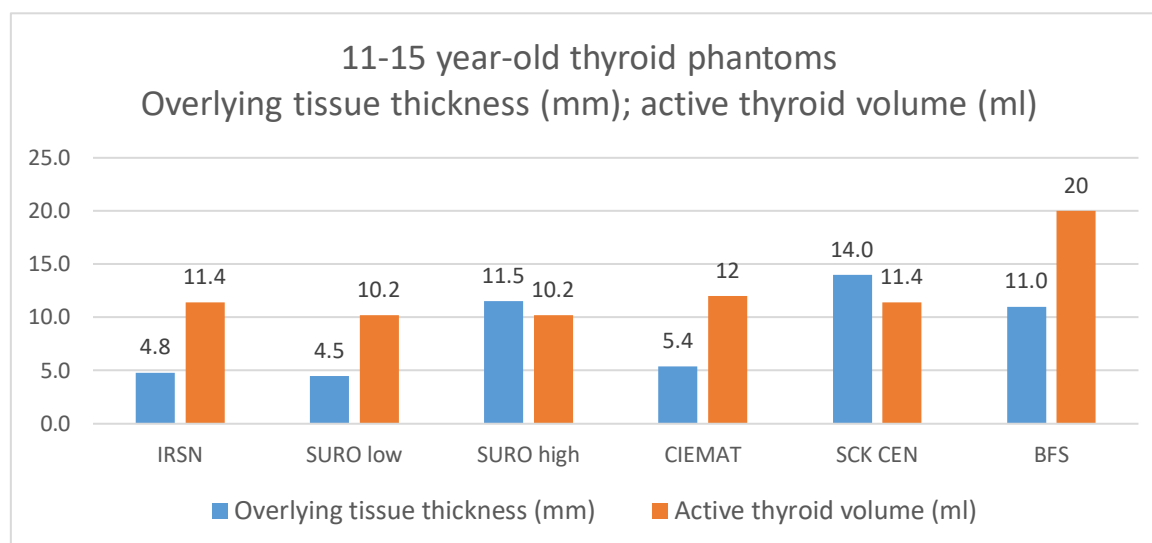


Figure 39. Overlying tissue thickness and active thyroid volume for “11-15-year-old” thyroid phantoms

6.2.3. Standard adult age group

As shown in Figure 40, the efficiency values for the “standard adult” age group vary significantly at the short detector-phantom distance ($d = 2$ cm), with discrepancies reaching up to 48%. These discrepancies decrease as the distance between the detector and the thyroid phantom increases, dropping to 36% at $d = 10$ cm and 34% at $d = 15$ cm. As shown in Figure 41, the thyroid volumes for all the phantoms are similar, around 20 ml according to ICRP 89. For that reason, in this case, the

overlying tissue thickness parameter clearly demonstrates its influence on efficiency, so that higher efficiency values are associated with lower overlying tissue thickness.

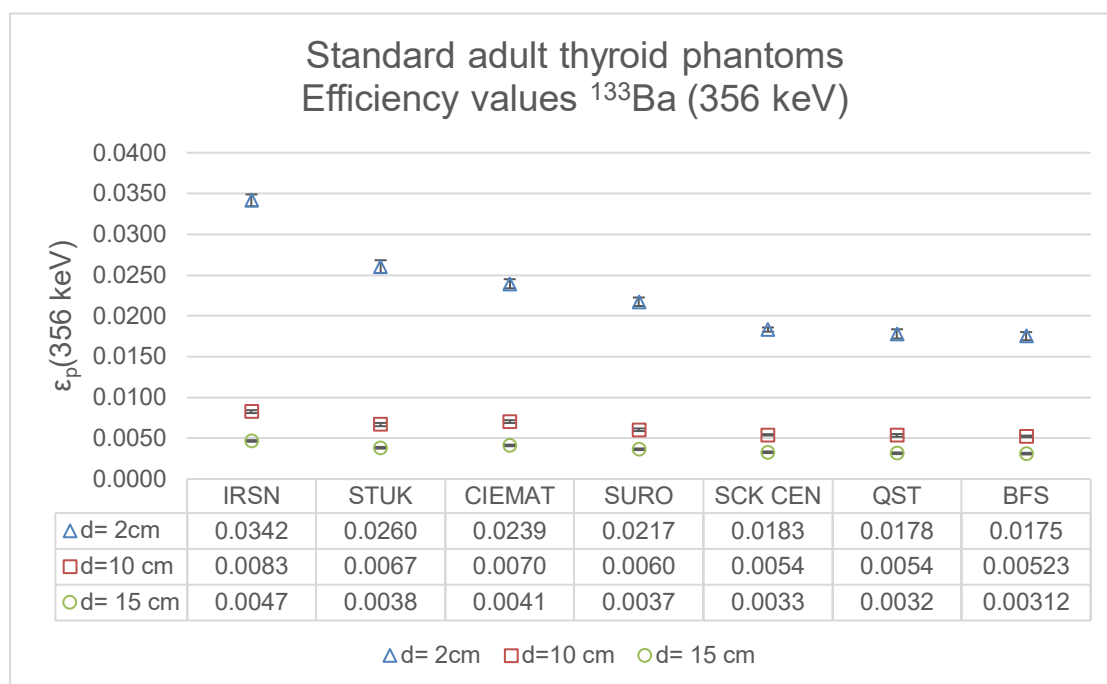


Figure 40. ^{133}Ba Efficiency values for standard adult thyroid phantoms

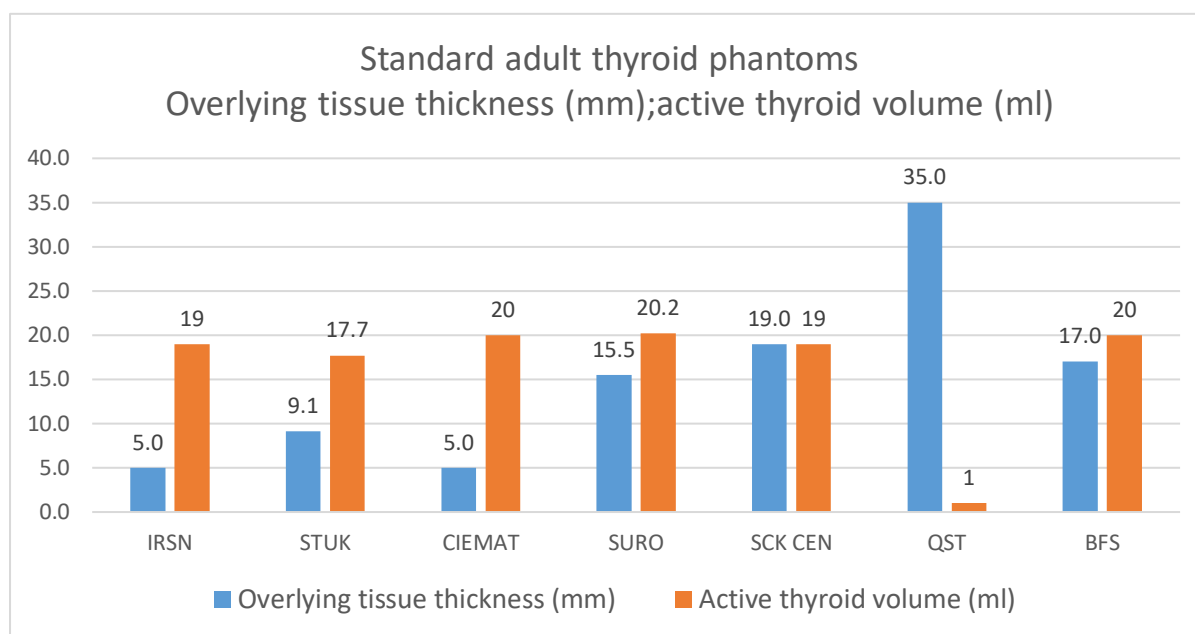


Figure 41. Overlying tissue thickness and active thyroid volume for “standard adult” thyroid phantoms

6.2.4. 1-year-old age group

As shown in Figure 42, only two laboratories (SCK CEN, CIEMAT) have provided 1-year-old thyroid phantoms. In this case, the efficiency values are very similar across all measurement geometries, showing negligible discrepancies (1–2%). This could be because the overlying tissue thickness of both phantoms is similar (1.7–1.8 mm), as is the active thyroid volume, according to ICRP 89 (ICRP, 2002).

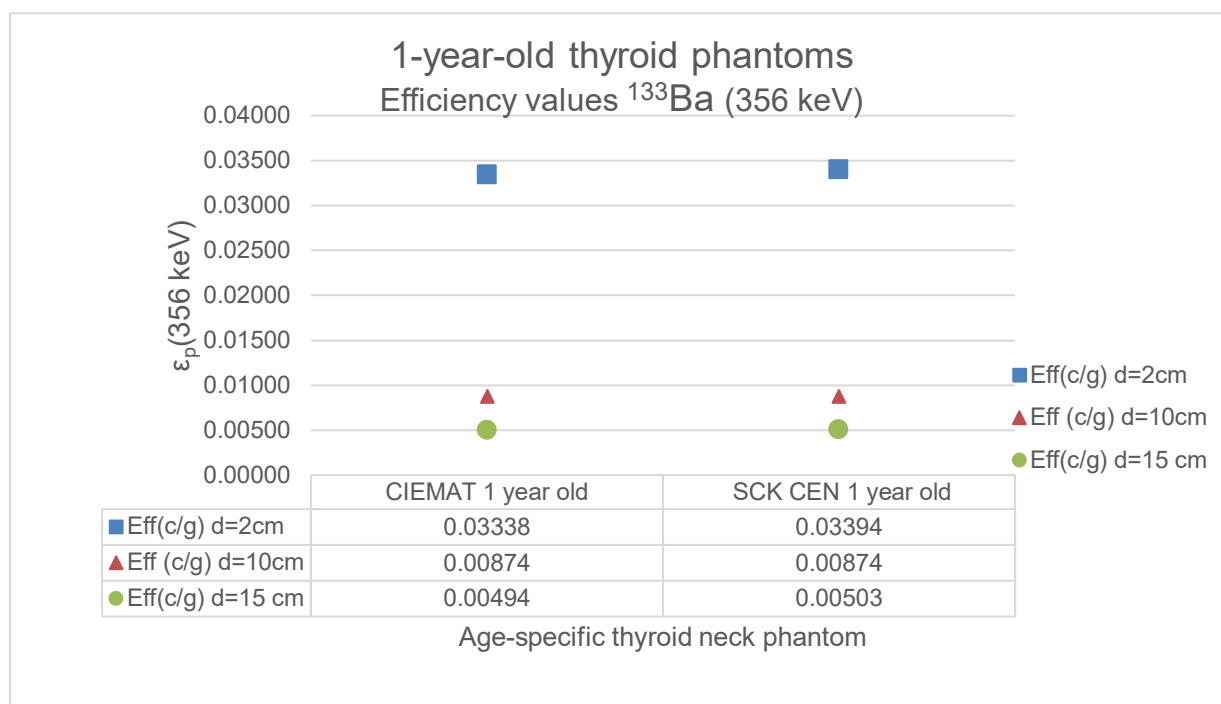


Figure 42. ^{133}Ba Efficiency values for 1-year-old thyroid phantoms

6.2.5. 10-year-old age group

As shown in Figure 43, the efficiency values for the "10-year-old" age group exhibit variation at the short detector-phantom distance ($d = 2$ cm), with discrepancies reaching up to 30%. These discrepancies decrease as the distance between the detector and the thyroid phantom increases, dropping to 12% at $d = 10$ cm and $d = 15$ cm.

As shown in Figure 44, higher efficiency values (i.e. see "IRSN" and "CIEMAT" values) are associated with lower overlying tissue thickness.

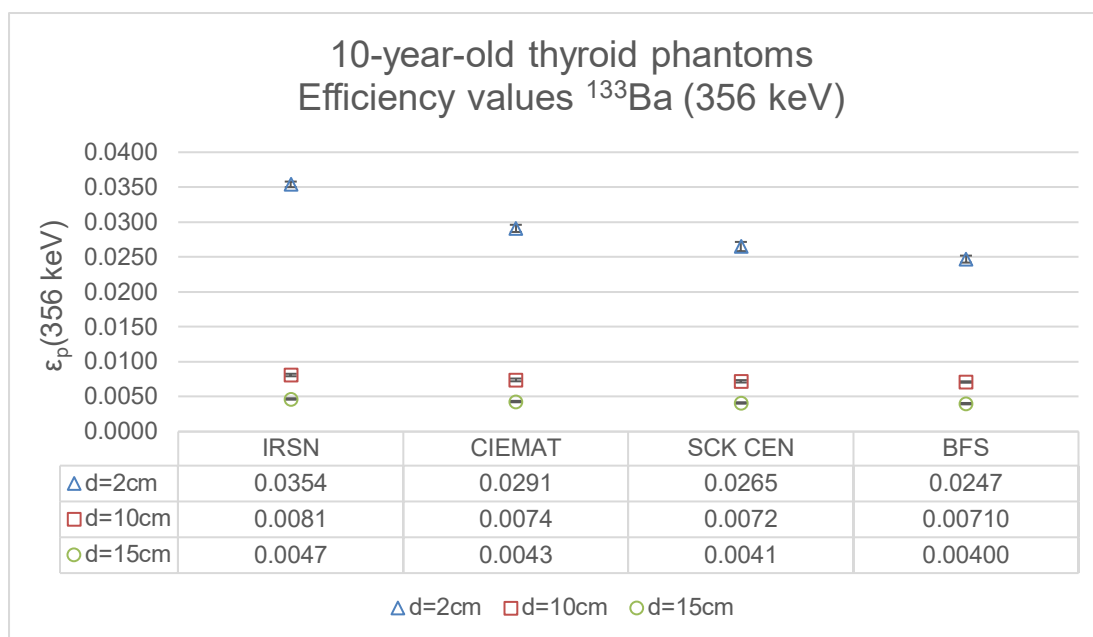
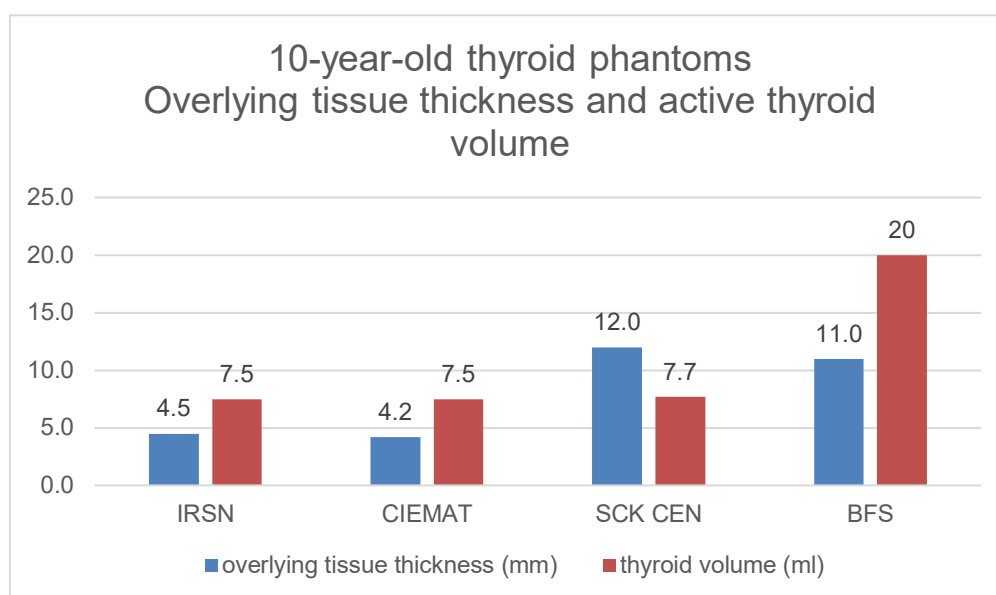
Figure 43. ^{133}Ba Efficiency values for 10-year-old thyroid phantoms

Figure 44. Overlying tissue thickness and active thyroid volume for “10-year-old” thyroid phantoms

7. Conclusions.

There are significant differences in the design of the different phantoms among the participating laboratories, with respect to the simulation of the overlying tissue thickness, thyroid volume, tissue-equivalence of the phantom material and dimensions of vials simulating thyroid lobes, etc. Such differences give rise to significant variations in the efficiency values, especially at short and medium detector-phantom distance. The active thyroid volume and the thickness of the overlying tissue layer are parameters that may have the greatest influence on the differences in efficiency values.

In summary, the results obtained in the intercomparison exercise confirmed that efficiency decreases with increasing thyroid volume (i.e., with age), where discrepancies could result in a difference of thyroid activity by a factor of two. These discrepancies decrease as the distance between the detector and the thyroid phantom increases. Additionally, higher efficiency values are associated with lower overlying tissue thickness of the thyroid phantom but this effect does not follow a regular pattern due to the influence of other parameters associated with the phantom. Therefore, it has been proven that the use of age-dependent thyroid phantoms for children and adults allows a greater reliability in the calculation of ^{131}I activity deposited in the thyroid, improving thyroid dose assessment. In cases where age-dependent phantoms are not available, it will always be effective to perform calibration at distances above 15-20 cm in order to reduce differences in efficiency values (Gómez-Ros et al., 2019, Broggio et al., 2019).

Remaining gaps.

A consensus on the design of reference age-dependent thyroid phantoms is needed to optimize and harmonize calibration and measurement procedures. It would be advisable to design a set of age-dependent phantoms for both children and adults, with characteristics agreed upon by experts in the field. For this issue, additional experimental studies and Monte-Carlo calculations are needed, particularly for fitting the values for the critical parameters in the design of the thyroid phantoms (mainly overlying tissue thickness and thyroid volume). For that purpose, one can reliably rely on the ICRP recommendations for defining thyroid volumes by age. The main challenges in achieving a realistic and widely accepted phantom design lie in determining the shape and the thickness of the overlying tissue, which is, in fact, poorly described in the literature.

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9. Annexes

9.1. Annex I: Invitation letter for potential participants



9.2. Annex II: Protocol of measurements: Technical questionnaire



Technical questionnaire

Intercomparison of age-dependent thyroid phantoms for thyroid monitoring

WG 7. TASK GROUP Emergency Dosimetry

Participating laboratory:	
Laboratory name	
Laboratory address	
Availability for sending to CIEMAT thyroid neck phantoms, calibration sources and empty vials for blank measurements (please check one or more options)	☐ April ☐ May ☐ June ☐ July ☐ September ☐ October
Is one or two technician expected to travel to CIEMAT	☐ Yes, if COVID situation allows ☐ No

Laboratory contact person	
Name	
Email address	
Phone number	

Detection system (*)	
Manufacturer	
Model	
Detector type (NaI, broad energy Germanium, low energy germanium, etc.)	
Detector size (crystal dimensions)	Surface (mm ²): Thickness (mm ²):
Spectrometry software	
Energy range (keV), number of channels	
Signal Processing (integrated electronics, analogic chain)	
Picture	

(*) Fill this table for each detection system.

9.4. Annex IV: Protocol of measurements: Thyroid blank measurements excel sheet

WG 7. TASK GROUP Emergency Dosimetry					
TASK. Intercomparison of age-dependent thyroid phantoms for thyroid monitoring at WBC Laboratory (CIEMAT)					
Detector system: BEGe (Left)					
Participating laboratory:					

Age-specific thyroid phantom (1y, 5y, 10y, 15y, female, male, other)	Measuring date yy/mm/dd	Detector-phantom distance (2 cm, 8 cm, 15 cm)	Counting Time (s)(*)	Background (counts)(**)	Uncertainty 2σ (%)	Minimum detectable activity MDA(Bq)	Additional information

(*) Tc= 600 s

(**) (ROI 356 keV Ba-133)