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Development and implementation of a measurement system for PTW water phantom in the determination of absorbed dose to water

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Abstract: At Secondary Standard Dosimetry Laboratory (SSDL) in Venezuela is the only one in the country that performs calibrations of dosimetry systems with an IAEA water phantom. However, SSDL has a PTW water phantom, for which there is no procedure for the calibration of dosimetry systems. Therefore, a methodology was developed for its validation using a cobalt-60 equipment, a secondary standard, an IAEA water phantom and a PTW phantom. The adapter for ionization chamber type NE 2561 was studied and designed to protect it from water. The methodology consisted of calculate of absorbed dose rate to water in IAEA water phantom and PTW water phantom. Subsequently, the absorbed dose rates to water were compared between both phantoms and finally, the validation of the new procedures and their respective uncertainties was performed. The adapter of ionization chamber was built with PMMA material. Comparisons between absorbed dose rates to water showed that there is no difference between the two phantoms. The absorbed dose rate to water was calculated with the procedure updates along with their associated uncertainties, obtaining $\dot{D}_w$=0.13482 ± 0.00292 Gy/min. Finally, the validation obtained a value of less than 0.7%, which means that the implementation of the new procedures for the calibration of dosimetry systems is valid and applied at the SSDL-Venezuela.

Keywords: Metrology and dosimetry, dosimeter system, absorbed dose to water, calibration, water phantom.

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Desarrollo e implementación de un sistema de medición para un maniquí de agua PTW en la estimación de la dosis absorbida en agua

Resumen: El Laboratorio Secundario de Calibración Dosimétrica (LSCD) en Venezuela es el único del país que realiza las calibraciones de los sistemas dosimétricos con un maniquí de agua OIEA. Sin embargo, el LSCD cuenta con un maniquí PTW, del cual no existe procedimiento para la calibración de los sistemas dosimétricos. Por ello, se realizó una metodología para la validación del mismo utilizando un equipo de cobalto-60, un estándar secundario, un maniquí de agua OIEA y PTW. Se estudió y diseñó el adaptador para la cámara de ionización tipo NE 2561 para resguardarla del agua. La metodología consistió estimar la tasa de dosis absorbida en agua en el maniquí de agua OIEA y PTW. Posteriormente se compararon las tasas dosis absorbida en agua entre ambos maniquíes y por último se realizó la validación de los nuevos procedimientos y sus incertidumbres respectivas. Se construyó el adaptador de la cámara de ionización con material de PMMA. Las comparaciones entre las tasas de dosis absorbida en agua arrojaron que no existe diferencia entre ambos sistemas de medición. Se estimó la tasa de dosis absorbida en agua con las actualizaciones de los procedimientos junto a sus incertidumbres asociadas, obteniendo $\dot{D}_w = 0,13482 \pm 0,00292$ Gy/min. Por último, en la validación se obtuvo un valor menor de 0,7%, por lo cual, la implementación de los nuevos procedimientos para la calibración de los sistemas dosimétricos es válidos y son aplicados en el LSCD-Venezuela.

Palabras claves: Metrología y dosimetría, sistema dosimétrico, dosis absorbida en agua, calibración, maniquí de agua.

1. INTRODUCTION

At Secondary Standard Dosimetry Laboratory (SSDL) in Venezuelan Institute for Scientific Research (IVIC) of the Bolivarian Republic of Venezuela is the custodian of the national standard for measurements of ionizing radiation and dosimetry quantities such as air Kerma (K) and absorbed dose to water (D_w). At the same time, it provides services in calibration, quality control and metrology of ionizing radiation in the area of radiodiagnosis, radiotherapy, radiation protection and nuclear medicine, in public and private institutions. SSDL is the link between the Primary Standard Dosimetry Laboratories (PSDLs) and the users who require calibration services to ensure traceability in the use and applications of ionizing radiation in the various areas of nuclear energy [1].

Consequently, the absorbed dose to water is the quantity of main interest in radiotherapy, because it is closely related to the biological effects of radiation [2], managing to induce alterations at the DNA level of the cell.

The methodology at SSDL- IVIC for performing calibrations to dosimetry systems is based on Technical Reports Series No 398 (TRS No 398) [2], which is an international code of practice that meets the need for calibration of the ionization chambers in terms of absorbed dose to water. Therefore, Cobalt-60 (^{60}Co) [3,4], is used in SSDL to perform calibrations of dosimetry systems used in health centers.

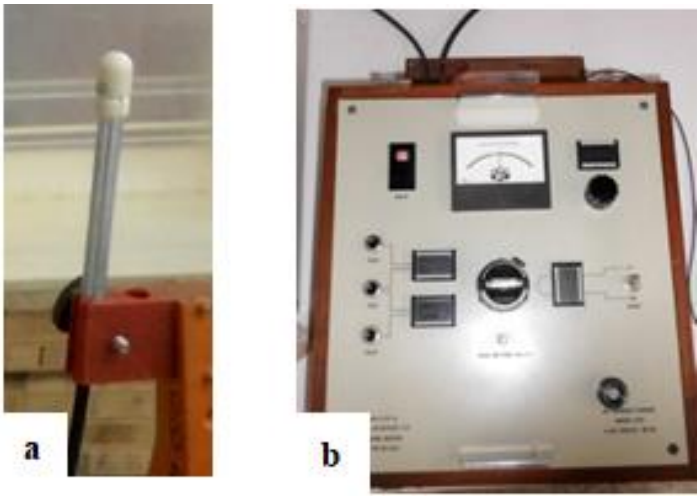
Thus, a properly calibrated dosimetry system with traceability to secondary standards is important to guarantee the adequate dose to be received by patients in radiotherapy centers. Dose determination in external beam radiotherapy is done using an ionization chamber, with a calibration factor $N_{D,w}$, helping medical physicists and all radiotherapy workers to achieve uniformity and consistency in dose administration of radiation [2].

Therefore, it is proposed to develop a procedure for the calculation of absorbed dose to water with the SSDL-IVIC secondary standard, based on the characteristics of the PTW water phantom, in order to characterize and validate the procedures for the calibration of the users' dosimetry systems and to determine the uncertainties associated with the measurements.

2. MATERIALS AND METHODS

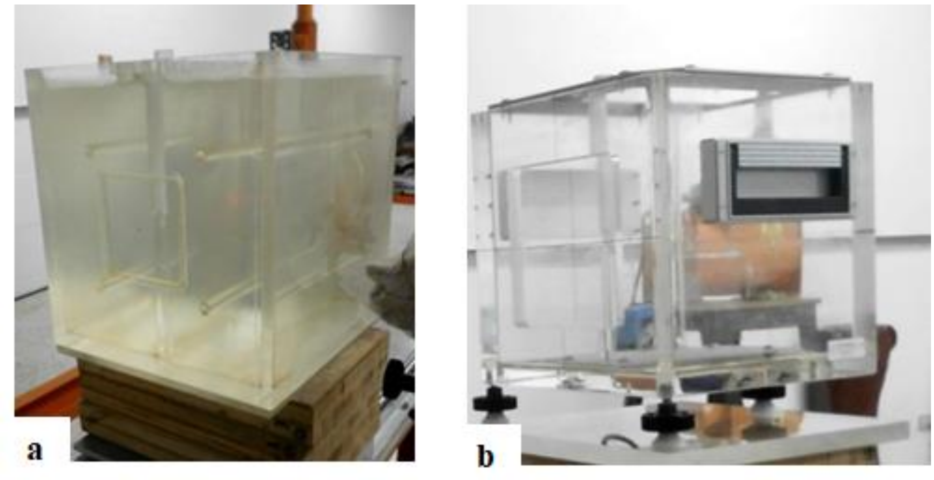
The SSDL-IVIC has a Nuclear Enterprise (NE) branded secondary standard for radiotherapy, which consists of the thimble Ionization Chamber type NE 2561 (figure 1-a) and Electrometer type NE 2560 (figure 1-b). This is used for calibrations in an IAEA water phantom with ^{60}Co.

Figure 1: Secondary standard. a: Ionization chamber type NE 2561; b: Electrometer type NE 2560.



The IAEA phantom (figure 2-a) of the SSDL-IVIC has been in use for more than 30 years and shows deterioration, imperfections in the walls, its leveling is complex and its positioning of the plane-parallel ionization chamber is difficult. However, the SSDL-IVIC has a PTW water phantom type 4322 (Figure 2-b), which allows three ionization chambers to be irradiated simultaneously, varying the depth of the measurement, decreasing the time of positioning and leveling, reducing the uncertainty in the measurements, among other features, which make the phantom more versatile in practice.

Figure 2: Water Phantom: a: IAEA; b: PTW.



2.1. Design of the adapter for ionization chamber type NE 2561.

Figure 3 illustrates the dimensions of the ionization chamber type NE 2561. The point effective of measuring is 5 mm from the graphite wall to the center of the electrode.

Figure 3: Dimensions of the ionization chamber type NE 2561.

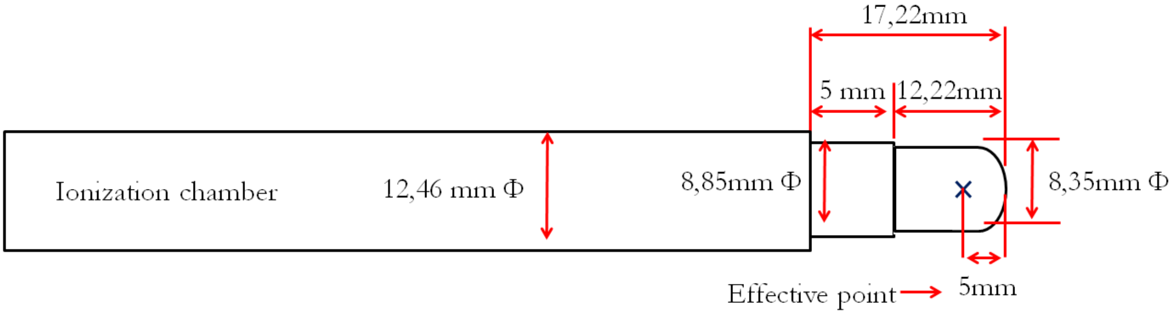


Figure 4 illustrates the inlet window (front face) of the PTW water phantom along with a schematic of its dimensions, which are used in the design of the adapter for ionization chamber type NE 2561.

Figure 4: Physical characteristics of the PTW water phantom.

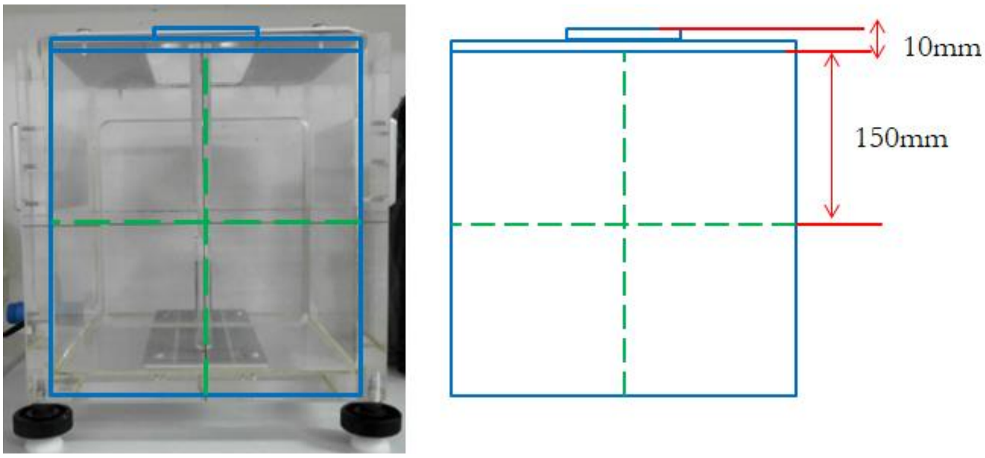


Figure 5 shows the lengths and diameters necessary for the design of the adapter to be implemented in the PTW water phantom, with an empty space where the ionization chamber type NE 2561 fits perfectly. The distance shown in Figure 6 (160 mm) is very important, because it is the distance that the ionization chamber must be positioned to coincide with the center of the radiation field of the cobalt equipment.

Figure 5: Dimensions of the adapter of ionization chamber type NE 2561.

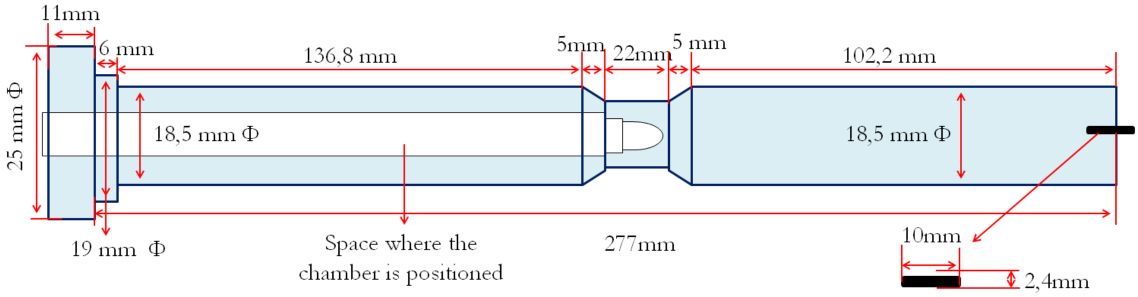


Figure 6: Important distance to coincide the effective point of the ionization chamber with the center of the radiation field in the cobalt equipment.

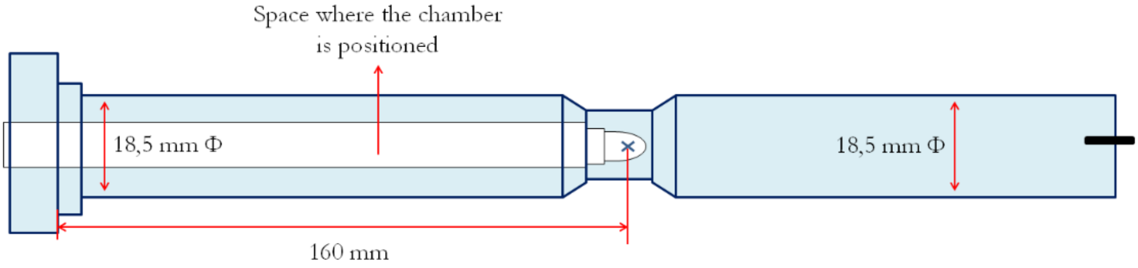
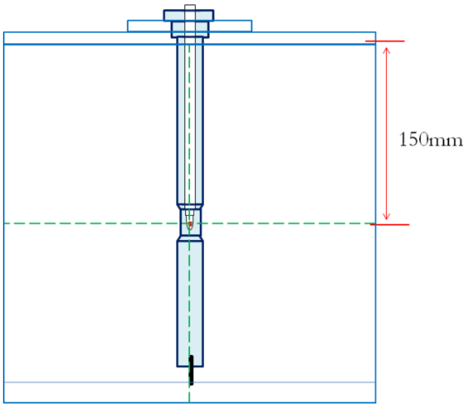


Figure 7 illustrates the final assembly where the ionization chamber is inside the adapter and the effective point coincides with the center of the phantom and in turn that point will coincide with the center of the radiation field in the cobalt equipment.

Figure 7: Positioning of the ionization chamber on the adapter inside the water phantom.

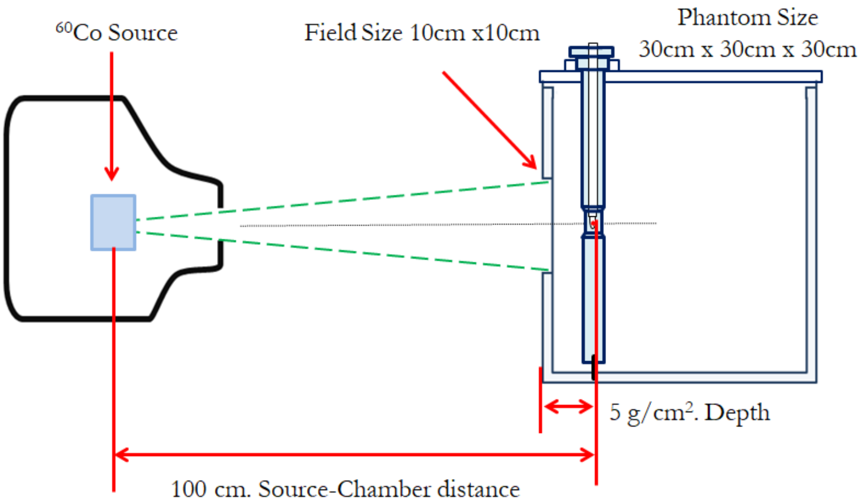


2.2. Absorbed dose rate to water in a reference beam with the IAEA and PTW phantoms.

The IAEA and PTW phantom were leveled and positioned, complying with the reference conditions of the TRS 398 (figure 8): source-chamber distance (100 cm), field size (10cm x 10cm), depth in phantom of the reference point of the chamber ($5 g/cm^2$), as illustrated in Figure 9.

Figure 8: Positioning of the phantoms in the SSDL bunker in Venezuela.

Figure 9: Reference conditions recommended in TRS No 398.



The calculation of the adsorbed dose rate to water under reference conditions for a ^{60}Co beam was calculated by the following equation:

$$\dot{D_w} = N_{D,w} \cdot \bar{X} \cdot k_{tp}$$

where $N_{D,W}$ is the calibration factor (0.01015 Gy/div), $\bar{X}$ (div/min) is the average of the reading and K_{tp} is the influence quantities of temperature and pressure. K_{tp} was obtained by the following equation:

$$k_{t,p} = \frac{(273{,}15 + T_m) \cdot P}{(273{,}15 + T) \cdot P_m}$$

where T_m is the average temperature between the initial and final temperature of each series, P_M is the average pressure between the initial and final pressure of each series, T and P are predetermined values of temperature and pressure, 20ºC and 1013.25 mbar respectively.

The calculation of the adsorbed dose rate to water with the secondary standard was performed based on Technical Reports Series No 469 (TRS No 469) [5], which was grouped in a run of 3 series and 7 measurements for each series. The first series was with the IAEA phantom, taking 7 measurements, temperatures and pressures at the beginning and end of the series. The second series was performed with the PTW phantom, obtaining in the same way 7 measurements, temperature and pressure at the beginning and end of the series. The third series was performed in the same way as the first. The doses of the first and third series were averaged, obtaining at the end an absorbed dose rate with the IAEA phantom and one with the PTW phantom.

In the end, 24 runs were performed, for a total of 24 estimates of absorbed dose rate to water in the IAEA and PTW phantom. It is important to note that each procedure involved disassembling and reassembling the entire system in order to consider reproducibility and consistency in the measurements.

2.3. Absorbed dose rate to water with the secondary standard of SSDL-IVIC with the new parameters.

The absorbed dose rate to water was calculated with the secondary standard with the updates of the procedures in the PTW phantom, together with its associated uncertainties. Subsequently, the dose rate obtained was compared with the theoretical absorbed dose rate value decayed to date, for its respective validation.

The evaluation of uncertainties associated with the measurements are expressed into type A and type B. Type A is by statistical analysis and type B is based on means other than statistical analysis [2]. Combining the uncertainties in quadrature in the types A and B yields the combined standard uncertainty. Finally, the combined standard uncertainty is multiplied by the coverage factor, k=2, to obtain an expanded uncertainty, which corresponds to 95% confidence limits.

3. RESULTS AND DISCUSSIONS

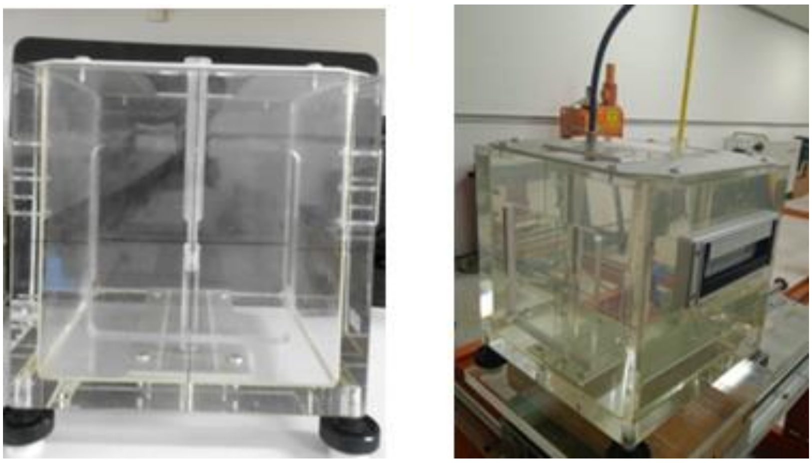
3.1. Adapter for ionization chamber type NE 2561 for PTW water Phantom.

The ionization chambers type NE 2561 is not designed to work in water; therefore, it is necessary to use adapters to protect them. Also, the adapter allows the ionization chamber to be accurately positioned at a given depth. The adapter material should be water equivalent; that is, have the same absorption and scatter as water. For these reasons, the adapter for ionization chamber type NE 2561 was constructed of PMMA material, see figure 10.

Figure 10: Adapter for ionization chamber type NE 2561.

In Figure 11 the adapter is positioned at a given depth in the PTW water phantom and the ionization chamber is positioned perfectly inside the phantom.

Figure 11: Positioning of the adapter on the PTW water phantom.



3.2. Comparison of the absorbed dose rate to water between the IAEA and PTW phantoms.

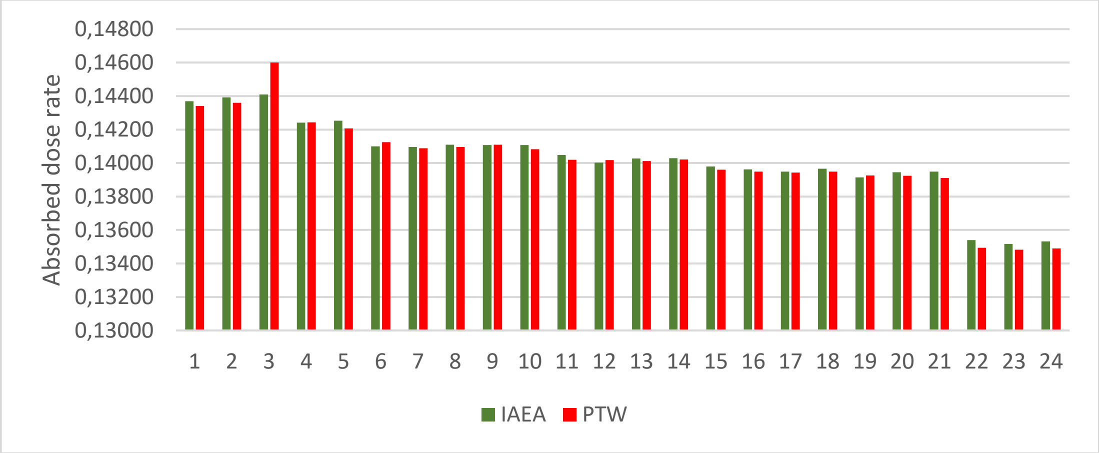
Table 1 shows the results obtained for the 24 absorbed dose rates in the IAEA phantom and the PTW phantom with the secondary standard of SSDL-IVIC.

Table 1: Absorbed dose rate to water of IAEA phantom and PTW phantom.

	$\dot{D}$ (Gy/min)	
Nº	IAEA	PTW
1	0.14369	0.14340
2	0.14393	0.14360
3	0.14409	0.14601
4	0.14240	0.14243
5	0.14252	0.14208
6	0.14101	0.14124
7	0.14095	0.14089
8	0.14109	0.14096
9	0.14107	0.14110
10	0.14108	0.14083
11	0.14048	0.14019
12	0.14002	0.14018
13	0.14027	0.14011
14	0.14028	0.14021
15	0.13979	0.13961
16	0.13963	0.13949
17	0.13948	0.13942
18	0.13966	0.13949
19	0.13915	0.13927
20	0.13945	0.13924
21	0.13948	0.13911
22	0.13539	0.13494
23	0.13516	0.13482
24	0.13532	0.13489

The absorbed dose rate was graphed with the table 1, see figure 12, where the green bar represents the values with the IAEA phantom and the red bars with the PTW phantom. They can be seen that the performance of the two phantoms are similar.

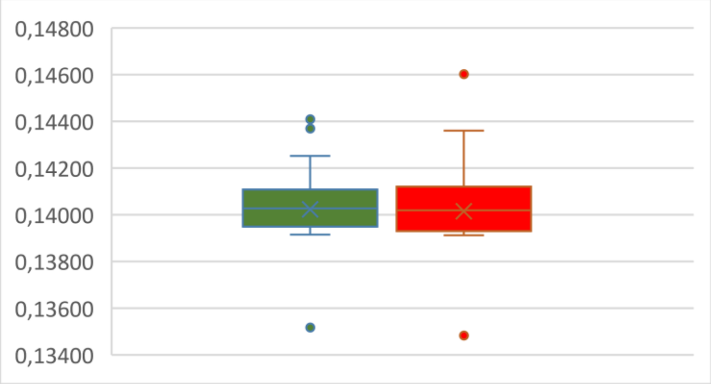
Figure 12: Absorbed dose rate in water in both water phantom.



With Table 1, the Shapiro-Wilk test was performed to evaluate whether the data follows a normal distribution. The result was a P-value of 0.001285, which means that the data does not follow a normal distribution.

The evaluation of homogeneity of variances or homoscedasticity can be seen in figure 13, where the homoscedasticity of the IAEA and PTW water phantoms are the equal. The homogeneity of variance test was performed using the Fligner-Killeen variance test for data that do not follow a normal distribution. With the absorbed dose rate of table 1, a P-value of 0.567 was obtained, therefore, the variances are equal.

Figure 13: The homogeneity of variance to absorbed dose rate in water in both water phantom.



Therefore, the Wilcoxon test was applied to compare the absorbed dose rate to water of the IAEA phantom with the PTW phantom. With the absorbed dose rate of table 1 a P-value of 0.6604 was obtained, so there is no difference in the absorbed dose rate to water between the IAEA phantom and the PTW phantom.

With the analyses previously described, there is no difference in the absorbed dose rate to water between the IAEA phantom and the PTW phantom.

3.3. Calculation of absorbed dose rate to water with the PTW phantom with the new parameters and uncertainty.

The absorbed dose rate to water was calculated with the secondary standard in the PTW water phantom with the updates of the adapter for ionization chamber type NE 2561 and their respective uncertainties. Table 2 shows the results of k_{tp}, average of the measurements (X_p), standard deviation ($S(x_i)$), coefficient of variation (CV%), the absorbed dose rate to water ($\dot{D_w}$), the percentage difference (dif%) between the calculated dose and the decayed dose.

Table 2: Absorbed dose rate to ionization chamber in the PTW phantom.

N_{Dwssdl} (Gy/div)	K_{tp}	n	X_p (div(min)	$S(X_i)$	CV%	$\dot{D_w}$ (Gy/min)	$\dot{D}$(decayed)	Dif%
0,01015	1,2156	7	10,92726	0,01	0,12	0,13482	0,13523	-0,30

Obtaining an absorbed dose rate of 0.13482 Gy/min with a percentage difference of -0.30% with a tolerance of 0.50% by SSDL, thus indicating that the positioning of the ionization chamber type NE 2561 in the PTW phantom is within the parameters established by the SSDL-IVIC.

On the other hand, the uncertainties associated with the measurements are shown in table 3. These are based on TRS N 398 [2] and Evaluation of measurement data [6].

Table 3: Estimated uncertainty in the determination of absorbed dose rate to water.

Relative uncertainty of absorbed dose rate to water ($\dot{D}_w$)		
	Uncertainty (%)	
	Type A	Type B
Calibration of secondary standard, $N_{D,W}$	-	0.48
Long term stability of secondary standard	-	0.56
Positioning	-	0.30
Readings	0.04	-
Temperature	0.51	0.29
Pressure	0.01	-
Combined relative uncertainty	0.51	0.85
Overall relative uncertainty	0.99	
Expanded relative uncertainty (k=2)	1.98	

The relative uncertainty for $N_{D,w}$ comes from the PSDLs calibration certificate and the long-term stability of secondary standard comes from the quality control performed at SSDL-IVIC.

In conclusion, the expanded relative uncertainty of 1.98% has a confidence probability of 95%, therefore, the true value of the absorbed dose rate to water is:

$$\dot{D}_w = 0{,}13482 \pm 0{,}00292\ [Gy/min]$$

3.4. Validation of the measurement system with the new parameters in the PTW water phantom.

According to the International Vocabulary of Metrology [7], the term validation reflects a verification that the procedures performed are adequate and appropriate for implementation in the calibrations of measurement systems. It is important to note that there are no specific processes for the validation of measurement systems, however, the ISO/IEC 17025:2017 international standard [8], leads to the necessary requirements for the validation of a procedure in calibration laboratories, which states that this process should include the comparison of the results with other methods, or with calibrations using primary standards, reference materials, evaluation of uncertainty, among others.

For this reason, the validation for the calibration procedure of the dosimetry systems with the new adapter in the PTW phantom was performed by comparing the absorbed dose rate to water with the ionization chamber type NE 2561 (0.13482 Gy/min) with the theoretical absorbed dose rate to water value decayed at the measurement date (0.13523 Gy/min). Obtaining that the percentage difference is 0.30%, which does not exceed ±0.7%, as recommended in the work of Alba Zaretzky et al [9]. Therefore, the implementation of the adapter for the ionization chamber type NE 2561 and the new parameters studied in the measurement system for the calculation of the absorbed dose rate to water are valid and are applied in the SSDL of Bolivarian Republic of Venezuela.

4. CONCLUSIONS

As a result of the research, the adapter for ionization chamber type NE 2561 for the PTW water phantom was designed and built with PMMA material, achieving a perfect positioning of the chamber inside the phantom and at the reference point. The comparison between the absorbed dose rate to water in the IAEA and PTW phantom showed that there is no difference in the absorbed dose rate to water between the phantoms. Subsequently, the absorbed dose rate to water was calculated with the new procedures with their respective uncertainties, obtaining $\dot{D}_w$=0.13482 ±0.00292 Gy/min.

Finally, the absorbed dose rate to water was compared, obtaining values lower than 0.7%. Therefore, the implementation of the new parameters studied in the measurement system in the PTW water phantom is valid and they are applied in the SSDL-IVIC of Bolivarian Republic of Venezuela.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] LEAL, C., et, al. (2021). Secondary Standard Dosimetry Laboratories. Knowledge Observer, Caracas, Special Edition, p. 23-42, 2021.

[2] IAEA, WHO, PAHO and ESTRO. Absorbed dose determination in external beams radiotherapy. An international code of practice for dosimetry based on standards of absorbed dose to water. Technical reports series N° 398. IAEA, Viena, 2000.

[3] AHMED, S. N. (2007). Physics and Engineering of Radiation Detection. United States of America. Elsevier. Pag. 40. 2007.

[4] MARTIN, J. E. Physics for Radiation Protection. Third Completely Updated Edition. Alemania: Wiley-VCH Verlag & Co. KGaA, 2013.

[5] IAEA, WHO. Callibration of reference dosimeters for external beam radiotherapy. Technical reports series N° 469. IAEA, Viena, 2009.

[6] JCGM. Evaluation of measurement data. Guide to the expression of uncertainty in measurement. First Edition. España. 2008.

[7] JCGM. International Metrology Vocabulary. Fundamental and general concepts and associated terms. Third Edition. España. 2012.

[8] ISO/IEC. General requirements for the competence of testing and calibration laboratories. Second Edition, 2005.

[9] ZARETKY, A., SARAVÍ, M., STEFANIC, A., MONTAÑO, G., & VALLEJOS, M. Optimization and validation for the calibration procedure of a dosimeter for radiotherapy in air and water, in cobalt 60. Metrology Symposium. National Metrology Center. 2010.

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