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Non-Standardized Methodology for the Evaluation of Shielding in Superficial X-Rays Radiation therapy

Metodología no Estandarizada para la Evaluación de Blindaje en Radioterapia Superficial con Rayos X

Metodologia Não Padronizada para Avaliação de Blindagem em Radioterapia Superficial com Raios-X

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ABSTRACT

Methodologies for the design of facilities dedicated to radiotherapy equipment are available in the literature, in which physical parameters of a very limited number of shielding materials are also offered. In this paper, a non-standard methodology is proposed for the evaluation and redesign of rooms used for superficial radiation therapy with energies of up to 100 kV, based on the calculation methodologies of relevant documents such as IAEA SRS No. 47 and the IPEM Report 75, in which the physical parameters of the materials are evaluated from the NIST data. The methodology was applied to the redesign of a room for the installation of a SENSUS SRT-100 equipment. Significant differences were found compared to conventional methodologies, especially for barriers that are insufficiently armored and that are very close to the source. For the rest of the barriers, the results show that there are no differences in the use of one or another methodology.

Keywords: radiation protection; shielding against radiation; superficial radiation therapy.

RESUMEN

En la literatura están disponibles metodologías para el diseño de instalaciones dedicadas a equipos de radioterapia, en las que además se ofrecen parámetros físicos de un número muy limitado de materiales para el blindaje. En este trabajo se propone una metodología no estandarizada para la evaluación y el rediseño de locales para equipos de radioterapia superficial con rayos X con potenciales generadores de hasta 100 kV, basada en las metodologías de cálculo de documentos relevantes como el IAEA SRS No. 47 y el IPEM Report 75 y en la cual los parámetros físicos de los materiales son evaluados a partir de los datos del NIST. La metodología fue aplicada al rediseño de un local para la instalación de un equipo SENSUS SRT-100. Se encontraron diferencias significativas en comparación con las metodologías convencionales, sobre todo para barreras insuficientemente blindadas y que se encuentran muy próximas a la fuente. Para el resto de las barreras, los resultados muestran que en términos prácticos y siempre que se utilicen valores de carga de trabajo, factores de uso y de ocupación suficientemente conservadores, no hay diferencias en el uso de una u otra metodología.

Palabras clave: protección radiológica; blindaje contra radiaciones; radioterapia superficial con rayos X.

RESUMO

Metodologias para o projeto de instalações dedicadas a equipamentos de radioterapia estão disponíveis na literatura, nas quais também são oferecidos parâmetros físicos de um número muito limitado de materiais para blindagem. Este trabalho propõe uma metodologia não padronizada para avaliação e redesenho de instalações para equipamentos de radioterapia superficial com raios X com potenciais geradores de até 100 kV, com base nas metodologias de cálculo de documentos relevantes como IAEA SRS No. 47 e IPEM Relatório 75 e no qual os parâmetros físicos dos materiais são avaliados a partir dos dados do NIST. A metodologia foi aplicada ao redesenho de uma sala para instalação de um equipamento SENSUS SRT-100. Diferenças significativas foram encontradas em relação às metodologias convencionais, principalmente para barreiras insuficientemente blindadas e muito próximas da fonte. Para as restantes barreiras, os resultados mostram que em termos práticos e desde que sejam utilizados valores suficientemente conservadores de fatores de carga de trabalho, uso e ocupação, não existem diferenças na utilização de uma ou outra metodologia.

Palavras chave: proteção contra radiação; blindagem contra radiação; radioterapia superficial com raios X.

INTRODUCTION

The optimization of radiation protection is one of the basic principles that apply not only to the operation but also to the design of the facility. This principle states that the probability of an exposure, the number of people exposed and the magnitude of their individual doses should be kept as low as reasonably achievable, taking into account economic and social factors (International Atomic Energy Agency (IAEA), 2018). To keep the magnitude of the doses as low as possible during the operation, validated calculation methodologies for the design of the facilities are used.

The existing methodologies in the literature are based on the design of new facilities, so their use in the remodeling of existing rooms or bunkers requires a correct interpretation or adaptation of them (Horton & Eaton, 2017; International Atomic Energy Agency (IAEA), 2006; National council on radiation protection and measurements, 2004).

Superficial X-ray radiation therapy stands out as an effective and safe treatment for non-melanoma skin cancer with a cure rate similar to many surgical options and superior cosmetic results. It is also cheaper, safer, simpler and generally more versatile than the rest of the radiotherapy modalities, with experience in its use of more than 120 years (Nazco et al., 2019; Pashazadeh et al., 2019).

For this reason, the Healthcare for Oncology Patients Center of Pinar del Río acquired one equipment for superficial X-ray radiotherapy manufactured by SENSUS Healthcare (Boca Raton, FL), model SRT-100^{TM}, with energies of up to 100 kV, which must be installed in a room where other equipment with a similar purpose was used for more than 20 years, but with different dosimetric characteristics, especially in terms of radiation qualities (up to 50 kV).

In the consulted literature, no recommendations were found for the evaluation and redesign of facilities of superficial radiotherapy equipment with energies of up to 100 kV.

The goal of this work is to develop a non-standardized methodology that allows evaluating the shielding of premises for the installation of superficial radiotherapy equipment with X-rays with energies of up to 100 kV, for its subsequent redesign.

MATERIALS AND METHODS

Treatment machine

The equipment is manufactured by the company SENSUS Healthcare (Boca Raton, FL), model SRT-100^{TM}. It consists of two main blocks: the treatment unit, which contains the X-ray tube which is located in the treatment room, and the operator's control console (Figure 1). These blocks can be distanced up to 30 meters.

Figura 1 – SENSUS SRT-100^{TM} Treatment unit and control panel.

The treatment unit presents a mobile and compact design, as well as a non-monoisocentric configuration based on an articulated arm, allowing space savings and providing flexibility for its location and the performance of treatments in any anatomical location (Sensus Healthcare, 2013).

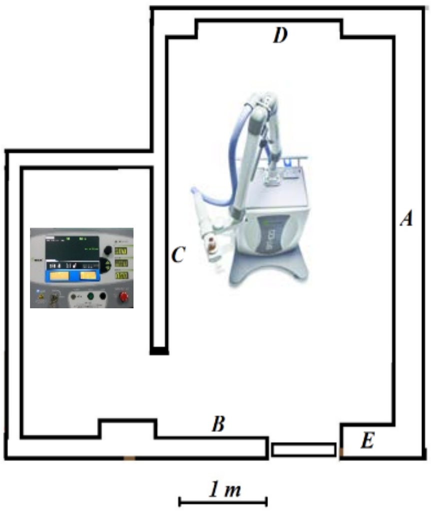
The machine is configured to deliver X-ray beams with clinical radiological qualities of 50, 70 and 100 kV with inherent filtrations of 0.4, 0.75 and 1.14 mm Al respectively. The internal filters are automatically positioned according to the selected energy reducing potential human errors. Physical-dosimetric parameters of a group of machines acquired by the country can be found in the research of Aguiar et al. (Aguiar et al., 2020)

Treatment room

The facility for the superficial X-ray therapy presents the following borders:

- To the north through the mold room
- To the south through a portal
- To the east through the patio where the emergency generator is located.
- To the west through the waiting room

Figure 3 shows a plan of the facility. It highlights the different barriers and their corresponding adjacent areas.



A – South portal
B– Waiting room
C – Console
D – East courtyard
E – Waiting room

Figure 2 - Diagram of the superficial radiotherapy room.

For each barrier, the National Applied Research Company (INVESCONS), took samples to be characterized in terms of composition, thickness and density of each of its components (Empresa Nacional de Investigaciones Aplicadas, 2019).

Calculation methodologies

Due to the non-monoisocentric assembly of the equipment, all the barriers were considered primary for a photon radiation quality of 100 keV monoenergetic.

The workflow consisted of calculating for each of the barriers the real attenuation (B_{real}) and the required attenuation (B_{req}), the latter considering that there are no previous barriers, and calculate the necessary thickness for the reinforcement knowing the TVL of the material with which it is desired to reinforce from the following equations (Horton & Eaton, 2017; International Atomic Energy Agency (IAEA), 2006).

$$B_{real} = e^{-ln10 \sum_{i=1}^{n} \frac{x_i}{TVL_i}} \quad [1]$$

$$B_{req} = P \frac{(d+SAD)^2}{WUT} \quad [2]$$

$$t_r = TVL_r log\left(\frac{B_{real}}{B_{req}}\right) \quad [3]$$

in which,
n: number of barrier components
x_i: thickness of the i-th barrier component
TVL_i: tenth value layer that corresponds to each thickness component x_i.

$P, W, U\ y\ T$: allowed dose for practice, workload, use factor and occupancy factor respectively.
SAD: distance from the source to the exit of the cone. The value used in the calculations was $SAD = 0{,}25\ \mathrm{m}$.
d: distance in meters from the exit of the cone to a point located 30 cm behind the barrier.
mass attenuation coefficients of the constituent substances of each of them, reported by the National Institute of Standards and Technologies of the United States. (NIST) its tables 3 and 4 (National Institute of Standards and Technology (NIST), s.f.).

t_r: minimum thickness necessary for the reinforcement of the barrier with the material r.
TVL_r: is the greatest tenth value layer for the reinforcing material in the range of photon energies up to 100 keV.

The TVL_i were calculated taking into account the chemical composition and the mass fractions of the barrier components, as well as the

The stoichiometric composition and mass fractions of the materials were obtained by consulting bibliographies on construction materials, although in some cases, such as concrete and calcium sulfate, NIST reports these values in its section dedicated to compounds materials (NIST, s.f., table 4).
The equations used for the calculation were:

$$TVL_i = \frac{ln10}{\mu_i} \qquad [4]$$

$$\mu_i = \rho_i \left(\mu/\rho\right)_i \qquad [5]$$

$$\left(\mu/\rho\right)_i = \sum_{k=1}^{m} w_k \left(\mu/\rho\right)_k \qquad [6]$$

Were:

TVL_i: is, as stated above, the tenth value layer for the energy of 100 keV, of each material that makes up the barrier.
μ_i, $\left(\mu/\rho\right)_i$ y ρ_i: linear attenuation coefficient, mass attenuation coefficient and density of each barrier material.
m: number of components of the i-th material.

w_k y $\left(\mu/\rho\right)_k$: mass fraction and mass attenuation coefficient for 100 keV, of the k-th element that composes the material.

The results were compared with the standard methodology recommended by IPEM Report 75 (Horton & Eaton, 2017) in which the equation used to calculate the TVL_i of construction materials is:

$$TVL_i = TVL_{conc}\frac{\rho_{conc}}{\rho_i} \quad [7]$$

were $\rho_{conc} = 2{,}35\ {}^{g}/_{cm^3}$ and $TVL_{conc} = 61\ mm$ are the density and TVL values for high-density concrete reported in table 18 of IAEA SRS No. 47 (International Atomic Energy Agency (IAEA), 2006).

Once the installation has been remodeled based on the proposed methodology, and with the aim of validating it, as well as obtaining the permission for clinical use from the regulatory authorities, the ambient dose equivalent rate measurements were performed in the areas outside the barriers. A 21 x 21 x 11.5 cm^3 water phantom, 100 kV energy and the largest cone (Ø 12.7 cm, SSD = 25 cm) was used. The phantom was placed at both ends of the treatment table as indicated in Figure 3, and irradiated from various directions.

RESULTS AND DISCUSSION

Once the study carried out by INVESCON was completed, the corresponding technical report was issued (Empresa Nacional de Investigaciones Aplicadas (INVESCON), 2019), with the results shown in Table 1.

Atenuación requerida (B_{req})

To calculate the attenuation required in each barrier, the following values were used *Workload (W)*

This is the value of the dose rate, in units of Gy/week at 1m from the source when irradiating patients or phantom with photon beams (International Atomic Energy Agency (IAEA), 2006). In estimating the workload, 50 patients/day x 5 days/week x 3 Gy/patient at the exit of the cone were considered, to which 3 Gy/week were added for quality controls, resulting in a value of W = 47.06 Gy/week.

Use factor (U)

In determining the use factors, it was taken into account that the equipment radiates with the same probability for each side of the room (U = 1/6 for each barrier), however, a higher value of U = 0.2 was taken.

Table 1 – Wall characteristics of the superficial radiotherapy equipment room. **Source:** INVESCONS (2019)

Wall	Material	Thickness (mm)	Density (g/cm³)
A	Mortar	75	2,072
	Lead	2	11,35
	Brick*	273	1,799
B	Mortar	95	1,803
	Lead	2	11,35
	Brick*	123	1,874
C	Mortar	50	2,000
	Lead	2	11,35
	Brick*	120	1,848
D	Mortar	50	2,222
	Concrete	150	2,650
E	Mortar	108	1,700
	Lead	2	11,35
	Concrete	170	2,313
	Brick*	120	1,873

Legend: * *Solid brick*

The occupancy factors, allowed dose values, as well as the distances from the exit of the cone to the exterior of each barrier are shown in Table 2. The allowed dose values were taken from the "Guía de seguridad para la práctica de radioterapia" (Centro Nacional de Seguridad Nuclear, 2011). The distances were taken from the outer edge of the treatment table closest to each barrier, up to 30 cm outside of the barriers (figure 3).

Real attenuation (B_{real})

The barrier *F* refers to the door of the facilitie, made of 5 mm thick Formica. For this barrier it was considered $B_{real} = 1$, that mean, full transmission.

For the rest of the barriers, as shown in Table 1, the materials to consider are: mortar, brick, concrete and lead. In the case of the last two, mass attenuation coefficients were taken directly from NIST data (NIST, s.f.).

The mortar was considered to be made up of a mixture of Portland cement (Cribillero Nizama & Quiñones Oliva, 2021) and silica sand, the brick was considered to be made up of 100 % basic clay, smectite or pyrophyllite type (Albereda Herrera, 1944; Besoain, 1985). It was found that the theoretical behavior related to absorption for different types of clay or cement does not present significant differences to make distinctions between them.

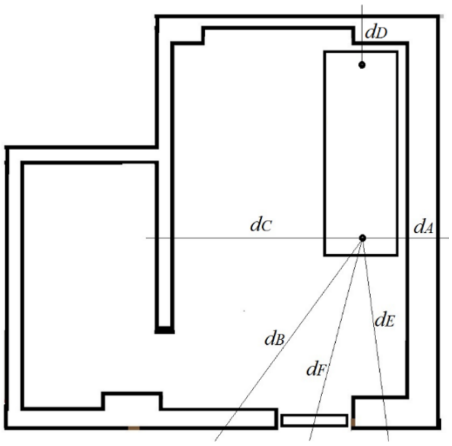


Figure 3 - Distances from the exit of the cone to each of the barriers.

Table 2 – Allowed dose, occupancy factor values, and distances from the exit of the cone to 30 cm outside of the barriers, as well as calculated values of the required attenuation according to equation [2]. **Source**: authors.

Barrier	P (Sv/week)	T	d (m)	B_{req}
A	10^{-5}	1	0,79	$1{,}15 \times 10^{-6}$
B	10^{-5}	1	2,75	$9{,}56 \times 10^{-6}$
C	2×10^{-4}	1	2,48	$1{,}58 \times 10^{-4}$
D	10^{-5}	1/16	0,8	$1{,}87 \times 10^{-5}$
E	10^{-5}	1	2,36	$7{,}24 \times 10^{-6}$
F	10^{-5}	1	2,56	$8{,}39 \times 10^{-6}$

Legend: P=alowed dose; T=occupancy factor; d=distance from the exit to the cone to behind the barrier; B_{req}=required attenuation.

Table 3 provides important details for the calculations of the elements. The graph of figure 4, on the other hand, presents the mass attenuation coefficients calculated using equation [6] and the NIST data, for each of the barrier components.

Table 3 - Stoichiometric composition and mass fractions of cement, sand and brick taken into account for the calculation of their corresponding mass attenuation coefficients. **Source**: Authors.

Component	Formula	Mass fraction
Portland Cement (Cribillero Nizama & Quiñones Oliva, 2021)		
Dicalcium silicate	Ca_2SiO_4	0,34
Tricalcium silicate	Ca_3SiO_5	0,43
Tricalcium aluminate	$Ca_3Al_2O_6$	0,10
Tetracalcium ferroaluminate	$Ca_3Al_2Fe_2O_{10}$	0,10
Calcium sulfate	$CaSO_4$	0,03
Clay (brick) (Besoain, 1985)		
Hydrated silicoaluminate	$Al_2O_{12}Si_4H_2$	1,00
Dry mortar		
Portland cement		0,33
Sand (Silicon)		0,67

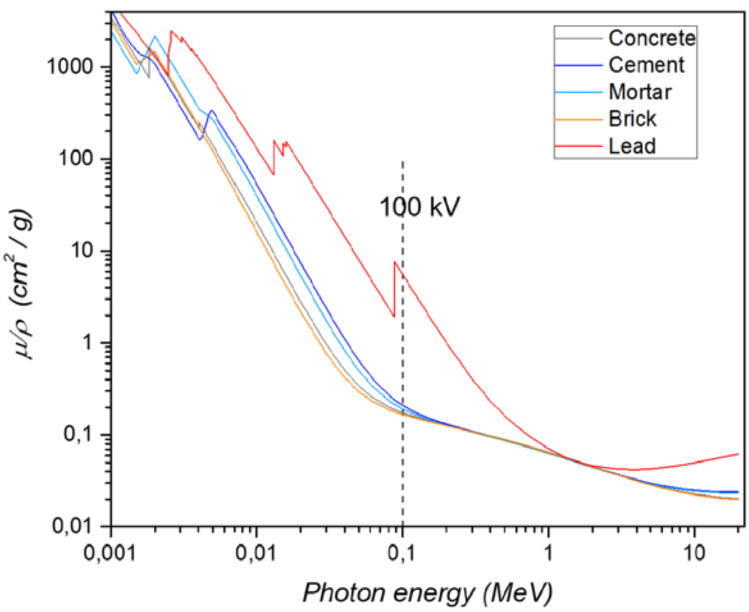


Figure 4 - Mass attenuation coefficients as function of the photon energy for components, calculated from equation [6] and NIST data.

Note: The curve corresponding to cement is also presented.

As shown above, the energy of 100 keV is very close to the absorption edge of the *K* layer of lead, therefore the highest TVL value for this material in the range up to 100 keV corresponds to the energy of 88 keV (1.06 mm).

In this way and without ceasing to be conservative, the value of $TVL_{Pb} = 0{,}9\ mm$ was chosen. Supported by IAEA SRS No. 47 (International Atomic Energy Agency (IAEA), 2006).

The lead thicknesses required for the reinforcement of the barriers, considering their actual constitution, are shown below.

Table 4. TVLs values, real attenuation and lead-equivalent thickness for the reinforcement of the barriers as results of the calculation by the proposed methodology (Horton & Eaton, 2017; NIST, s.f.). **Source:** authors.

Wall	Materials	TVL (mm)	B_{real}	B_{req}	$t_{Pb}\ (mm)$
A	Mortar	58,39	1,90 x 10^{-7}	1,15 x 10^{-6}	-0,704
	Lead	1,06			
	Brick	76,81			
B	Mortar	67,09	1,08 x 10^{-5}	9,56 x 10^{-6}	0,047
	Lead	1,06			
	Brick	73,74			
C	Mortar	60,49	4,85 x 10^{-5}	1,58 x 10^{-4}	-0,463
	Lead	1,06			
	Brick	74,78			
D	Mortar	54,44	1,21 x 10^{-4}	1,87 x 10^{-5}	0,728
	Concrete	49,99			
E	Mortar	71,16	1,01 x 10^{-8}	7,24 x 10^{-6}	-2,569
	Lead	1,06			
	Concrete	57,28			
	Brick	73,78			
F	Formica		1,00	8,39 x 10^{-6}	4,569

Legend: TVL=tenth value layer; B_{real}=real attenuation; B_{req}=required attenuation; T_{Pb}= lead-equivalent thickness.

Table 5 is similar to the previous one and shows the result of the calculations using the conventional methodology (International Atomic Energy Agency (IAEA), 2006; Horton & Eaton, 2017).

The requirement to reinforce barriers D and F, found by both methodologies, is fundamentally due. In the first case, because no lead sheet was used (Table 1), in addition, it is located at very short distance from the exit of the cone. In the second case (door) it is due to the lack of shielding even when it is separated a considerable distance from the exit of the cone.

Table 5. TVLs, real attenuation and lead-equivalent thickness values for the reinforcement of the barriers result of the calculation by the conventional methodology (International Atomic Energy Agency (IAEA), 2006) (Horton & Eaton, 2017). **Source:** authors.

Wall	Materials	TVL (mm)	B_{real}	B_{req}	$t_{Pb}\ (mm)$
A	Mortar	69,18	$1{,}85 \times 10^{-7}$	$1{,}15 \times 10^{-6}$	-0,713
	Lead	0,90			
	Brick	79,68			
B	Mortar	79,51	$9{,}44 \times 10^{-6}$	$9{,}56 \times 10^{-6}$	-0,005
	Lead	0,90			
	Brick	76,49			
C	Mortar	71,68	$3{,}41 \times 10^{-5}$	$1{,}58 \times 10^{-4}$	-0,600
	Lead	0,90			
	Brick	77,57			
D	Mortar	64,51	$2{,}83 \times 10^{-4}$	$1{,}87 \times 10^{-5}$	1,061
	Concrete	54,09			
E	Mortar	84,32	$1{,}53 \times 10^{-8}$	$7{,}24 \times 10^{-6}$	-2,406
	Lead	0,90			
	Concrete	61,98			
	Brick	76,53			
F	Formica		1,00	$8{,}39 \times 10^{-6}$	4,569

Legend: TVL=tenth value layer; B_{real}=real attenuation; B_{req}=required attenuation; T_{Pb}= lead-equivalent thickness.

Unlike the traditional methodology, the methodology proposed in this work shows that barrier B needs to be increased, however, the lead thickness necessary for this reinforcement does not exceed five hundredths of a millimeter, which in practical terms is negligible.

A quantitative comparison between both methodologies shows that the greatest difference between the lead thicknesses for reinforcement is 0.3 mm for barrier D, in favor of the conventional methodology. This value is not negligible since it represents 46% of the transmission in lead for the photon energy of 100 keV. This demonstrates that, in certain cases, the use of a simplified methodology can lead to considerable and unnecessary economic expenses, especially for insufficiently shielded barriers that are very close to the radiation source in which the effect of attenuation takes relevance over the inverse of the square law. For the rest of the barriers, the results show that in practical terms and taking sufficiently conservative workload, use factors and occupancy factors values, there are no differences in the use of one or another methodology in the evaluation of the shielding of facilities for superficial radiotherapy with generating potentials of up to 100 kV.

Validation

After the application of the proposed methodology in the remodeling of the facility, the measurements of the ambient dose equivalent rate outside the barriers yielded the expected values, which are acceptable for practice, thus validating the applied methodology.

CONCLUSIONS

A non-standardized methodology was developed based on the recommendations of the IAEA SRS No. 47, the IPEM Report 75 and the NIST data, for the evaluation and redesign of the shielding of facilities used in X-rays superficial radiation therapy with energies of up to 100kV.

This methodology can be extended to other applications and be used by medical physicists or by regulators who must evaluate and authorize the design of the facilities prior to the installation of the equipment.

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AUTHORS' CONTRIBUTION

AFY: elaboration of the methodology, bibliographic review, calculations and text writing

De la FPA and NTJ: bibliographic review, calculations and final revision of manuscript.

MBJ and BPL: bibliographic review, writing and revision of technical aspects.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.