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Journal Pre-proof



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EURADOS Intercomparison of age-dependent thyroid phantoms for thyroid monitoring in nuclear or radiological emergencies

J.F. Navarro^{1}, B. Pérez¹, M.A. López¹, J. Boeckx², V. Rovenska³, S. Helbig⁴, T. Torvela⁵, T. Beaumont⁶, M. Kowatari⁷, D. Frank⁶, A.L. Lebacqz², O. Meisenberg⁴, P. Fojtik³, D. Broggio⁶.*

1. CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas). Avda. Complutense 40, 28040, Madrid, Spain.
2. SCK CEN (Belgian Nuclear Research Center), Boeretang 200, Mol 2400, Belgium.
3. SÚRO (National Radiation Protection Institute), Prague, Czech Republic.
4. BfS (Bundesamt fuer Strahlenschutz), Neuherberg, Germany.
5. Radiation and Nuclear Safety Authority - STUK Helsinki (Finland).
6. IRSN (Institut de Radioprotection et de Sûreté Nucléaire), Fontenay-aux-Roses, France.
7. QST (National Institutes for Quantum Science and Technologies) Chiba, Japan.

*Corresponding author: jf.navarro@ciemat.es

Direct in-vivo measurement of radioiodine in the thyroid by gamma spectrometry is usually the preferred method for assessing intake of ^{131}I . To obtain reliable values of the committed doses related to these accidental intakes, detector systems have to be properly calibrated, using age-dependent thyroid phantoms for simulating the internal contamination for individuals of different age groups. In-vivo monitoring laboratories all over the world usually use adult thyroid phantoms for calibrating purposes, however, only a few of them have age-dependent thyroid phantoms. For improving and harmonizing the calibration procedures for in-vivo thyroid monitoring, particularly for children in case of radiological or nuclear emergencies, members of the EURADOS WG7 “Internal Dosimetry” have organized and carried out an intercomparison exercise aimed at comparing different age-dependent thyroid phantoms. Intercomparison measurements were conducted at the Whole Body Counter Laboratory (WBC) of CIEMAT. This paper presents the design and development of the campaign as well as a summary of the most relevant results obtained and conclusions.

1. INTRODUCTION

In a nuclear accident, large amounts of radioiodine may be released to the environment with the subsequent risk of contamination of the population. The accidents at the Chernobyl and Fukushima Daiichi nuclear power plants revealed that thyroid cancer, particularly in children, was the main concern when evaluating the health effects associated to internal exposures. In such scenarios, ^{131}I is noteworthy because is one of the major releases. (Pröhl et al., 2002) (UNSCEAR, 2013). Direct in-vivo measurement of ^{131}I in thyroid is the recommended technique for assessing intake (EC Directorate-General for Energy, Radiation Protection n° 188). This can be accomplished using spectrometric instruments commonly equipped with either sodium iodide detectors (NaI(Tl)) or germanium detectors. To obtain reliable values of the committed doses related to these accidental intakes, detectors must be properly calibrated, using thyroid phantoms and calibration radioactive sources for simulating the internal contamination in

the thyroid of individuals of different age groups due to the significant variation in thyroid gland size. Hence, employing age-dependent phantoms could reduce the uncertainties of measurement and, consequently, enhance the reliability of dose assessment. Regarding radioactive sources, due to the short half-life of ^{131}I , ^{133}Ba or a mixture of ^{133}Ba and ^{137}Cs are commonly used for calibration purposes as surrogate of ^{131}I because their longer half-life and similar spectrum when comparing with ^{131}I .

In-vivo monitoring laboratories usually use adult thyroid phantoms for calibration purposes. The ANSI adult phantom (ANSI/HPS N13.44, 2014) can be considered as a reference phantom for adult monitoring. However, there are no established specific standards for designing age-dependent phantoms.

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 (R. M. Harrison et al., 2021). Consequently, members of the EURADOS WG7 “Internal Dosimetry” have organized and carried out an intercomparison exercise aimed at comparing different age-dependent thyroid phantoms by using the same germanium detection system for calibration purposes, in order to achieve a better analysis of the differences among the participating laboratories.

1.1. Organization of the intercomparison exercise.

Before starting the exercise, an invitation letter was sent to the whole-body counter laboratories all over the world for enrolling participants under the condition that they could provide not only adult but also children thyroid phantoms. Furthermore, a technical questionnaire was also sent to the laboratories for gathering information about their equipment and capabilities. As shown in Table 1, seven laboratories were enrolled to participate in the exercise. For carrying out the intercomparison exercise, a protocol of measurements was designed and distributed to the participating laboratories. Each of them sent their phantoms and radioactive sources at the Whole Body Counter laboratory of CIEMAT following a previously agreed-upon schedule. Three geometries of measurements were agreed for comparing efficiency values at short (2 cm), medium (10 cm) and long (15 cm) detector-phantom distance. Efficiency calibration for the main emission of ^{133}Ba (356 keV) were performed for each geometry of measurement and age-dependent thyroid phantom.

2. MATERIALS AND METHODS

2.1. Detector System and shielded room.

The facility, where the measurement system is located, consists of a shielded chamber of inner dimensions 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 Mirion Broad Energy Germanium Detector (BEGe) model BE6530 with an excellent resolution Resolution (0.75 KeV at 122 keV) and good efficiency in the energy range of 10 keV to 2000 keV (60% Relative Efficiency at 1332 keV) (figure 1). The BEGe detector has a diameter of approximately 91 mm, a thickness of 31 mm, and an active surface area of 6500 mm².



Figure 1: Thyroid measurement detection system (BEGe) WBC Laboratory CIEMAT



2.2. Age-dependent thyroid phantoms.

The participants submitted the technical questionnaire with a detailed description of their age-dependent phantoms. As shown in Table 1, all the participants have one or more phantom settings for resembling adults, however not all of them have settings for each age group of both children and teenagers. Most of the participants utilize pairs of vials for mimicking both lobes of the thyroid, whereas only two of them utilize single vials or point sources. Furthermore, all the participants utilize ¹³³Ba or a mixture of ¹³³Ba and ¹³⁷Cs as a surrogate of ¹³¹I, and active thyroid volumes with values according to ICRP Publication 89 (ICRP, 2002) or closely aligned with it. Gathered information from technical

questionnaires was used to create a database to be used for the statistical analysis of the intercomparison results.

Table 1. Age-dependent thyroid phantoms 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, E.D., 2013)	8 mm (1y) 10 mm (5y) 12 mm (10y) 14 mm (15y) 19 mm (adult)	Ba-133 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	Ba-133 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)	Ba-133 Pairs of vials	3,8 ml (6y) 17,7 ml (adult) ICRP 89	
IRSN (France)	1-y-old child, 10-y-old; 15-y old teenager; Adult (standard male) (Beaumont, T et al., 2017)	4 mm (5y) 4,5 mm (10y) 4,8 mm (15y) 5 mm (adult)	Ba-133 3D-print thyroid	translucent resin (VeroClear) ICRP 89	
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) (Frankfurt am Main,1990)	4,5 to 10 mm young people age 4 to 15 y 11 mm to 29 mm adults	Ba-133 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)	2,1 mm (1y) 3 mm (5y) 4,2 mm (10y) 5,4 mm (15y)	Ba-133 Cs-137 Single vials	1,8 ml to 20 ml ICRP 89	

	Lucite (PMMA) (Pérez et al, 2018)	5 mm (adult)			
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)	Ba-133 Single vials and point source	1ml vial or point source	 

3. RESULTS AND DISCUSSION

This study only focuses on the most significant findings regarding the calculated efficiencies for the different age-dependent phantoms within the agreed calibration geometries specified in the protocol. The full results obtained in this exercise will be published in a report within the framework of EURADOS WG 7.

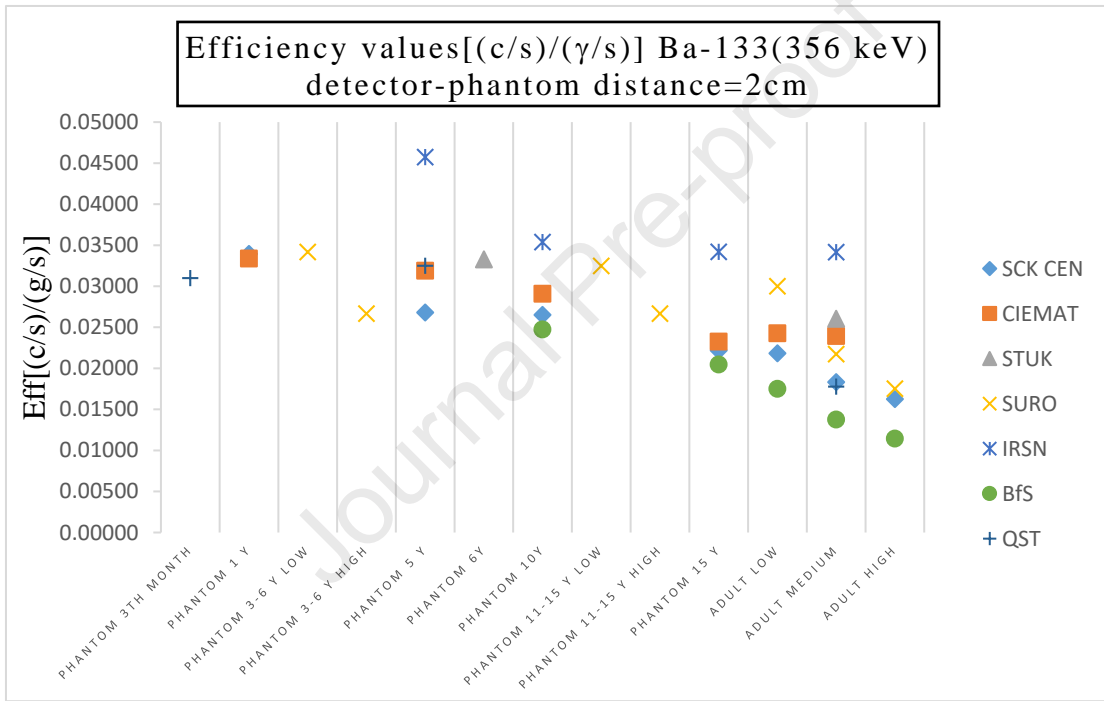
3.1. Calibration of BEGe detector for each age-dependent thyroid phantom from the participating laboratories.

Following the protocol of measurements, efficiency values for the main emission of ^{133}Ba were calculated for each age-dependent thyroid phantom at the three counting geometries. The efficiency values and uncertainties (coverage factor $k = 2$), expressed as the ratio between detected counts per second and emitted photons per second [(c/s) / (γ /s)], are presented below. As illustrated in Table 2, 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 (J.M. Gómez-Ros et al., 2019). This effect is more significant at short (Figure 2A) than at medium and long detector-phantom distances (Figures 2B and 2C) 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 2. Efficiency and uncertainty values [cps/(g/s)] for Ba-133 (356 keV) at $d = 2\text{cm}$

d = 2cm	SCK CEN	CIEMAT	STUK	SURO	IRSN	BFS	QST
phantom	Efficiency [c/ γ]	Efficiency [c/ γ]	Efficiency [c/ γ]	Efficiency [c/ γ]	Efficiency [c/ γ]	Efficiency [c/ γ]	Efficiency [c/ γ]
3th 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±0,0005			
5 y	0,0268 ± 0,0018	0,0319 ± 0,0007			0,0457 ± 0,0009	0,0247±0,0007	0,0325 ± 0,0010
6y			0,0333 ± 0,0010				
10y	0,0265±0,0004	0,0291 ± 0,0007			0,0354 ± 0,0007		
11-15y low				0,0325±0,0008			
11-15y high				0,0267±0,0005			
15 y	0,0222±0,0014	0,0233 ± 0,0005			0,0342 ± 0,0007	0,0205 ± 0,0006	
adult low	0,0218 ± 0,0003	0,0243 ± 0,0006		0,0300±0,0007		0,0175 ± 0,0005	
Std adult	0,0183 ± 0,0003	0,0239±0,0006	0,0260±0,0008	0,0217±0,0005	0,0342 ± 0,0007	0,0138 ± 0,0004	0,0178 ± 0,00057
adult high	0,0163 ± 0,0002			0,0175±0,0004		0,0115 ± 0,0003	



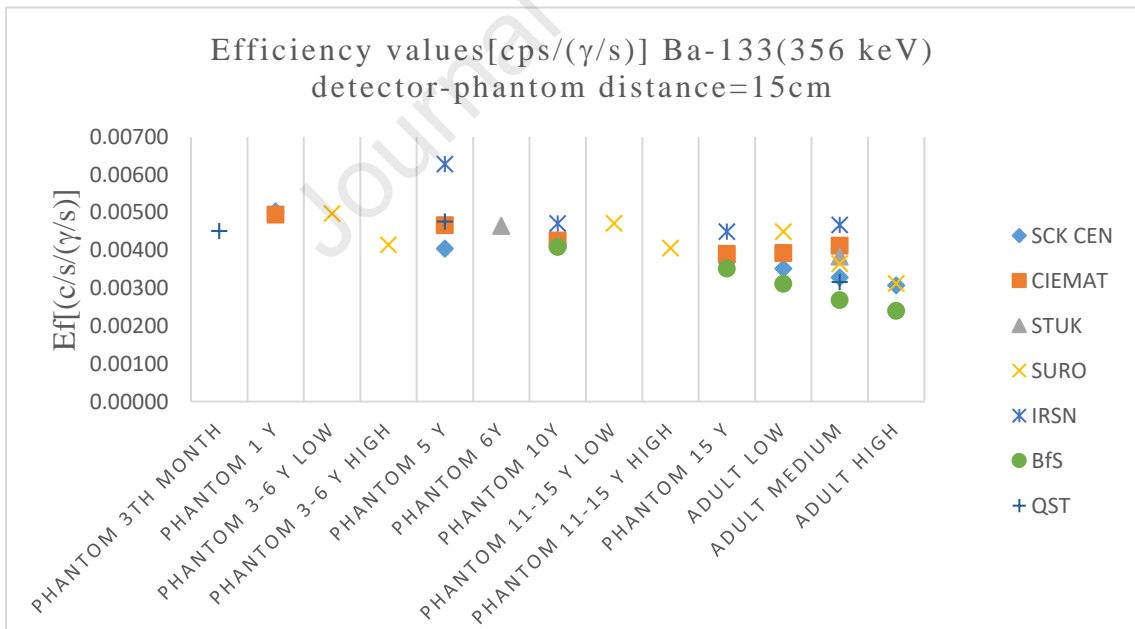
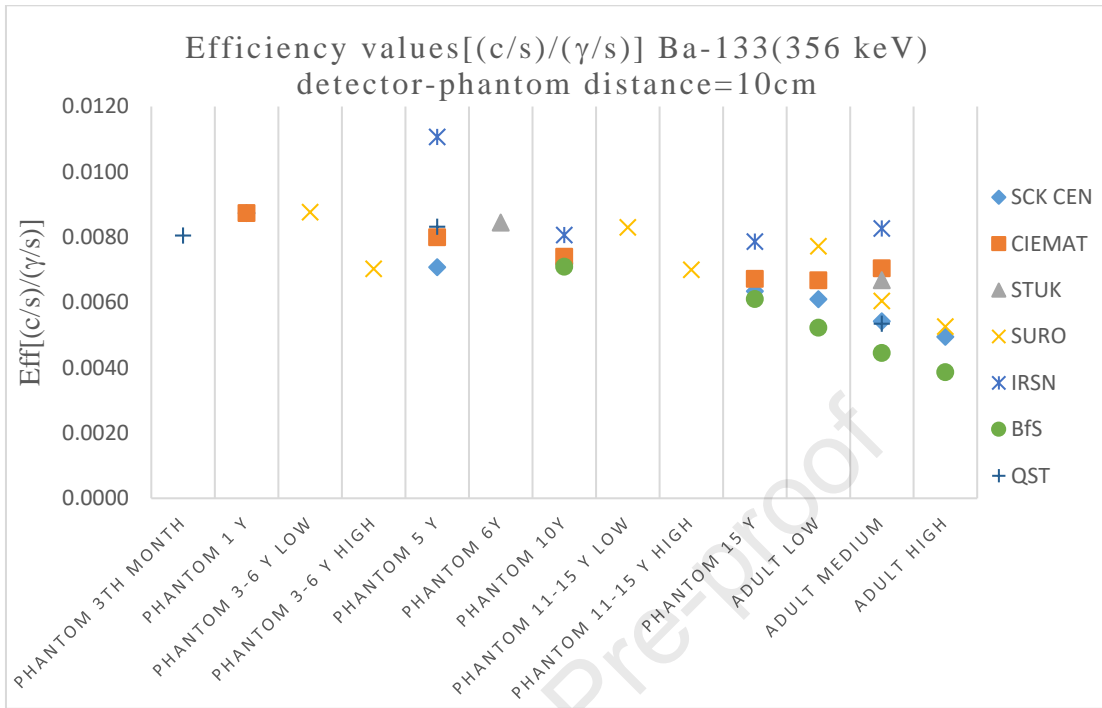
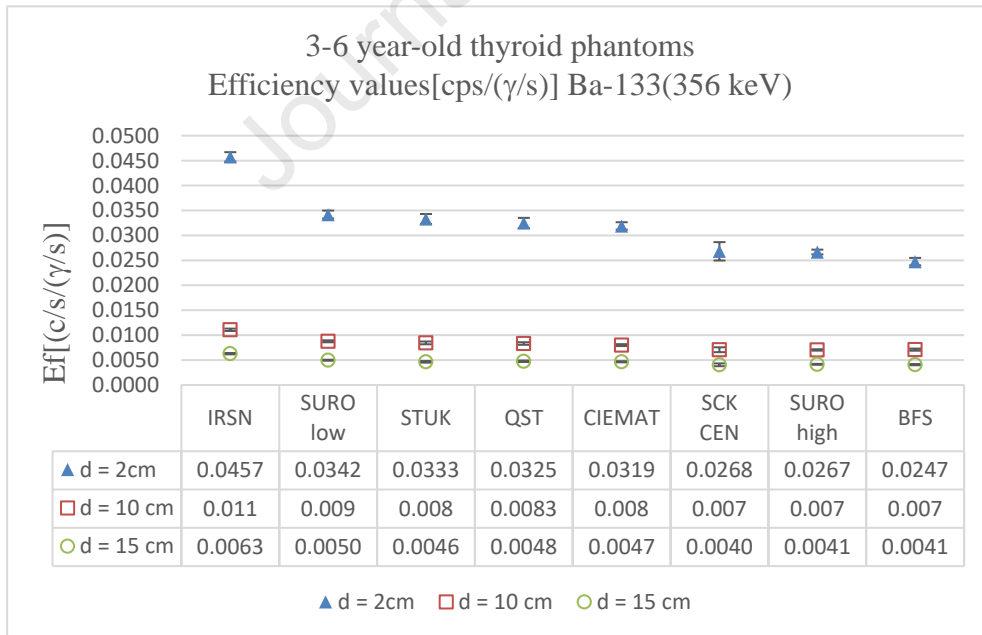


Figure 2. Efficiency values for Ba-133(356 keV): A) detector-phantom distance = 2cm B) detector-phantom distance = 10 cm C) detector-phantom distance = 15 cm

3.2. A 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. This work focuses on “3-6” years-old, “11-15” years-old teenagers and standard-adult thyroid phantoms. As illustrated in Figure 3A, efficiency values for “3-6 y” age group vary significantly at short detector-phantom distance where discrepancies can reach up to 45%. These discrepancies decrease as the distance between the detector and the thyroid phantom increases. As illustrated in Figures 4A and 5A, the same trend can be observed for “11-15 y” age group and standard adult phantoms respectively. With the aim of analyzing the causes behind these 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. As illustrate in Figure 3B, efficiency is also affected by the thickness of the overlying tissue. In general, higher efficiency values (i.e. see IRSN value) are associate with lower overlying tissue thickness but this effect doesn’t follow a regular pattern (i.e. see QST value) because other parameters such as thyroid volume, simulation of lobes, tissue-equivalent material, etc. could influence the variations of the values as well. A similar trend can be observed for “11-15 y” (Figure 4B) and adult phantoms (Figure 5B).



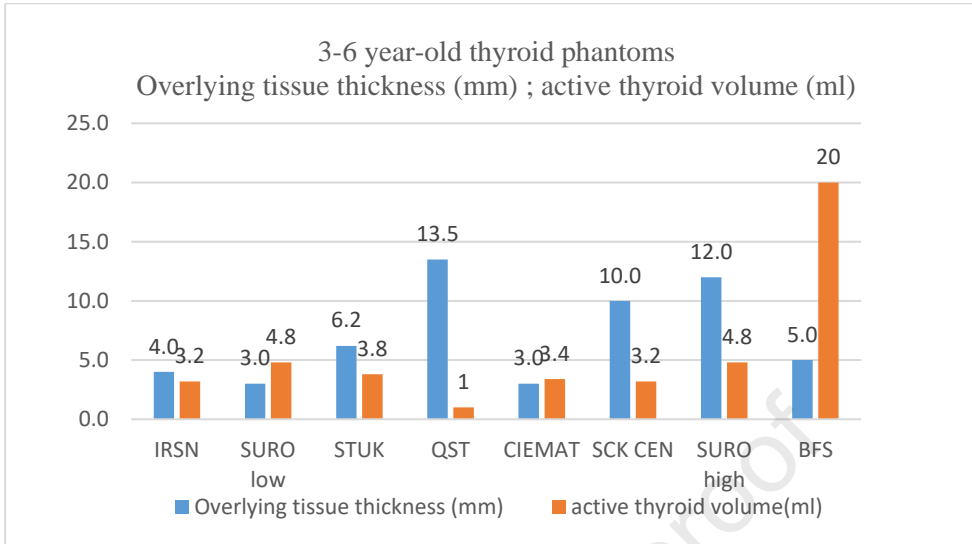
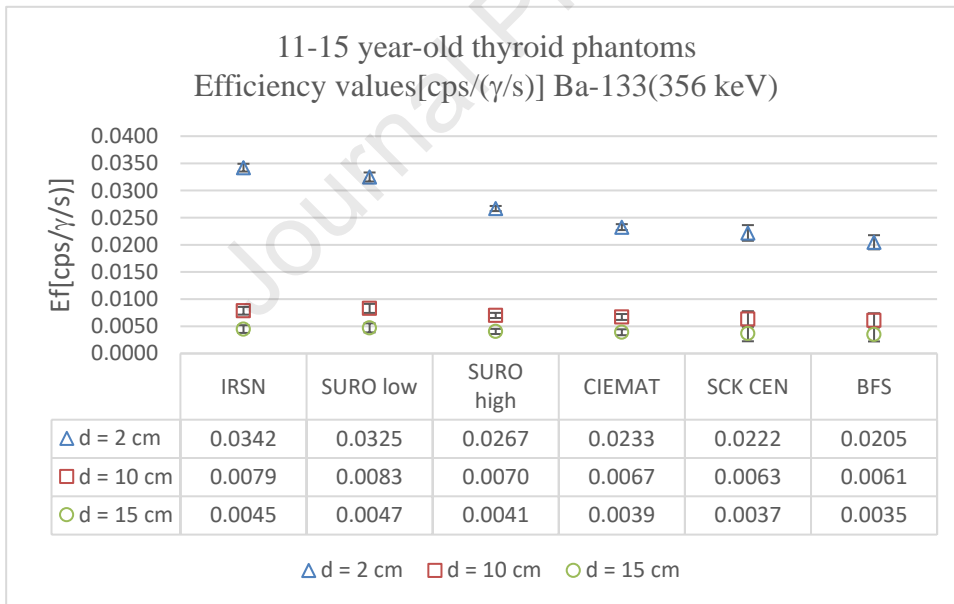


Figure 3. A) ¹³³Ba Efficiency values for “3-6 y” thyroid phantoms B) overlying tissue thickness and active thyroid volume for “3-6 y” thyroid phantoms



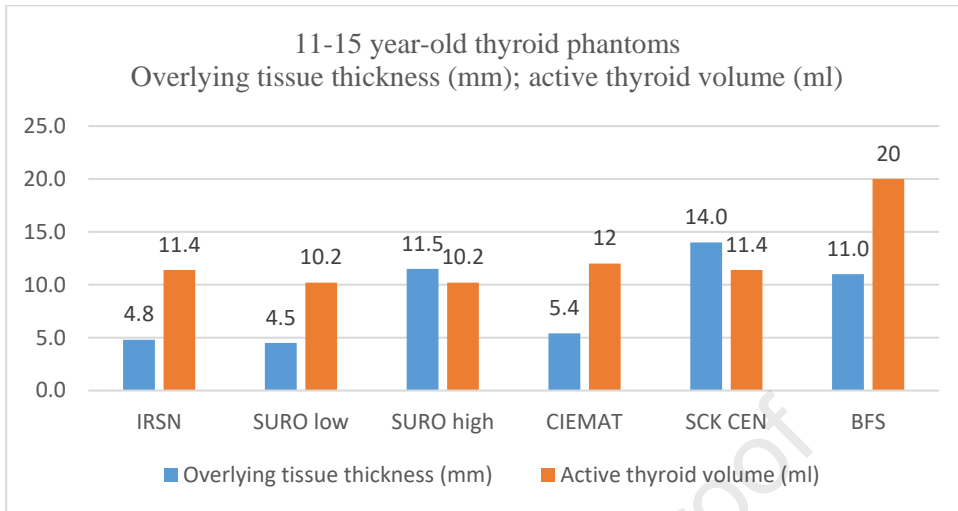
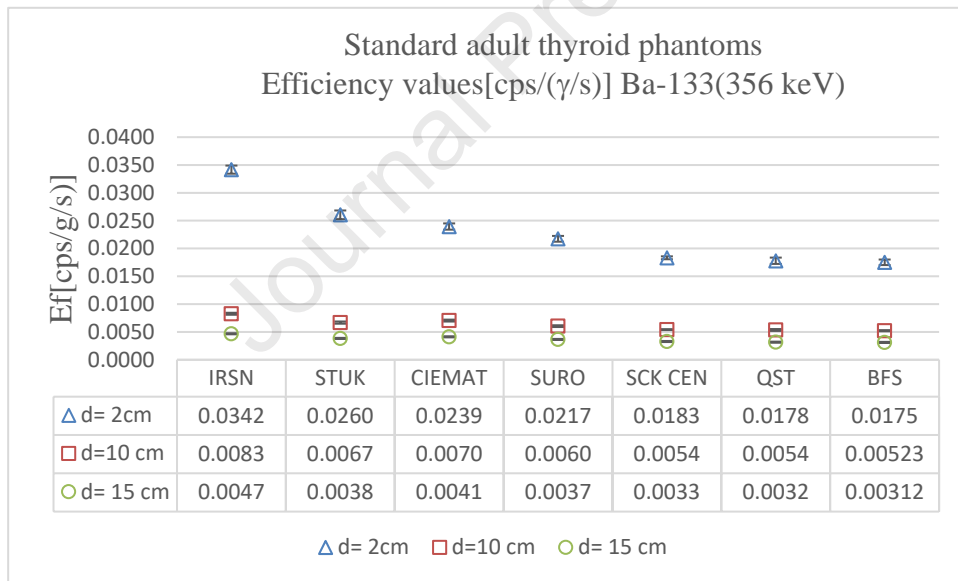


Figure 4. A) ^{133}Ba Efficiency values for “11-15 y” thyroid phantoms B) overlying tissue thickness and active thyroid volume for “11-15 y” thyroid phantoms



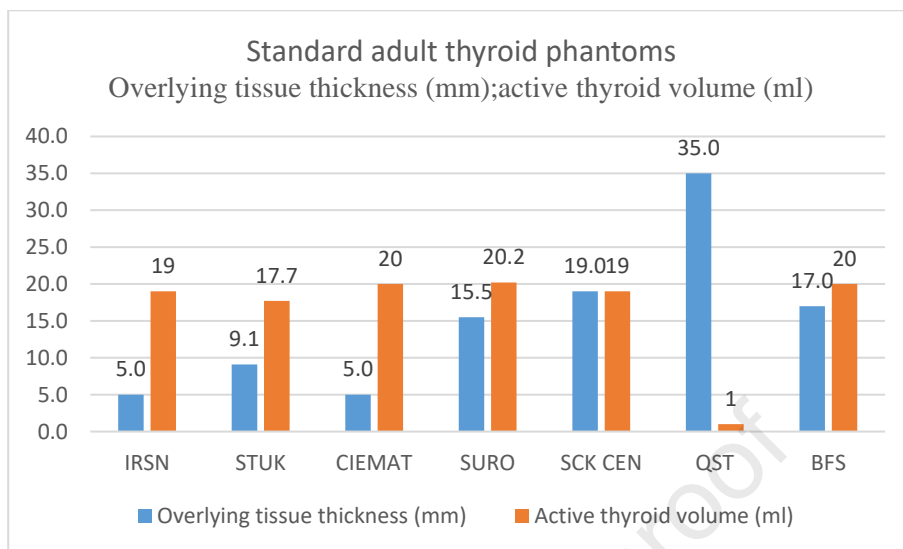


Figure 5. A) ^{133}Ba Efficiency values for standard adult thyroid phantoms B) overlying tissue thickness and active thyroid volume for standard adult thyroid phantoms

4. CONCLUSIONS

There are significant differences in the design of the different age-dependent phantoms among the participating laboratories. Such differences give rise to significant variations in the efficiency values. The thyroid volume and overlying tissue thickness 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 an underestimation 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 (J.M. Gómez-Ros et al, 2019) (CATHyMARA, 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).

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HIGHLIGHTS

- Intercomparison Age-dependent thyroid phantoms for calibration and in vivo monitoring of ^{131}I in thyroid.
- To enhance the assessment of ^{131}I incorporation in thyroid, it is advisable to develop age-dependent thyroid phantoms
- employing age-dependent phantoms enhances the reliability of thyroid dose assessment
- Differences in the design of age-dependent phantoms give rise to significant variations in the detection efficiency.
- Consensus on the design of reference age-dependent thyroid phantoms is needed to optimize and harmonize procedures.

Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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